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Glacial-related morphology and sedimentary setting of a high-latitude lacustrine basin: The Lago Chepelmut (Tierra del Fuego)

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Abstract
Lago Chepelmut is a relatively small lake in size, of ellipsoidal shape, located in the outer fold-and-thrust belt of the Fuegian Andes (southernmost South America). High-resolution single-channel seismic profiles, integrated with geological information in the surrounding area, have allowed to reconstruct for the first time a bathymetric map of the lake and the architecture, distribution and thickness of the sedimentary cover. Two main seismic units were identified in the seismic records: (i) a Lower Unit of glacial nature, likely associated to the Last Glacial Maximum (LGM), and irregularly distributed through the basin, and (ii) an Upper Unit of lacustrine origin which drapes the entire basin. Submerged moraine deposits within the lake were also found from seismic data, and correlated with moraine arcs widespread distributed in the surroundings of the basin. These morphologies represent the recessional deposits left by the Ewan glacier lobe, one of the easternmost fronts of the Tierra del Fuego glaciers during the LGM. The lacustrine sedimentary record shows that the lake level was not constant through the recent history of the lake. Moreover, data analyses has shown that there is also an important structural component that has conditioned the evolution of the basin, in addition to that linked to glacial activity.

Keywords: Tierra del Fuego, Lago Chepelmut, single-channel seismic profiles, sedimentary sequences, glacial morphology, Quaternary evolution

1. Introduction

Lago Chepelmut is located in the southernmost Andes, in Isla Grande de Tierra del Fuego (Figure 1), an area where superposed tectonic phases occurred since the Mid Cretaceous, in combination with repeated glacial events, have significantly shaped the landscape (see Menichetti et al., 2008, and references therein). The basin lies just to the north (12 km) of Lago Fagnano, the largest freshwater lake in the entire island, interpreted as a pull-apart basin developed within the principal deformation zone of the Magallanes Fagnano Fault System, which marks the western segment of the South America-Scotia transform boundary (Lodolo et al., 2002, 2003; Esteban et al., 2012, 2014, among others). Several kilometers to the west of Lago Chepelmut, the Deseado Fault Zone appears as a subsidiary structure associated with the Magallanes-Fagnano Fault System (Klepeis, 1994b).

