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Impact of the 1960 major subduction earthquake in Northern Patagonia (Chile, Argentina)

Emmanuel Chapron[a,b,*], Daniel Ariztegui[c], Sandor Mulsow[d], Gustavo Villarosa[e], Mario Pino[d], Valeria Outes[e], Etienne Juvignié[f], Ernesto Crivelli[e]

[a]Renard Centre of Marine Geology, Ghent University, Ghent, Belgium
[b]Geological Institute, ETH Zentrum, Zürich, Switzerland
[c]Institute F.A. Forel and Department of Geology and Paleontology, University of Geneva, Geneva, Switzerland
[d]Instituto de Geociencias, Universidad Austral de Chile, Valdivia, Chile
[e]Centro Regional Universitario Bariloche, Universidad Nacional del Comahue, Bariloche, Argentina
[f]Physical Geography, Université de Liège, Liège, Belgium

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Abstract

The recent sedimentation processes in four contrasting lacustrine and marine basins of Northern Patagonia are documented by high-resolution seismic reflection profiling and short cores at selected sites in deep lacustrine basins. The regional correlation of the cores is provided by the combination of ^{137}Cs dating in lakes Puyehue (Chile) and Frías (Argentina), and by the identification of Cordon Caulle 1921–22 and 1960 tephras in lakes Puyehue and Nahuel Huapi (Argentina) and in their catchment areas. This event stratigraphy allows correlation of the formation of striking sedimentary events in these basins with the consequences of the May–June 1960 earthquakes and the induced Cordon Caulle eruption along the Liquiñe-Ofqui Fault Zone (LOFZ) in the Andes. While this catastrophe induced a major hyperpycnal flood deposit of ca. $3 \times 10^6\,m^3$ in the proximal basin of Lago Puyehue, it only triggered an unusual organic rich layer in the proximal basin of Lago Frías, as well as destructive waves and a large sub-aqueous slide in the distal basin of Lago Nahuel Huapi. A very recent mega-turbidite in the two distal basins of Reloncavi fjord located close to the LOFZ suggests that 1960 co-seismic movements in this area may have triggered the remobilization of ca. $187 \times 10^6\,m^3$ of marine sediments.

1. Introduction

The significant historical seismicity and volcanic activity of Northern Patagonia covers the last ca. 500 years (Casertano, 1963; Lomnitz, 1970; Beck et al., 1998). It is also deeply rooted in the culture of the Mapuche native population since the 15th century. However, it is not possible to properly establish the recurrence of major destructive subduction earthquakes in South America based only on historical data and cultural heritage (Bartsch-Winkler and Schmoll, 1993) such as those of 21–22 May 1960, the strongest (Mw 9.5) ever instrumentally recorded (Kanamori, 1977).

In this part of Chile and Argentina, the active subduction setting, the melting of the Patagonian Ice Sheet during the Lateglacial and the concomitant growth of large stratocones over the most active volcanoes of the Americas (Figs. 1 and 2), resulted in a complex Late Quaternary geomorphology (Laugénie, 1982) including many sub-aqueous environments (lakes of glacial, tectonic or volcanic origin, fjords and bays, Fig. 1). Because lakes of glacial origin and fjords have significant sedimentation rates and contrasting sub-aqueous morphologies, they are sensitive natural archives of past environmental changes. Especially when they contain several deep sub-basins, lake and fjords are sedimentary environments with a high preservation potential and constitute ideal natural environments to asses the seismic risk of an area over several millennia (Siegenthaler et al, 1987; Doig, 1990; Syvitski and Schafer, 1996; Beck et al., 1996; Chapron et al., 1999; Schnellmann et al., 2002; St. Onge et al., 2004).

*Corresponding author. Geological Institute, ETH Zentrum, Zürich, Switzerland. Tel.: +41 44 632 68 49; fax: +41 44 632 10 75.
E-mail address: emmanuel.chapron@erdw.ethz.ch (E. Chapron).

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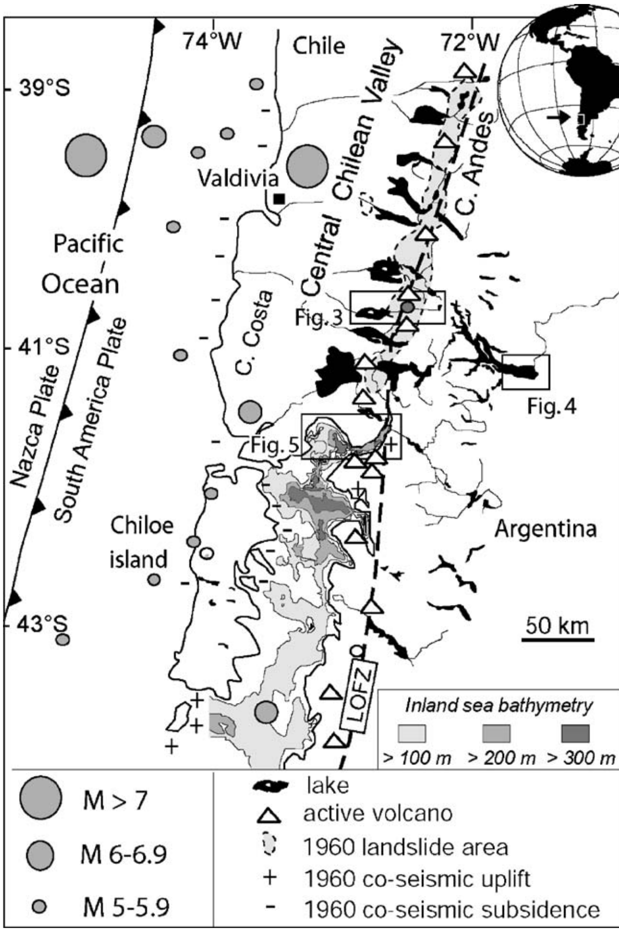

Fig. 1. General location of the study areas in Northern Patagonia and their relations with active volcanoes and the impact of 21–22 May 1960 subduction earthquake (main epicentres = gray circles, area affected by extensive earthquake-induced landslides = gray-shaded area with doted line, and co-seismic uplift (+) and subsidence (−), after Rothé, 1961 and Hervé and Ota, 1993). The active volcanoes are located in the vicinity of the NNE-trending Liquiñe-Ofqui Fault Zone (LOFZ), corresponding to an intra-arc shear zone according to Cembrano et al. (2000). The bathymetry of the inland sea next to Chiloe Island has been simplified from the results of the cruise Cimar-Fiordo 1 (Rodrigo, 1996). The catchment area of Lago Puyehue and its lacustrine infill are presented in Fig. 3. The infill of the distal basin of Lago Nahuel Huapi and the location of Lago Frías are presented in Fig. 4. Fig. 5 illustrate the seismic grid in the Reloncavi Bay and the Reloncavi Fjord and indicate the locations of seismic profiles shown in Fig. 6.