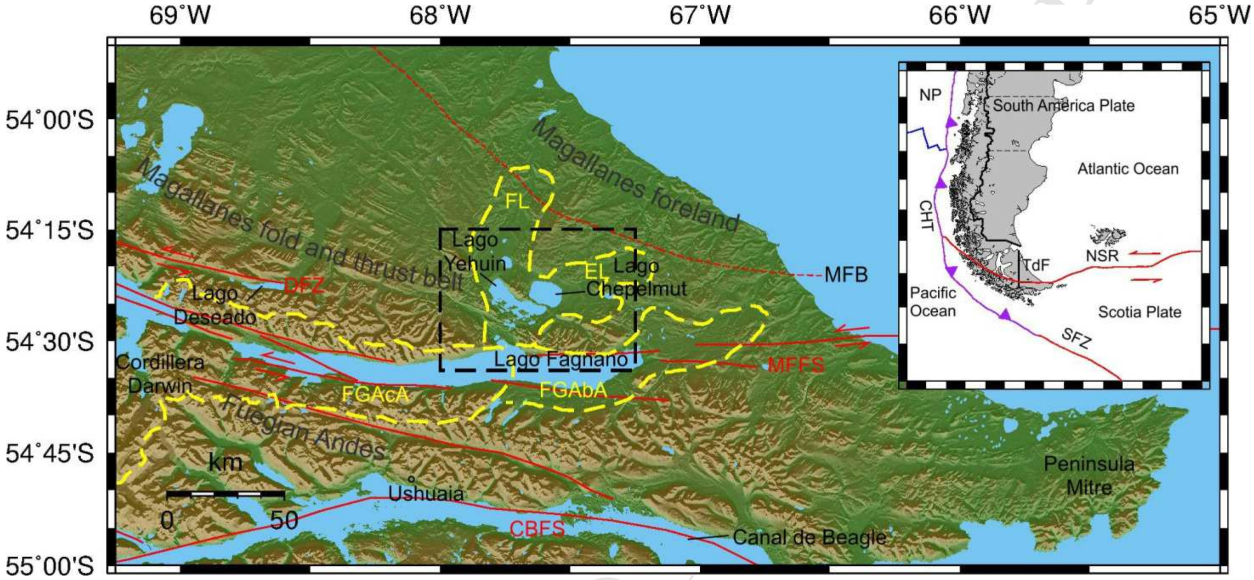

Figure 1. Physiographic and structural provinces in Isla Grande de Tierra del Fuego. Magallanes fold and thrust belt corresponds to the external fold and thrust belt; Fuegian Andes corresponds to the internal fold and thrust belt. The red dashed line is the thrust front of the Magallanes fold and thrust belt (MFB). Magallanes-Fagnano Fault System (MFFS), Canal de Beagle Fault System (CBFS) and Deseado Fault Zone (DFZ) are also indicated in red lines. FGAbA: Fagnano glacier ablation area; FGAcA: Fagnano glacier accumulation area; FL: Fuego ice lobe; EL: Ewan ice lobe. The inset box shows the current plate tectonic frame of the southern tip of South America and Scotia Sea. NP: Nazca Plate; CHT: Chile Trench; TdF: Tierra del Fuego; NSR: North Scotia Ridge. The black dashed box bounds the studied area.

The Lago Chepelmut, which displays an ellipsoidal shape (average major and minor axis of 8 and 5 km, respectively), is located in a low altitude zone (between 900 and 50 m.a.s.l.) within the “Corazón de la Isla” Provincial Reserve. The lake, along with the Lago Yehuin, are the two main freshwater lacustrine bodies within the reserve and in the Fuegian steppe. Río In connects both basins and provides the water input from Lago Chepelmut to Lago Yehuin (Figure 2).

A series of geophysical surveys have been conducted in Tierra del Fuego region since 2001, primarily focusing in deciphering the tectonic evolution of the South America-Scotia plate during the Cenozoic (Esteban et al., 2011, 2014; Lippai et al., 2004; Lodolo et al., 2002, 2003, 2007; Menichetti et al., 2001, 2007a and b, 2008; Tassone et al., 2005, 2010, 2011; Waldmann et al., 2008, 2009, 2010a, b). Several works, mainly of geophysical nature, have been devoted to other Fuegian lakes, i.e. Lago Fagnano (Lippai et al., 2004; Zanolla et al., 2011; Waldmann et al., 2008, 2010, 2011; Esteban et al., 2014), Lago Roca (Lodolo et al., 2010) and, more recently, Lago Yehuin (Lozano et al., 2018).

The main objective of this work is to reconstruct the genesis of Lago Chepelmut basin and analyze the nature, depositional architecture and thickness of the sedimentary infill from the interpretation of high-resolution seismic records acquired within the lake. This represents the first geophysical survey performed in the lake. Almost 23 km of profiles were acquired and used to present a new bathymetric map of the lake, to reconstruct the geometry and morphology of the cover, and analyze the possible relationship between pre-existing structures and the recent sedimentary setting.

This study contributes to the knowledge of the lake evolution during the Quaternary and analyzes its depositional history in an environment that was strongly affected by glacial activity, within a complex geological setting presently dominated by strike-slip tectonics.

2. Regional and geologic framework of Lago Chepelmut

2.1. The Fuegian Andes

The regional geologic history of the Fuegian Andes is the product of a succession of contrasting tectonic regimes. A widespread extensional regime in the Late Jurassic was established along the southern Patagonian and Fuegian continental margin which resulted in the formation of the Rocas Verdes marginal basin and the silicic volcanic deposition of Lemaire or Tobífera Formation (Dalziel et al., 1974; Suárez and Pettigrew, 1976; Hanson and Wilson, 1991; Calderón et al., 2007). An extended fault array consisting of N- to NW-oriented grabens and half-grabens and E- to NE-oriented transfer faults were developed within this Jurassic stage (Ghiglione et al., 2013). Since the Late Jurassic to Early Cretaceous, the stretching produced oceanic floor in the Rocas Verdes basin (Mukasa and Dalziel, 1996; Calderón et al., 2007), which was filled by Early Cretaceous marginal marine to arc-derived sequences, such as the Yaghan, Beauvoir, Zapata, Erezcano and Hardy formations (Olivero and Martinioni, 2001; Fildani and Hessler, 2005, Torres Carbonell et al., 2014). During the Late Cretaceous, a compressive tectonic regime in the Pacific margin of the South America Plate (i.e., the Andean Orogeny) led to the closure and inversion of the Rocas Verdes basin and to the development of the fold and thrust belt (Dalziel et al., 1974; Bruhn, 1979; Nelson et al., 1980; Wilson, 1991; Klepeis, 1994a; Diraison et al., 2000; Kraemer, 2003; Menichetti et al., 2008; Klepeis et al., 2010; Torres Carbonell et al., 2011, 2013).

During the Paleocene – Early Eocene, an extensional period characterized the area (Dalziel and Brown, 1989; Galeazzi, 1998; Ghiglione et al., 2008, 2010), with the development of extensional structures recognized near Canal de Beagle (Dalziel and Brown, 1989) and offshore in the Malvinas Basin (Galeazzi, 1998; Baristeas et al., 2013). Later, during the Late Eocene, the tectonic regime changed to a further compressive period and the propagation of the fold and thrust belt (Ghiglione, 2016).

Finally, a strike-slip tectonic regime was established during the Cenozoic in the central and southern area of the Tierra del Fuego, coeval with the formation of the Scotia Plate and its northern boundary with the South America Plate, represented by the Magallanes-Fagnano fault system (Klepeis and Austin, 1997; Diraison et al., 2000; Lodolo et al., 2002, 2003; Ghiglione and Ramos, 2005). Since then, this transform boundary accommodates the relative movement between South America and Scotia plates. The associated structures are mainly transtensional in nature, with the development of pull-apart basins along the main wrench faults (Lodolo et al., 2003; Menichetti et al., 2008). The Deseado Fault Zone (Figure 1) is one of the secondary structures associated with the plate boundary and with the Magallanes-Fagnano Fault System. The Deseado Fault Zone is a linear structure about 50 km long with a left-lateral movement and associated extensional component which runs across Lago Deseado, in the Chilean territory, outside the studied area (Klepeis, 1994b).

2.2. Geology and morphology of the Lago Chepelmut area

The main structural features of the Lago Chepelmut area are represented by NE-verging thrusts, with a morphology characterized by elongated NW valleys (Figure 2; Buatois and Camacho, 1993). The landscape surrounding the lake displays a smooth relief of elongated mounds, crossed by small and mostly rectilinear valleys. These valleys run parallel to the mounds with an N direction and parallel to the lake margin. The area, located in the central part of Isla Grande de Tierra del Fuego, exposes a succession of Lower Cretaceous to Eocene units outcropping along WNW-oriented belts (Figure 2; Malumián and Olivero, 2006; Olivero and Malumián, 2008; Martinioni et al., 2013). The Lower Cretaceous Beauvoir Formation is found along the northern margin of Lago Fagnano; it is part of the fill of the former Rocas Verdes marginal basin, and is composed of slates, mudstones and subordined sandstones of hemipelagic deep-marine environment. The Upper Cretaceous formations of Arroyo Castorera, Río Rodríguez and Policarpo are mudstone-dominated, with an upward increase in coarse sand material and represent the transition to the Late Cretaceous Austral foreland basin evolution. This transition is interpreted as a turbiditic deposits that were progressively accumulated in front of the rising Fuegian Andes (Martinioni et al., 2013). The exposures of Policarpo Formation in the vicinity of Lago Chepelmut display a fairly constant WNW strike and are often affected by thrusting (Buatois and Camacho, 1993, Torres Carbonell et al., 2013). The Paleocene Tres Amigos Formation (known as Cerro Apen Beds in Martinioni et al., 2013) consists of conglomerates, sandstones and siltstones from fan delta deposits. Leticia and Cerro Colorado formations, both from Eocene of La Despedida Group (Martinioni et al., 2013), crops out in the northeast area, near the Lago Chepelmut. These formations consist of grey to green sandstones of SW dip, intercalated with yellow mudstones and sandstones of a coastal environment (Malumián and Olivero, 2006).