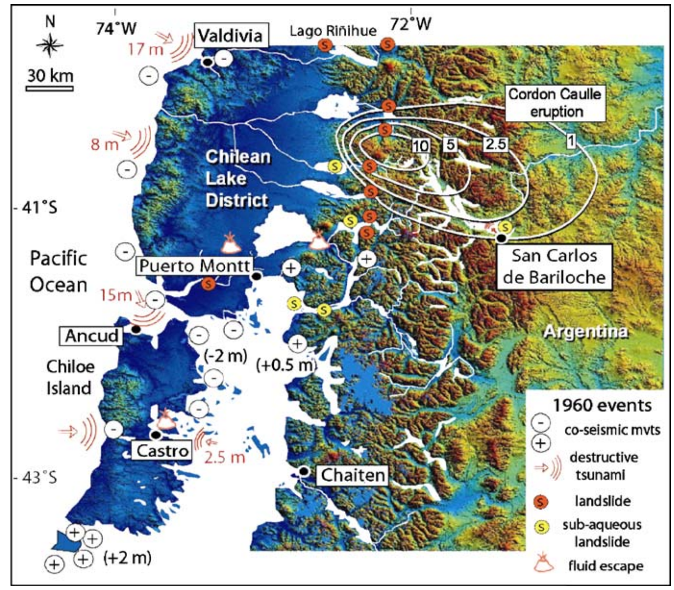

Fig. 2. Synthetic map of Northern Patagonia illustrating the impact of May–June 1960 events along the Chilean coast, in the Chilean Lake District and adjacent Argentina. The main cities mentioned in the text are also located. Large amplitude tsunami waves affected the Pacific coast, while in the inland sea south of Puerto Mont, co-seismic movements essentially changed the timing and the amplitude of the tide (after Sievers et al., 1963; Dobrovolny et al., 1963; Bartsch-Winkler and Schmoll, 1993). Large site effects and some fluid escape phenomena affected the areas filled by thick postglacial sedimentary infill during the last deglaciation near Castro and Puerto Montt (after Dobrovolny et al., 1963; Galli and Sanchez, 1963). The main sub-aerial and sub-aqueous landslides triggered by the 21–22 May earthquakes are indicated by drak gray (red) circles (after Wright and Mella, 1963) and by light gray (yellow) circles (after Wright and Mella, 1963; this study), respectively. Note that most of these slides occurred along the LOFZ in the Andes or within thick postglacial outcrops next to large rivers draining glacial lakes (e.g. the well-documented slide at the outlet of Lago Riñihue). In Lago Nahuel Huapi destructive waves offshore of San Carlos de Bariloche on 22 May (Barros, 1961) were probably triggered by a large sub-aqueous slide near the city (this study). The volume and extension of 1960 earthquake induced eruption at Cordon Caulle (isopach lines are in cm), highlights the influence of strong westerly winds during the eruption on the distribution of volcanoclastic particles across the Andes (after Wright and Mella (1963) and this study). The total volume of this eruption can be estimated as ca. $56 \times 10^7\,m^3$.

The main impact of the 21–22 May 1960 major subduction earthquake on land have been well-documented by an international team of earth scientists after this catastrophe (Fig. 1; Veyl, 1960; Rothé, 1961; Saint-Amand, 1963). Special attention has been given to the impact of the 22 May tsunamigenic seismic shocks offshore of Valdivia, in the main cities of South-Central Chile, i.e. Valdivia, Puerto Montt and Ancud (Fig. 2; Rothé, 1961; Sievers et al., 1963; Dobrovolny et al., 1963). However, only a few studies have addressed the impact of this major earthquake and the induced volcanic eruption of Puyehue Cordon Caulle volcanic complex from 24 May to 3 June, on the geomorphology and the stratigraphy of the Andes cordillera across Northern Patagonia (Tazieff, 1962; Wright and Mella, 1963; Weischet, 1963; Lara et al., 2004). Despite the number of fjords and lakes in Northern Patagonia (Fig. 1), their proximity to the epicentres of the 1960 earthquake and the descriptions of striking lake water oscillations (Barros, 1961), very little has been done so far in establishing the impact of this major event in these natural archives.

In this paper we present the impacts of May–June 1960 events in contrasted areas of Northern Patagonia where the integration of historical chronicles and multidisciplinary investigations of sub-aqueous sedimentary environments can provide detailed chronologies and paleoenvironment reconstructions: (i) Lago Puyehue (40.5° S, Chile, 170 m a.s.l.) draining the slopes of Puyehue and Casablanca active volcanoes (Fig. 3); (ii) proglacial lakes Frías and Nahuel Huapi (41° S, Argentina, 775 and 764 m a.s.l., respectively) draining the north-eastern slopes of the Tronador inactive volcano (Fig. 4) and (iii) the Reloncavi fjord embayment (41.5° S, Chile) with a large catchment area culminating at the Tronador volcano (3554 m a.s.l.) and draining several large Argentinean and Chilean glacial lakes (Figs. 1 and 2).

2. Geological setting

The subduction of the oceanic Nazca plate beneath the continental South America plate is developing an active volcanic arc in the study area (Fig. 1) where three main morphological units can be distinguished (Fig. 2): from west to east these are the cordillera de la Costa, the Central Chilean Valley and the cordillera de Los Andes (Hervé and Ota, 1993; Lopez-Escobar et al., 1995). The Southern

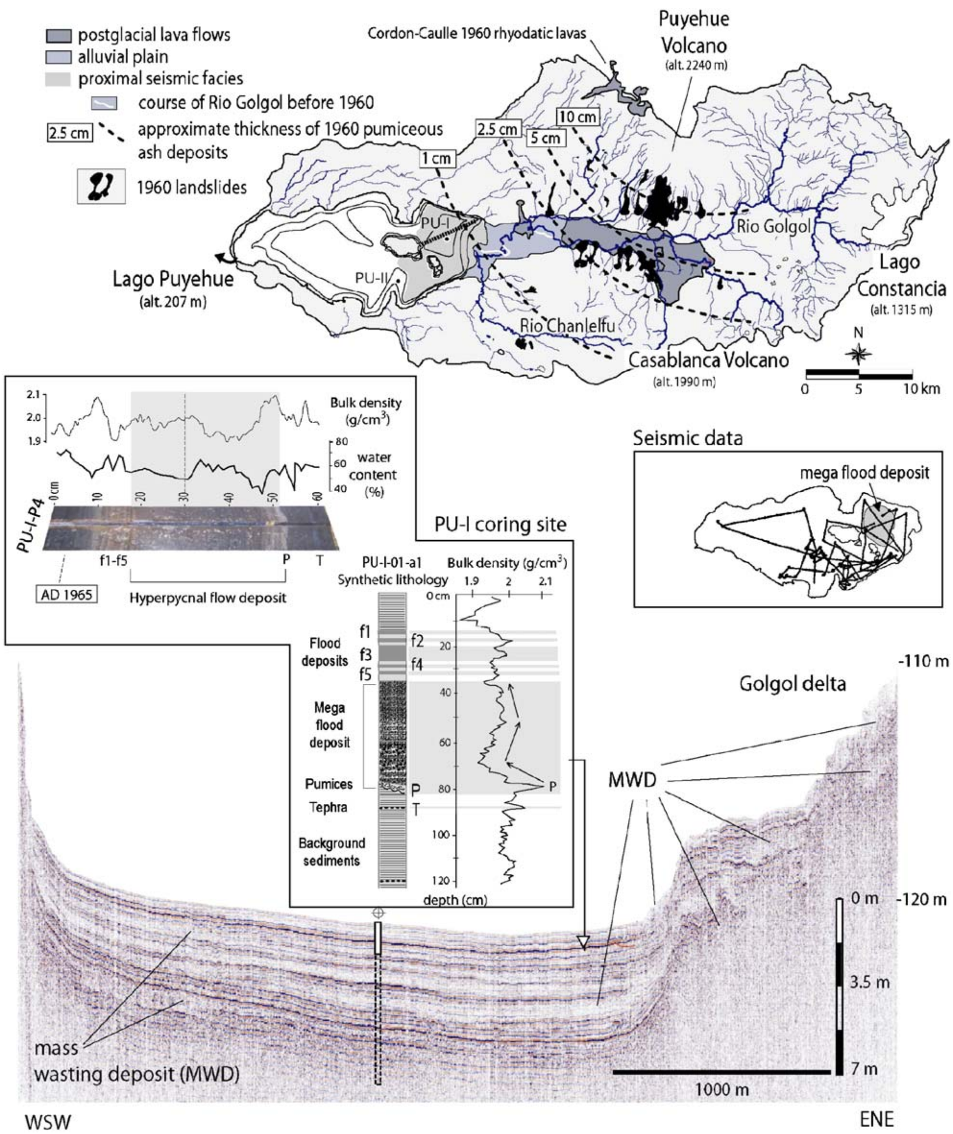

Fig. 3. Synthetic presentation of available field work, seismic reflection and sediment cores data illustrating the impact of 1960 earthquake and Cordon Caulle induced-eruption in the catchment area of Lago Puyehue. Earthquake-triggered landslides in the catchment are indicated in black (this study), while the isopachs of 1960 pumiceous ash deposits established by Wright and Mella (1963) are shown by the dark dotted lines. Some of the landslides affected the course of Rio Golgol and induced temporary dams. White asterisks near Rio Golgol indicate the location of the outcrops of Antillaca (toward the East) and El Caulle (toward the West) presented in Plate 1. After the eruption, heavy rain falls and dam outbursts induced a mega flood event and Rio Golgol developed a new course at several locations in the alluvial plain (white lines). In the deep proximal basin of Lago Puyehue, the 3.5 kHz seismic profile (thick doted line in the bathymetric map) presented in the lower panel is illustrating the location of PU-I coring site. The location in the lake of coring site PU-II (black circle) discussed in the text is also shown in the bathymetric map (isobaths 40 m, after Campos et al., 1989). At site PU-I, short gravity (PU-I-P4) and piston (PU-I-01-a1) cores are characterized by several sedimentary events detailed in the text and associated with fluctuations of bulk density and water content. The base of the 1960 mega flood deposit produces an outstanding high-amplitude reflection on seismic profiles. Based on the seismic grid, the extension of this major flood event in this sub-basin can be documented (gray-shaded area in the right panel).