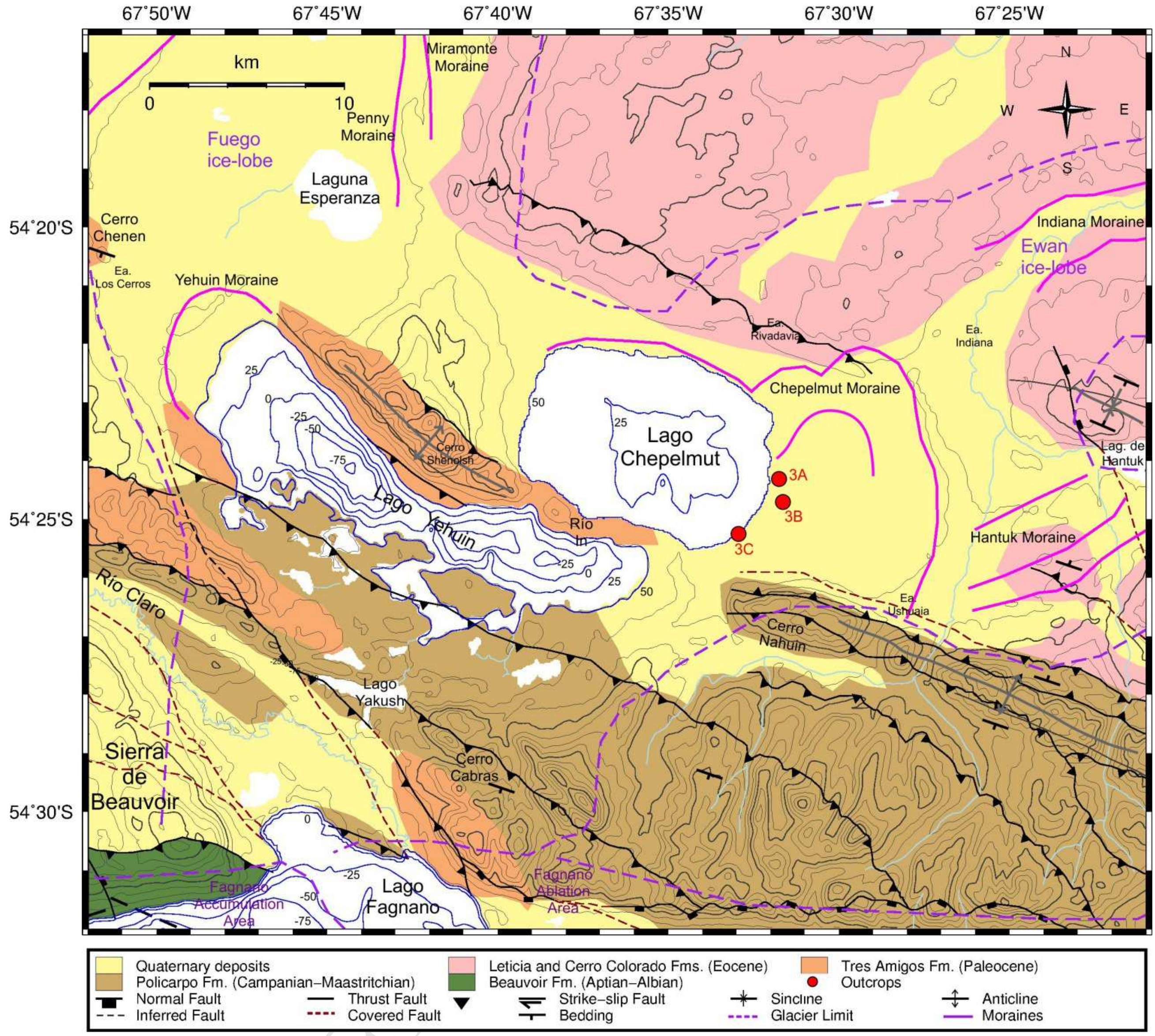

Figure 2. Geologic map of the Lago Chepelmut and its surroundings. Location is displayed in Figure 1. The bathymetry of the Lago Chepelmut (from this paper), Lago Yehuin and Lago Fagnano are also shown. Map adapted from Buatois and Camacho (1993), Menichetti et al. (2008), Martinioni et al. (2013), Torres Carbonell et al. (2013) and Esteban et al. (2014). Red dots show the position of some of the studied outcrops in the area, with the reference to the respective figure. The purple dashed lines enclose the area of the Fagnano palaeo-glacier, Fuego and Ewan glacier lobes after Coronato et al. (2009).

A significant proportion of the surrounding area of Lago Chepelmut is dominated by Quaternary deposits, mostly of glacial origin. During the Late Pleistocene, glaciers originating from the Cordillera Darwin ice sheet flowed to the east (Caldenius, 1932; Meglioli, 1992; Bujalesky et al., 1997). During the Last Glacial Maximum (LGM), ca. 25 ky B.P., multiple tributary glaciers flowed from the northern and southern sides of the Fagnano glacier (Coronato et al., 2009; Rabassa et al., 2011) which drained into the Atlantic Ocean through four main lobes (Figure 1). Among these, two ice-tongues (i.e., Fuego and Ewan), flowed through the studied area (Figure 2), as evidenced by the presence of frontal moraines along the valleys of Fuego and Ewan rivers (Coronato et al., 2008a, b). The Chepelmut moraine (Figure 3A) is located at the eastern side of the lake, and it represents the most proximal onland moraine of the Ewan valley. Its elevation is between 100 and 200 m.a.s.l. and is distributed along the northern margin of Lago Chepelmut. An inner arc of the moraine with an elevation between 70 and 100 m.a.s.l. is observed next to the eastern margin of the lake.

The Lago Chepelmut, together with Lago Yehuin and Lago Fagnano, were included in an older moraine-dammed lake known as Paleolago Fueguino, which drained their waters to the Atlantic. Progressively, this lake drained and decreased their water level, and left evidence in the sedimentary deposits within the lakes (Del Valle et al., 2007). The most notable features are the fluvial terraces in the Ewan river valley and the lake terraces along the eastern margin of Lago Chepelmut (Figure 3B).

Near the eastern margin of Lago Fagnano, the basal till that overlies the glacio-lacustrine and glacio-fluvial deposits is composed by sedimentary breccia which includes boulder of siltstone, sandstone and fossil peat. In other locations, laminated clayey-sandy silts overlie gravel beds, and yellowish grey, fine sands with planar-parallel bedding are also recognized (Bujalesky et al., 1997). At the eastern margin of the Lago Chepelmut, cross-bedded sands with some gravel layers compose the post-glacial deposits (Figure 3C).