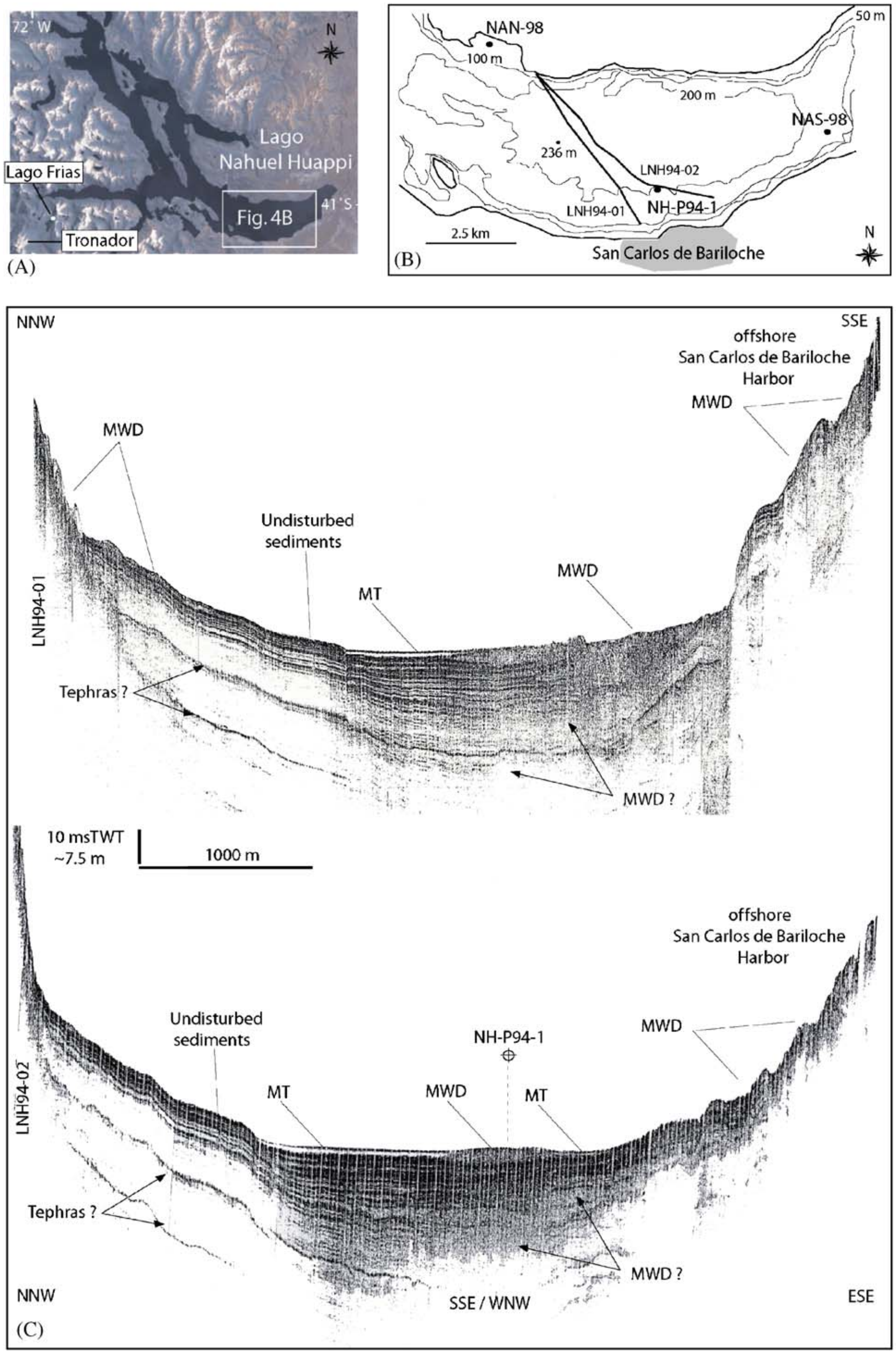

Fig. 4. Impact of 1960 events in the area of Lago Nahuel Huapi. Satellite image shown in 4A indicate the location of the distal basin of Lago Nahuel Huapi presented in 4B and the position of Lago Frías in the catchment area. Seismic profiles presented in 4C are located in 4B on the detailed bathymetric map of the basin facing the city of San Carlos de Bariloche, together with the short gravity cores NAN-98 and NAS-98 discussed in the text and core NH-P94-1 presented in Plate 1. On the seismic profiles a very recent mass wasting deposit (MDW) offshore of the harbor of Bariloche is associated with the formation of a mega-turbidite (MT) in the deepest part of the basin.

Volcanic Zone (SVZ) in this part of the cordillera de Los Andes is characterized by intense Late glacial to Holocene volcanism expressed by numerous composite stratovolcanoes and hundreds of minor eruptive centers (Gerlach et al., 1988; Lopez-Escobar et al, 1995; Naranjo and Stern, 2004). The volcanic activity is focused in the vicinity of the ca. 1000 km long NNE-trending Liquiñe–Ofqui Fault Zone (LOFZ, Fig. 1), a major trench-linked dextral strike-slip active structure corresponding to an intra-arc shear zone, according to Cembrano et al. (2000).

More than 1000 m thick glaciers covered Northern Patagonia during the last glaciation, at this latitude called

Llanquihue and *Nahuel Huapi* in Chile and Argentina, respectively. Ice flows originating from the Andes formed large piedmont glaciers in Chile and large alpine tongues in Argentina. At both side of the Andes, ice melting induced the development of large deep lakes damned by frontal moraines and outwash plains since the early stages of the deglaciation (Figs. 1 and 2; Laugénie, 1982; Clapperton, 1993; Denton et al., 1999). South of 41° S in the Chilean Lake District (Fig. 2), the Llanquihue moraine belts reach most of the Chilean Central Valley, form the western limit of Reloncavi Bay, and reach the Pacific coast at the latitude of Castro in Chiloe Island. South of Puerto Montt, the Reloncavi Bay and the gulfs of Ancud and Corcovado consist of a continuous series of deep marine basins (up to 458 m water depth) formed by glacial erosion but also tectonic sinking of the Central Chilean Valley during the Quaternary (Denton et al., 1999; Silva and Prego, 2002). The inland sea between Chiloe Island and the Andes (Fig. 1), first covered by the Reloncavi, Ancud and Corcovado large piedmont ice lobes (Denton et al., 1999), was then partially covered by proglacial lakes during the last glaciation interstadials (Heusser, 1977; Roig et al., 2001) and the deglaciation, before being flooded by the postglacial sea level rise (Laugénie, 1982; Silva and Prego, 2002). Frequent sills essentially made of glacial rock bars and moraine deposits in the bays, gulfs and fjords south of 41° S, are today acting as barriers against the circulation of bottom waters of marine and estuarine origin and are locally favoring strong currents and high sedimentation rates (Pickard and Stanton, 1980, Silva et al., 1998).