Figure 3. Landscape details and outcrops in the Lago Chepelmut area (location in Figure 2). A) An east-view of the inner arc of the Chepelmut moraine, pointed with an arrow. B) Lake terraces located at the eastern margin of the Lago Chepelmut. The terraces represent older stages of the lake shoreline. C) Deposits of a dissected lake terrace at a river meander with cross-bedded sands.

3. Data acquisition

In the period March-April 2014, four high-resolution, DGPS-navigated single-channel seismic profiles were acquired in the Lago Chepelmut (Figure 4). The acquisition, performed on board a Zodiac boat, was carried out with a Boomer as a seismic source and a 10-m-long streamer (see Donda et al., 2008, Baradello and Carcione, 2008, Lodolo et al., 2012, for technical details of the H-R system used). Sampling rate was 50 µs, and the recording length 400 ms. Along-track horizontal resolution of 1 trace every 1.0 m was achieved shooting at 0.5 s interval (at an average speed of 4 knots). Data were first edited for noise traces, and a time-variant filtering and spike deconvolution were applied to improve the signal/noise ratio. To obtain the final version of the profiles for interpretation, we applied on traces the spherical divergence correction and an automatic gain (10 ms). The seismic profiles have been uploaded, displayed and interpreted using the Kingdom Suite®software package (version 8.3). To convert the two-way travel time of the high-resolution profiles to depth, we have assumed different sound velocities based on the observable characteristics of each defined seismic unit and according to the glacial deposits studied by Pugin et al. (1999). A water sound velocity of 1432 m/s was used to produce the lake bathymetry, following Zanolla et al. (2011). Grids were created applying a Kriging method. In order to remove incoherent data, minor editing was applied to these grids. Considering that it has not been possible to create a regular grid of seismic lines to completely and evenly cover the lake due to the often severe weather conditions, the construction of the bathymetric map has required some interpolations. One of them was made assuming certain uniform bathymetry between the beginning of each line and the shoreline, and smoothing significantly the automatic contour produced by the algorithm from one line to the adjacent. For the thicknesses grids, data were also interpolated between the four lines, assuming a virtual absence of sedimentary thickness in the proximity of the lake margins. However, to verify the coherence between the thickness maps of the two interpreted seismic units and the total sedimentary infill, a stacking of the grids was made to check that no incoherent values exist between the stacked lower and upper units and the directly calculated total sedimentary infill. Finally, the GMT software (Wessel and Smith, 1991) was used to generate all the maps presented in this work.

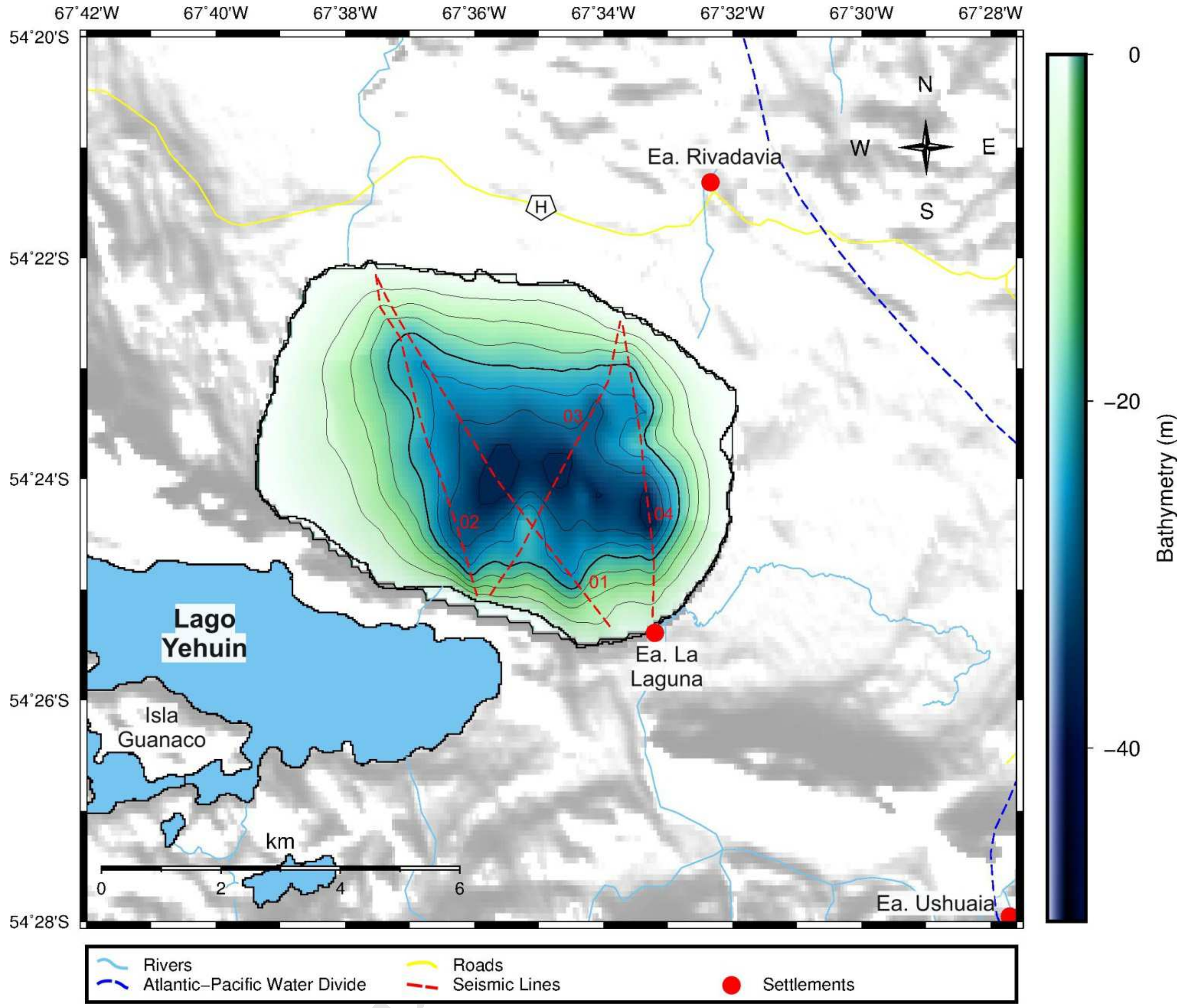

Figure 4. The Lago Chepelmut area with the main geographic references and settlements. The location of the acquired seismic lines is displayed in red dashed lines. The drainage net in this sector includes both Lago Yehuin and Lago Chepelmut. The blue dashed line is the Atlantic/Pacific water divide. In addition, the bathymetric map of the Lago Chepelmut is displayed, showing the deepest zone of the lake near the center of the basin. The lake shoreline is located at 52 m.a.s.l.; contour lines are every 5 meters.

4. Seismic record of Lago Chepelmut

4.1. Bathymetry and acoustic basement

The high-resolution seismic lines provided the information to produce the bathymetric map of the Lago Chepelmut (Figure 4). This map shows a deepest zone of almost 40 m located near the center of the lake. The margin slopes are relatively smooth, mainly in the western part (0.7° in the western and 1.7° in the eastern margin, respectively). The northern and southern margins are slightly steep (0.9°

and 1.4°, respectively). Some mound-shaped structures are located near the southern and eastern side at 15 to 20 m water depth, respectively.

The substratum of the Lago Chepelmut is represented by the acoustic basement, which is characterized by low-amplitude, discontinuous reflectors with no internal arrangement or particular reflector termination. Figure 5A shows the topography of the basement top. The depth increases progressively from the margins to the center of the lake, in concordance with the bathymetric map. The maximum depth reached is almost 110 m near the mid part of the seismic line 03. The western slope is gently sloping (1.4°), while the northern and southern slopes are steeper, with angles of 1.8° and 3.2°, respectively. The eastern slope is the steepest, with angles between 3.8° to 4.2°.