Precipitation events in Northern Patagonia during glacials and interglacials are essentially driven by the strength and latitude of the Westerlies over the SE Pacific (Lamy et al., 2004; Kaiser et al., 2005). Today, a significant rain shadow effect across the coastal range and the Andes favors snow accumulations at altitudes above 800–1000 m in the Andes and a drier climate in the Argentinean piedmont. Strong westerly winds and intense volcanic activity in the study area result in the formation of thick and unstable andosoils (soils developed on volcanic ash) draping the steep morphologies of the Andes (Wright and Mella, 1963). The climate and soils favor the development of a very dense vegetation cover up to an altitude of ca. 1500 m consisting of a temperate evergreen rainforest (Veblen and Ashton, 1978; Moreno, 2004; Abarzúa et al., 2004).

The 21–22 May 1960 major subduction earthquake caused significant co-seismic movements and destructive tsunami waves along the Chilean coast over an approximate length of 1000 and 150 km width between latitudes 37° S and 48° S (Sievers et al., 1963; Plafker and Savage, 1970; Hervé and Ota, 1993). In the Chilean Central valley, in Chiloe Island and at the piedmont of the Chilean Andes (Figs. 1 and 2), it caused strong site effects together with some fluid escape phenomena (sand boils, degassing) and soil liquefaction (Dobrovolny et al., 1963; Weischet, 1963; Bartsch-Winkler and Schmoll, 1993). In the Andes, thousands of landslides were reported in the vicinity of the LOFZ (Veyl, 1960; Rothé, 1961; Tazieff, 1962; Wright and Mella, 1963; Weischet, 1963; Laugénie, 1982). Some of these landslides deeply affected the drainage basins of the Chilean Lake District and induced destructive impact waves in several Chilean lakes of glacial or volcanic origin. Striking lake water oscillations and destructive waves were as well reported in Chilean and Argentinean large lakes between 39.5° and 46° S (Barros, 1961).

On 24 May, i.e. 38 h after the main shock offshore Valdivia, a rhyodacitic fissure eruption started on the Cordon Caulle plateau, next to the crater of the Puyehue Volcano (Figs. 2 and 3). During the seven following days, an explosive subplinian phase formed an eruptive "mushroom-like" column of ca. 8 km high and the generation of pyroclastic plumes. These plumes essentially dispersed white lapilli pumices around the main crater and were blown towards Argentina by strong south-westerly winds (Wright and Mella, 1963; Laya, 1977; Lara et al., 2004).

3. Materials and methods

3.1. High-resolution sub bottom profiling

In January 1994 two high-resolution seismic profiles were collected in the distal sedimentary infill of Lago Nahuel Huapi offshore the city of Bariloche (Figs. 1 and 4) using an ORE-Geopulse 3.5 kHz analog single channel pinger system. In Lago Nahuel Huapi conventional GPS was used for navigation onboard a vessel from the Argentinean Coastguard and the system achieved a maximum of 50–60 m penetration with a vertical resolution of approximately 10–20 cm. In Lago Frías this sub-bottom profiling system only achieved a maximum penetration of

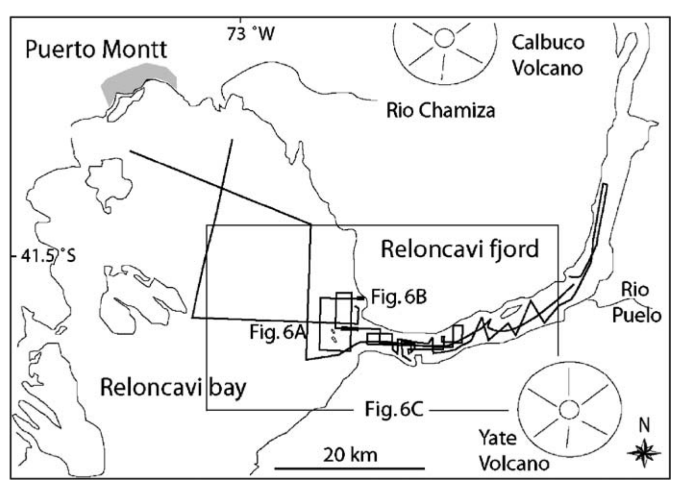

Fig. 5. Available seismic reflection data in the bay and fjord of Reloncavi discussed in the text and presented in Fig. 6 (thick black lines). The topography and bathymetry of the fjord embayment illustrated in Fig. 6C is also located. Rio Puelo is the main tributary of the fjord and its delta is located close to the LOFZ.

ca. 3 m in the main basin next to the Rio Frías delta (Ariztegui et al., personal communication).

In December 2000, more than 130 km of high-resolution single channel seismic profiling were digitally recorded from the sedimentary infill of Lago Puyehue (Figs. 1 and 3). Two different seismic sources were used from the R/V Hualla II with conventional GPS navigation to map the sedimentary infill: the 1 kHz ''Centipede'' sparker of the RCMG (Gent University, Belgium) and a Geoacoustic 3.5 kHz digital pinger system (De Batist et al., submitted). Basic and advanced seismic processing routines applied to these data are described in Charlet et al. (in press) and Charlet et al. (submitted). In the deep eastern sub basin of Lago Puyehue facing the Rio Golgol delta (Fig. 3), a proximal seismic facies is characterized by limited acoustic penetration (ca. 7 m) with both seismic sources. The pinger profiles shown with true amplitudes and after spiking deconvolution (Fig. 3) have approximately 10–20 cm vertical resolution.

In November 2004 more than 250 km of high-resolution single channel seismic profiling using the RCMG's sparker and pinger systems were digitally recorded in the Bay and the Fjord of Reloncavi (Figs. 1, 5 and 6). Conventional GPS was used for navigation onboard the R/V Don Este and the system achieved a maximum of 240 and 40 m of penetration in the bay with the sparker and pinger sources, respectively. Within the fjord, however, both seismic sources provided limited penetration (ca. 20 m). Pinger profiles in the fjord embayment achieved a vertical resolution of approximately 10–20 cm.

3.2. Sediment cores

Sub-bottom profiling was essential to select the most suitable coring sites in lakes Nahuel Huapi, Frías and Puyehue. In 1994 the ETH-Zürich short gravity coring device allowed retrieval of 60 cm of sediments in the distal basin of Lago Nahuel Huapi at 200 m water depth (core NH-94-P1, Fig. 4 and Plate 1) and 110 cm of sediments in the central part of the main basin of Lago Frías at ca. 73 m water depth (core LF-94-P2, Fig. 4 and Plate 1). In 1998, short gravity cores were also taken with the same device in the northern (NAN-98) and south western (NAS-98) parts of the distal basin of Lago Nahuel Huapi, in order to sample and analyze recent tephra layers. Cores NAN-98 and NAS-98 were retrieved in 40 m water depth in a small

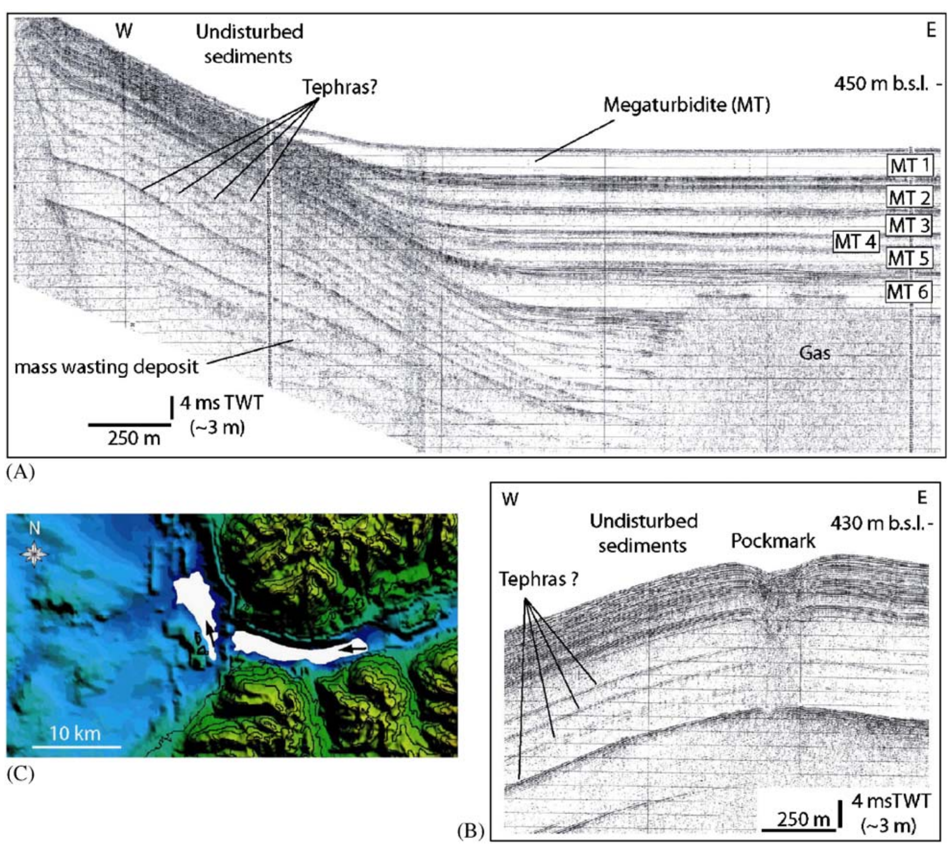

Fig. 6. Detailed seismic sections of the Reloncavi fjord embayment (Fig. 6A and B) illustrating the seismic facies of undisturbed sediments and mega-turbidites. High-amplitude reflections in undisturbed sediments are probably due to tephra layers essentially originating from nearby volcanoes Calbuco and Yate located in Fig. 5. The extension (white area) and source area (black arrows) of the very recent mega-turbidite MT1 in the distal basins of the fjord embayment (in Fig. 6C) is deduced form the 3.5 kHz seismic profiles and the bathymetric data. Some wipe-out or low-amplitude patches and the reconnaissance of large pockmarks in the seismic data suggest that the presence of gas and fluids in the sediments is reducing their stability.

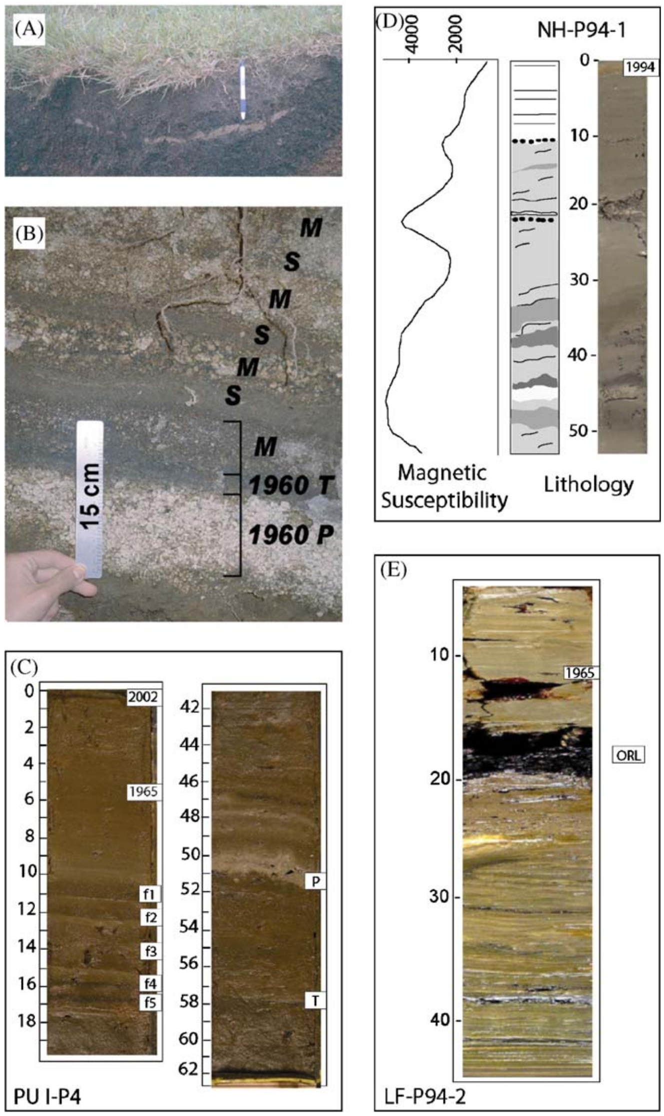

Plate 1. Sedimentary events associated with the 22 May 1960 earthquake and the induced Cordon Caulle volcanic eruption in Northern Patagonia. (A) 1960 fallout silts in the depressions of the Golgol alluvial plain at El Caulle. (B) 1960 fallout coarse white pumices (1960 P) at Antillanca are thinning upward into a darker sandy tephra layer (1960 T) and where very quickly reworked as indicated by the occurrence of mix layers made of coarse white pumices and dark sands (M) just above 1960 T and intercalated in overlying soils (S). (C) Contrasted lithologies of background sedimentation and sedimentary events T, P and f1–f5 in short core PU-I-P4 in the proximal basin of Lago Puyehue. (D) Lithology and magnetic susceptibility (10^{-6} SI) of core NH-P94-1 sediments retrieved in the distal basin of Lago Nahuel Huapi. Most of the core contains a slump deposit (gray facies from 10 to 54 cm). (E) Lithology of the upper sediments retrieved in the proximal basin of Lago Frías (core LF-P94-2) illustrating the striking organic rich layer (ORL) deposited in 1960. In cores PU-I-P4 and LF-P94-2, the position of the peak in ^{137}Cs is also indicated.

bay and at 150 m water depth toward the lake outlet, respectively (Fig. 4).

In 2001, short gravity and piston cores were retrieved based on GPS positioning by 122 m water depth in the proximal basin of Lago Puyehue (Fig. 3, Plate 1) using an UWITEC coring platform and coring devices (Chapron et al., 2004a). Short coring allowed retrieval of 60 cm of undisturbed sediments at site PU-I, but successive decimeter thick sandy layers and gas-rich sediments induced significant coring disturbances in the 7 m long piston core and prevented good recovery of the lower sections. As a result, only the upper 120 cm of the piston core could be used in this study.

3.3. Fieldwork

Since 1998, several tephrostratigraphic studies have been carried out in outcrops of the northern Nahuel Huapi basin in order to establish the tephrostratigraphy and tephrochronology of the postglacial tephra sequence originating from the Puyehue Cordon Caulle volcanic complex (Villarosa et al., 2004, this volume).

In December 2004 fieldwork was undertaken in the catchment area of Lago Puyehue in order to interview the population, to sample the pumices associated with the 1960 Cordon Caulle eruption (Fig. 3; Plate 1) and to map the extension of 1960 earthquake-triggered landslides. This mapping is based on 1:50 000 topographic maps, Landsat satellite images and the composition of the vegetation cover (Fig. 3).

3.4. Event stratigraphy

The chronology of the sedimentary cores is based on (i) detailed analyses of the lithologies, (ii) reconnaissance of sedimentary events (instantaneous deposits) contrasting with the background sedimentation, (iii) radionuclide dating using ^{137}Cs activities and (iv) the correlation of sedimentary events with major historical events reported in the catchment area.

Gamma density in Lago Puyehue sediment cores PU-I-P4 and PU-I-01-a1 were measured very 0.5 cm with a GEOTEK multisensor track at the G.F.Z. Potsdam (Germany). Once open and split at Liège University (Belgium), the lithologies of these cores were described and digital pictures were taken (Fig. 3, Plate 1). Short core PU-I-P4 was sampled for radionuclide dating (Arnaud et al., in press) and the sediments were further characterized by high-resolution measurements of laser grain size and water content as described by Bertrand et al. (2005) and Chapron et al. (submitted).

Magnetic susceptibility (MS) of lakes Nahuel Huapi and Frías sediment cores were measured every 1 cm before opening using a Bartington loop sensor at the University of Geneva. The lithologies were then described and digital pictures were taken (Plate 1). Although the uppermost part of the core was partially disturbed during coring operations, ^{137}Cs content of the sediments of Lago Frías were measured every 1 cm in undisturbed sections at the Institute F.A. Forel in Geneva (Switzerland), as described in Ariztegui et al. (personal communication).

Recent chronology in this part of the Andes is essentially based on the occurrence in outcrops and lacustrine sediment cores of two well-described key regional fallout tephra layers originating from Chile: the 1921–22 and 1960 Cordon Caulle eruptions (Wright and Mella, 1963; Gerlach et al., 1988; Lara et al., 2004; Villarosa et al., 2004). Fig. 2 illustrates the spatial dispersion of volcanoclastic particles associated with the 1960 eruption. The geochemistry of these volcanoclastic deposits in the catchment areas of lakes Puyehue and Nahuel Huapi has been characterized by conventional tephrostratigraphic analyses under binocular lens, polarizing microscope, microprobe and XRF at Liège University and at the INGEIS in Buenos Aires, for Chilean and Argentinean samples, respectively. Pumice samples from the catchment area of Rio Golgol and the short core PU-I-P4 (Fig. 3, Plate 1) were also characterized by micro-XRF analyses of major and trace elements at the Department of Geology and Paleontology, University of Geneva.

4. Results

4.1. Lago Puyehue sedimentary record

The proximal seismic facies in Lago Puyehue covers most of the eastern sub-basin and its western limit follows the 100 m isobath (Fig. 3). It involves the Golgol delta characterized by a wide and abrupt delta front affected by limited but recurrent mass wasting deposits (MWDs) occurring as lens-shaped bodies with low-amplitude chaotic internal reflections. The flat basin fill facing this delta is made of several discrete high-amplitude and continuous reflections with an on-lapping configuration interpreted as large hyperpycnal flood deposits (Van Rensbergen et al., 1999; Chapron et al., 2004b). At least two of these large flood deposits occurring at ca. 75 and 375 cm below the lake floor overlie MWDs originating from the steep basin edges (Fig. 3).

The complex succession of sedimentary facies characterizing the cores at site PU-I is highlighted by the lithofacies and the measurements of bulk density and water content (Fig. 3). Background sedimentation in PU-I-P4 consists of dark-gray finely laminated sandy silts between 0–10 cm and 51–62 cm and is interrupted by several sedimentary events (Chapron et al. 2004a, Fig. 3, Plate 1): (i) five fine grained successive brownish silty deposits with a sharp base but a gradual top (f1–f5, from 10 to 18 cm); (ii) a coarser light gray to brownish sandy silt deposit (from 18 to 51 cm) starting at 51 cm with an erosive white layer (event P, made of coarse pumice pebbles and a massive silty fabric) and including a laminated coarsening upward sequence from 50 to 30 cm that is sharply passing into a massive sandy silt sequence slightly fining upward (from 30 to 18 cm) and (iii) a coarser sandy silt tephra layer (event T, between 58 and 57.5 cm).

The sharp-based and graded sedimentary events f1–f5 at site PU-I have the typical signatures of flood deposits resulting from the development of density currents (hyperpycnal flow or underflow, cf. Lambert and Hsü, 1979; Ashley et al., 1985; Chapron et al., 1999, 2002; Mulder et al., 2001). Lower densities and higher water content in these flood deposits indicate high accumulation rates. Similarly, the complex succession of sedimentary facies from 18 to 51 cm in core PU-I-P4 and their signatures in grain size, density and water content are interpreted as resulting from the occurrence of a mega hyperpycnal flood deposit (cf. Syvitski and Schafer, 1996; Mulder et al., 1998; Schneider et al., 2004; St. Onge et al, 2004). This mega bed can be sub-divided from base to top into: (i) the deposition of an erosive bed at 51 cm, reworking white pumice debris embedded in a white silty fabric (event P); (ii) a laminated basal sequence developing inverse grading during the rising limb of the flood (waxing flow); and (iii) a massive deposit with normal grading during the falling limb of the flood (waning flow).

Chronology at site PU-I is provided by three key events, and suggests strong fluctuations in sedimentation rates during the last century. The peak in ^{137}Cs activity between 5 and 6 cm in PU-I-P4 is interpreted as resulting from the AD 1965 culminating impact of atmospheric nuclear tests in the southern hemisphere (Schuller et al., 2002; Arnaud et al., in press). The erosive pumice layer (event P) consisting of small glass shards and few coarse pumices have the chemical composition of rhyolite and are correlated to the one deposited during the 1960 eruption in the catchment area of Rio Golgol (Fig. 3, Plate 1). This implies that the mega-hyperpycnal flood event occurred in 1960 after the eruption and partly reworked the fallout pumices from the catchment of Rio Golgol. This interpretation is further supported (i) by historical data (Tazieff, 1962; Wright and Mella, 1963); (ii) by the occurrence of a 1960-mixed layer in the catchment area just above the fallout pumices (Plate 1); (iii) by comparable Fe, Ca, K, Mn and V ratios determined on micro-XRF samples from the catchment and from core PU-I-P4; and (iv) by ^{210}Pb content anomalies reflecting reworking of very recent sediments in the basal sequence of the mega hyperpycnal flood event (Chapron et al., submitted). Finally, the tephra layer event T characterized by a very high amount of phenocrystals and being dominated by orthopyroxene heavy mineral can be correlated to an identical fallout tephra retrieved in the lake at coring site PU-II, in a more distal sedimentary environment. At site PU-II, this tephra is well-dated by radionuclides and biochemical varve counting (Bertrand et al., 2005; Arnaud et al., in press; Boes and Fagel, accepted) and is identified as the 1921–1922 eruption of Cordon Caulle that strongly affected the vegetation cover in the catchment area of Lago Puyehue (Gerlach et al., 1988; Lara et al., 2004; Pollmann and Veblen, 2004).

In spite of coring disturbance in PU-I-01-a1, the correlation of key horizons (f1–f5, P and T) and bulk density profiles between this piston core and PU-I-P4, shows the effects of compaction during short gravity coring operations. But the clear density fluctuations above event P on the piston core from 80 to 50 cm are sufficient to trigger a change in acoustic impedance in the sediments and to form the upper high-amplitude reflection on pinger profiles at ca. 75 cm below the lake floor (Fig. 3). The correlation of the basal sequence of the mega-flood deposit with the first outstanding high-amplitude reflection in the deep basin, allows to further documentation of the geometry of the 1960 mega-flood deposit (Fig. 3) and provides an estimate that ca. $3 \times 10^6\,m^3$ of sediments accumulated during this major event, when assuming an average thickness of 30 cm across the basin (Chapron et al. 2004a).

4.2. Lago Nahuel Huapi sedimentary record

In the distal deep basin of Lago Nahuel Huapi, undisturbed sediments are characterized by a ponded seismic facies made of high-frequency and amplitude continuous reflections (Fig. 4). At depths, few high-amplitude and continuous reflections draping the former lake floor morphologies also bear the typical acoustic signature of fallout tephras in southern Argentinean lakes as described by Gilli et al. (2001). However, essentially along the SSE edge of the basin and offshore the harbor of San Carlos de Bariloche, the lake floor is characterized by large and very recent MWDs occurring as tilted blocks of stratified or chaotic sediments along the slope. Towards the basin, they develop hummocky morphologies ranging into lens-shaped bodies with low-amplitude chaotic internal reflections. In the deepest part of the basin these lenses are covered by ponded transparent acoustic facies a few meters thick. The latter seismic facies is typical of mega-turbidites (MT) or seiche deposits associated with large sub-aqueous landslides (Siegenthaler et al., 1987; Van Rensbergen et al., 1999; Schnellmann et al., 2002). Analogously, the occurrence of several chaotic lens-shaped bodies at depth in the central basin suggests former MWDs.

Short core NH-P94-1 retrieved on the uppermost MWD (Fig. 4) is characterized in the top 10 cm by faintly laminated sediments with rather low MS values. Most of the core comprises contorted light gray to brownish sediments (Plate 1). These reworked deposits bear high MS values at the base of the core and two outstanding peaks in MS that are associated with sandy layers at 11 and 22 cm, respectively. This association of remoulded sediments is interpreted as resulting from a recent slump deposit reworking coastal and older lacustrine sediments.

4.3. Lago Frías sedimentary record

Short core LF-P94-2 retrieved at the centre of Lago Frías main basin is characterized by two contrasting sedimentary facies and two major sedimentary events. The upper 25 cm of the core contains slightly laminated sediments that are sharply interrupted by an organic-rich layer (ORL) between 16 and 20 cm containing macrophytes as well as leaves and branches debris (Plate 1). The rest of the core contains finely laminated sediments holding a variable degree of development. Between 80 and 83 cm (not shown) these sediments are suddenly interrupted by a dark sandy, mostly reworked tephra layer that generates a strong peak in MS (Ariztegui et al., personal communication).

The chronology of this core is provided by a clear ^{137}Cs peak between 13 and 14 cm associated to the culmination of atmospheric nuclear tests in AD 1965. Assuming a constant sedimentation rate, the upper ORL can be attributed to the 1960 AD earthquake (Ariztegui et al., personal communication).

4.4. Reloncavi fjord embayment sedimentary record

Undisturbed sediments in the fjord of Reloncavi and its embayment are characterized on the pinger profiles by parallel high-amplitude and frequency continuous reflections in the first 6 m of sediments (assuming a P wave velocity of 1500 m/s in the sediments, Fig. 6). Deeper in the sedimentary infill, continuous and parallel high-amplitude reflections with lower frequency suggest the occurrence of various fallout tephras intercalated in the background sediments. Locally, the lower and upper seismic facies in the fjord and its embayment are also affected by some MWDs, occurring as lens-shaped bodies made of transparent to chaotic internal reflections. In the embayment, near the sill of the fjord, some fluid escape features such as large pockmarks are as well locally observed (Fig. 6).

However, the main regional feature is a very recent mega-turbidite bearing ca. 3 m thick transparent acoustic facies pinching out at ca. 450 m below sea level (MT1 in Fig. 6A). This mega-bed occurs in the distal sub-basin of the fjord and in the adjacent sub-basin in its embayment separated by the steep frontal moraines of the Reloncavi ice lobe (Fig. 6C). In the fjord, the source area of this mega-bed seems to be the Rio Puelo delta (Fig. 5) near the course of the LOFZ (Fig. 1), where MWDs range basinward into the mega-turdidite. Although little acoustic penetration characterizes the infill in the fjord, the embayment basin highlights the occurrence of up to six mega-turbidites stacked in the deepest part of the depression (Fig. 6A). In this sub-basin of the Reloncavi Bay, the MTs seem to be essentially originating from the southern slopes of the embayment, where MWDs range basinward into the MTs. Based on the available seismic and bathymetric data sets (Figs. 5 and 6), a volume of ca. $187 \times 10^6\,m^3$ can be estimated for the most recent mega-turbidite MT1 in the fjord and its embayment.

5. Discussion

5.1. Impacts of May–June 1960 events in lacustrine environments

In the catchment of Lago Puyehue, among the 23 larger earthquake-induced landslides, four were triggered along the northern flank of the Casablanca volcano and reworked large blocs, andosoils and the vegetation cover. These landslides evolved into debris avalanches, cut the road to Argentina and deeply affected the course of Rio Golgol where they induced temporary dams (Tazieff, 1962; Wright and Mella, 1963; Fig. 3). Several small MWDs were probably also triggered during the earthquake along the steep slopes of the proximal basin, as suggested by historical data (Veyl, 1960) and the occurrence of limited MWDs underlying the 1960 flood deposit on pinger profiles (Fig. 3). In the following days the population was evacuated, as the earthquake-induced Cordon Caulle eruption started to deposit white pumiceous ashes in the catchment area (Fig. 3). When people came back 22 days after the earthquake, up to $7 \times 10^6\,m^3$ of pumiceous ashes were deposited in the catchment and partly reworked (Plate 1), the landslide dams had collapsed and the course of the river had changed at several locations downstream of these dams, in the alluvial plain and near the Golgol delta (Fig. 3). Based on the sedimentary record in the catchment area of Rio Golgol and in the proximal basin of Lago Puyehue, the following scenario can be reconstructed. Heavy winter rain falls after the catastrophe induced flooding, reworked some of the 1960 coarse pumices from the upper catchment area draining Puyehue volcano (Tazieff, 1962; Lara et al., 2004) and triggered successive dam outbursts upstream the alluvial plain of Rio Golgol. These outbursts reworked most of the avalanche debris accumulated in the course of the river (andosoils, dead trees, pebbles) but left in place the large blocks. Rain falls and flooding also reworked most of the white silty pumices deposited in topographic depressions toward the lake (Wright and Mella, 1963). As a result, the sustained flooding event bearing a high-suspended load shifted the course of the river at several locations, reworked alluvial sediments and triggered an erosive major hyperpycnal flow at the lake floor. During the rising and falling limbs of the flood event, the 1960 pumices accumulated in the deep basin at PU-I coring site and were covered by a mixture of soils, alluvial and lacustrine sediments (Chapron et al., submitted). After this crisis, regressive erosion in the alluvial plain took place during the following months, as the river readjusted its dynamics (E. Real, personal communnication, December 2004). The recovery of Rio Golgol induced the successive flood events f1–f5 at site PU-I soon after this geomorphologic change (Fig. 3).

Little acoustic penetration in the sedimentary infill of Lago Frías and a lack of reported historical events associated with the 1960 earthquake in its catchment area limit paleoearthquake reconstructions. However, based on available seismic data (Ariztegui et al., personal communication), as well as on the particular features of the 1960s ORL retrieved in the deep basin of the lake and the nearby descriptions of lake's water oscillations and earthquake-induced landslides (Barros, 1961; Kitzberger et al., 1995) the following hypothesis can be advanced and tested by future investigations. The ORL could either result from (i) earthquake-induced landslides affecting the lake and evolving into a MWD; (ii) an impact wave induced by 1960 earthquake-triggered landslides and producing strong erosion along the lake's shore rich in organic materials; or (iii) earthquake-induced lake water oscillations (seiche effect) reworking organic rich deposits from the lake shore.

In Lago Nahuel Huapi, detailed historical reports and photographs of the catastrophic impact of 22 May 1960 earthquake offshore the harbor of San Carlos de Bariloche (Barros, 1961; Parsons, 2002) are available. The 1960-pumice fallout over Lago Nahuel Huapi (Fig. 2) started the day after the occurrence of the earthquake-triggered waves that partly destroyed the harbour and caused two fatalities at the lakeshore (M. Cita, personal communication, July 2005). In the following days a subsequent ash fall was described over the city of Bariloche and can locally be identified in several outcrops in the catchment area of Lago Nahuel Huapi (Fig. 2). Historical information together with the seismic and coring data for this part of the lake (Fig. 4, Plate 1) suggest that the collapse of the harbor of Bariloche, the generation of up to 2.5 m high destructive waves and significant water turbulences near the shore, resulted from the destabilization of the steep lake floor offshore the harbor during the main seismic shock. Similar phenomena and deposits were previously described during strong local earthquakes in deep glacial alpine lakes (Siegenthaler et al., 1987; Schnellmann et al, 2002; Chapron et al., 2004b). However, in order to confirm this hypothesis, more seismic data are required in Lago Nahuel Huapi to map the detailed extension of the large landslide reworking the sub-aqueous slopes offshore San Carlos de Bariloche. Furthermore, to confirm the origin of the sub-aqueous landslide and the development of destructive waves offshore Bariloche, future investigations should also include transects of short gravity cores across the basin at key locations. The chronologies of the recent slump, the associated mega turbidite and the 1960 fallout tephra, could be confirmed by radionuclide dating and tephrostratigraphic analyses. Available ^{210}Pb measurements and tephrostratigraphic studies in lacustrine sediments from Lago Nahuel Huapi and nearby Lago Morenito (Ribeiro-Guevara et al., 1999; Villarosa et al., 2004) already identified the 1960 white-gray ash layer locally outcropping in the catchment areas. In core NAN-98 for example, the 1960 and 1921–22 tephras were recognized based on their petrography and geochemical fingerprint at 29 and 42 cm below the lake floor, respectively. In core NAS-98, an outstanding sandy layer is bearing similar macroscopic characteristics (color, grain size and thickness) than the 1960 tephra in core NAN-98 and the upper sandy layer retrieved at 11 cm above the slump in core NH-P94-1. The occurrence of these similar sandy layers in the distal basin suggest that the major MWD offshore Bariloche was probably triggered by the 1960 earthquake and is now caped by the 1960 subsequent fallout tephra.

5.2. Impacts of May–June 1960 events in deep marine environments

According to Barros (1961), Galli and Sanchez (1963) and Bartsch-Winkler and Schmoll (1993), the destructive tsunami waves that affected the western coast of Chiloe in 22 May 1960 did not propagate eastward of the island into the inland sea (Figs. 1 and 2). In Reloncavi Bay and in the gulfs of Ancud and Corcovado, co-seismic subsidence and uplift essentially resulted in a relative sea-level rise of ca. 1.8 m and an immediate change in the timing (with respect to the tide at Puerto Montt) and amplitude of the tide (Plafker and Savage, 1970; Hervé and Ota, 1993; Bartsch-Winkler and Schmoll, 1993). Earthquake-induced landslides along the LOFZ in the Andes (Fig. 2) were related to significant co-seismic movements along the fault zone (Weischet, 1963). Similarly, southward of the Chilean Lake District, the MWD evolving into MT1 in Reloncavi Fjord was initiated offshore the Rio Puelo delta close to the LOFZ (Figs. 2 and 6). In this context, the simultaneous development of MT1 in two sub-basins from the fjord and its embayment with two different source areas suggest that these major MWDs where triggered by recent co-seismic movements. The high sedimentation rate in front of Rio Puelo delta is most probably the main factor reducing the stability of the sedimentary infill in the vicinity of the LOFZ. However, in the fjord embayment, high sedimentation rate along steep slopes resulting from the interactions of tributaries sediment plumes with strong currents, together with the occurrence of fluid escape phenomena (Fig. 6) are probably strongly limiting the stability of the sediments (cf. Nisbet and Piper, 1998; Chapron et al., 2004b).

A mean recent sedimentation rate (SR) of ca. 4 mm/yr based on ^{210}Pb dating from superficial cores in the Reloncavi area is only available in the western part of the bay (Bravo et al. submitted). The application and the extrapolation of this SR to the undisturbed sediments deposited above MT1 and between MT1 and MT2 in the fjord embayment (Fig. 6 C) suggests that MT1 may have occurred around 1959 and MT2 around 1585. As a working hypothesis and based on historical data, these two mega-turbidites could well be related to the 1960 and 1575 major subduction earthquakes located offshore Valdivia. These two very similar events were both associated with destructive tsunamis, earthquake-induced landslides in the Chilean Lake District, significant co-seismic movements in the study area and both induced a volcanic eruption (Weischet, 1963; Lomnitz, 1970; Plafker and Savage, 1970; Atwater et al., 1992; Bartsch-Winkler and Schmoll, 1993; Beck et al., 1998; Petit-Breuilh 1999). Cores selected at key sites in the fjord, its embayment and in the bay, in future will provide a better understanding of the SR, the stabilities of the sediments and the age of these MTs. Chronologies will be based on radionuclide dating and on the reconnaissance of well-know eruptions of nearby volcanoes (Petit-Breuilh 1999; Villarosa et al., 2004).

5.3. Preservation potential of sedimentary environments in Northern Patagonia and implication for paleo-earthquake reconstructions

In the drainage basins of Northern Patagonia, tree rings studies on dead or surviving trees can provide detailed reconstructions of earthquake-triggered land slides along glacially over deepened slopes where unstable volcanic ash substrates are prevailing. Strong variations in tree-growth patterns from *Nothofagus* on alluvial fans surrounding Lago Traful located north of Lago Nahuel Huapi, allowed Kitzberger et al. (1995) to further document four major seismic events (estimated magnitude >7) of south central Chile that occurred over the last four centuries (including the 1960 event). However, the synergistic effects of climatic variation and earthquake events must be carefully considered, and such key reconstructions in remote areas may also be limited to historical earthquakes because of the maximum age these trees can reach.

Caves bearing archaeological remains are rare in our study area. However, these environments can document the occurrence of catastrophic rock fall events capped by volcanic ashes and therefore provide key evidence for Holocene major subduction earthquakes similar to the one of 1960 (Villarosa et al., this volume).

Coastal marine environments are often suitable for detailed chronologies based on ^{14}C dating and may preserve former tsunami deposits in south central Chile (Atwater et al., 1992). However, these tsunami reconstructions are limited in our study area by the significant co-seismic movements and by their complex pattern, especially around the inland sea between Chiloe and the Andes (Bartsch-Winkler and Schmoll, 1995).

In such a setting, deep lacustrine and marine basins may provide the best natural archives of past major seismic events in Northern Patagonia. While proximal basins are prone to the development of large hyperpycnal flood deposits eventually resulting from earthquake-induced changes in the drainage basin; distal basins have a higher preservation potential and are prone to the development of mega-turbidites associated with sub-aqueous MWDs. Moreover, distal basins are ideal environments to document regional fallout tephra layers that can provide accurate chronologies since the Late glacial. The occurrence of numerous sub basins in the inland sea south of the Chilean Lake District and in the large lakes of glacial origin in Northern Patagonia are also suitable to establish robust regional event stratigraphies of earthquake-induced MWDs.

Based on available data sets in our study area and on the understanding of the impact of May–June 1960 events in the basin fill of Puyehue, Nahuel Huapi, Frías and Reloncavi, it seems that similar major events occurred in the past. In the proximal basin of Lago Puyehue a 1960-like high-amplitude onlapping reflection at ca. 375 cm below the lake floor is covering limited MWDs occurring along the steep slopes of the basin (Fig. 3). In the distal basin of Lago Nahuel Huapi, at least two generations of large MWDs below the upper one are visible on seismic profiles (Fig. 4). This suggests that the 1960 major crisis was not a unique event in the catchment areas of these two lakes. In the distal basin of the Reloncavi fjord embayment, up to six MTs also suggest that the LOFZ was affected by successive significant co-seismic movements during the late Holocene, in agreement with former studies in the Andes (Weischet, 1963; Hervé and Ota, 1993). While the two upper MTs could be related to the major historical subduction earthquakes of 1960 and 1575, the former ones highlight a complex recurrence of such catastrophic phenomena.

6. Conclusions

High-resolution sub-bottom profiling in the contrasted lacustrine and marine basins of glacial origin on both sides of the Andes in Northern Patagonia highlight the recurrent incidence of major sedimentary events during the late Holocene. Short sedimentary cores retrieved at key locations in the deep basins of lakes Puyehue, Frías and Nahuel Huapi are characterized by recent fallout tephra layers and striking sedimentary layers contrasting with the background sedimentation. Chronologies in these cores and their regional correlation are provided by the combination of radionuclide dating using ^{137}Cs (in lakes Puyehue and Frías) and by the identification of Cordon Caulle 1921–22 and 1960 tephras in lakes Puyehue and Nahuel Huapi as well as in their drainage basins.

While May–June 1960 seismic shocks and Cordon Caulle eruption induced a major hyperpycnal flood deposit of ca. $3 \times 10^6\,m^3$ in the proximal basin of Lago Puyehue, they only triggered an unusual organic rich layer in the proximal basin of Lago Frías, but destructive waves and a large sub-aqueous slide in the distal basin of Lago Nahuel Huapi. A very recent mega-turbidite characterizes the infill of the two distal basins of Reloncavi fjord located close to the LOFZ and suggests that 1960 co-seismic movements in this area triggered the remobilization of ca. $187 \times 10^6\,m^3$ of marine sediments.

In order to confirm these reconstructions on the impact of 1960 subduction earthquakes in Northern Patagonia, further studies should include dense grids of high-resolution seismic profiling and detailed studies of sediment cores across these deep lacustrine and marine basins. On the most suitable sites, such as the distal basin of the Reloncavi fjord embayment, long coring could document the recurrence of major subduction earthquakes in this part of South America over several millennia. These data should however be integrated with the geomorphology and the tephrostratigraphy of the related catchment areas and be compared with available tree ring studies to disentangle the impact of subduction earthquakes from the effects of volcanism and climate variability.

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