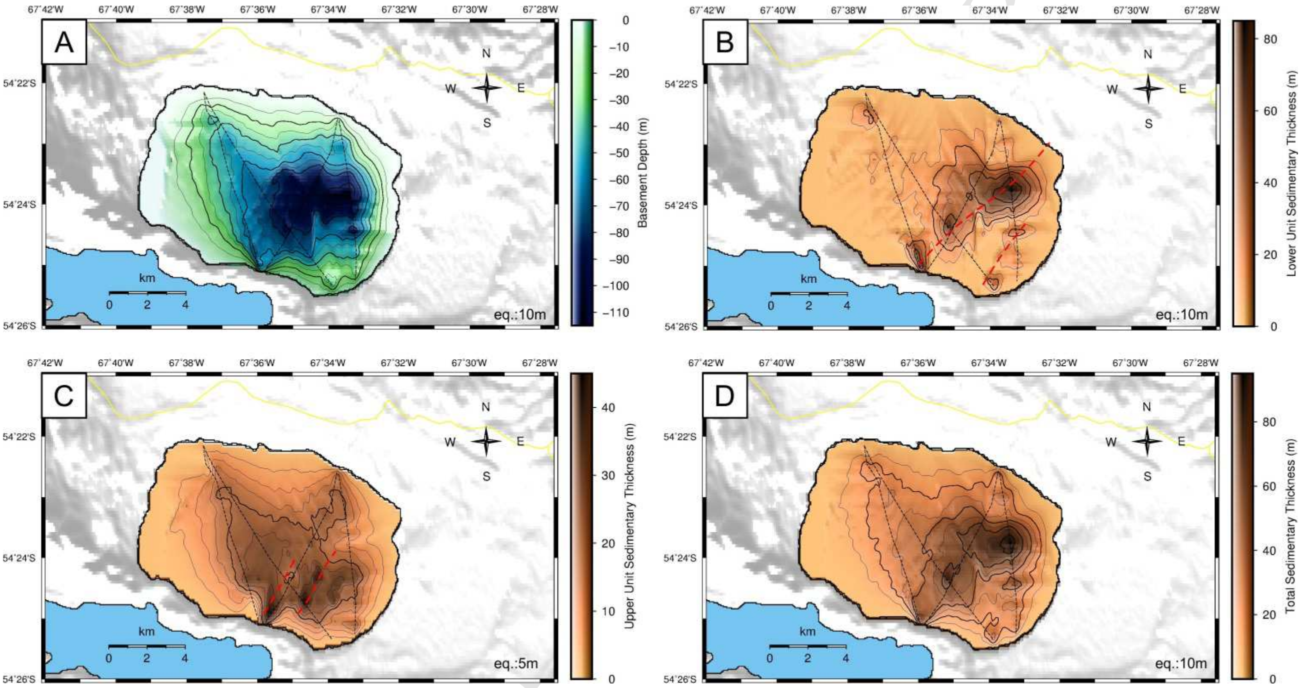

Figure 5. A) Topographic map of the acoustic basement beneath the Lago Chepelmut, with a contour interval of 10 m. B) Map of the sedimentary thickness of the Lower Unit. The dashed red line indicates the NE orientation of the mounds. C) Sedimentary thickness of the Upper Unit. The dashed red line indicates the orientation of the deposits of the Upper Unit. D) Total sedimentary thickness.

4.2. Seismic stratigraphy

The sedimentary infill of the Lago Chepelmut has been differentiated into two seismic units on the basis of geometric patterns and internal architecture of the seismic reflectors: The Lower Unit, which can be well recognized in the seismic lines 01 (Figure 6) and 04 (Figure 8) by their particular mound-like geometry; the Upper Unit, which covers the entire basin and smooth the topography (Figure 7).

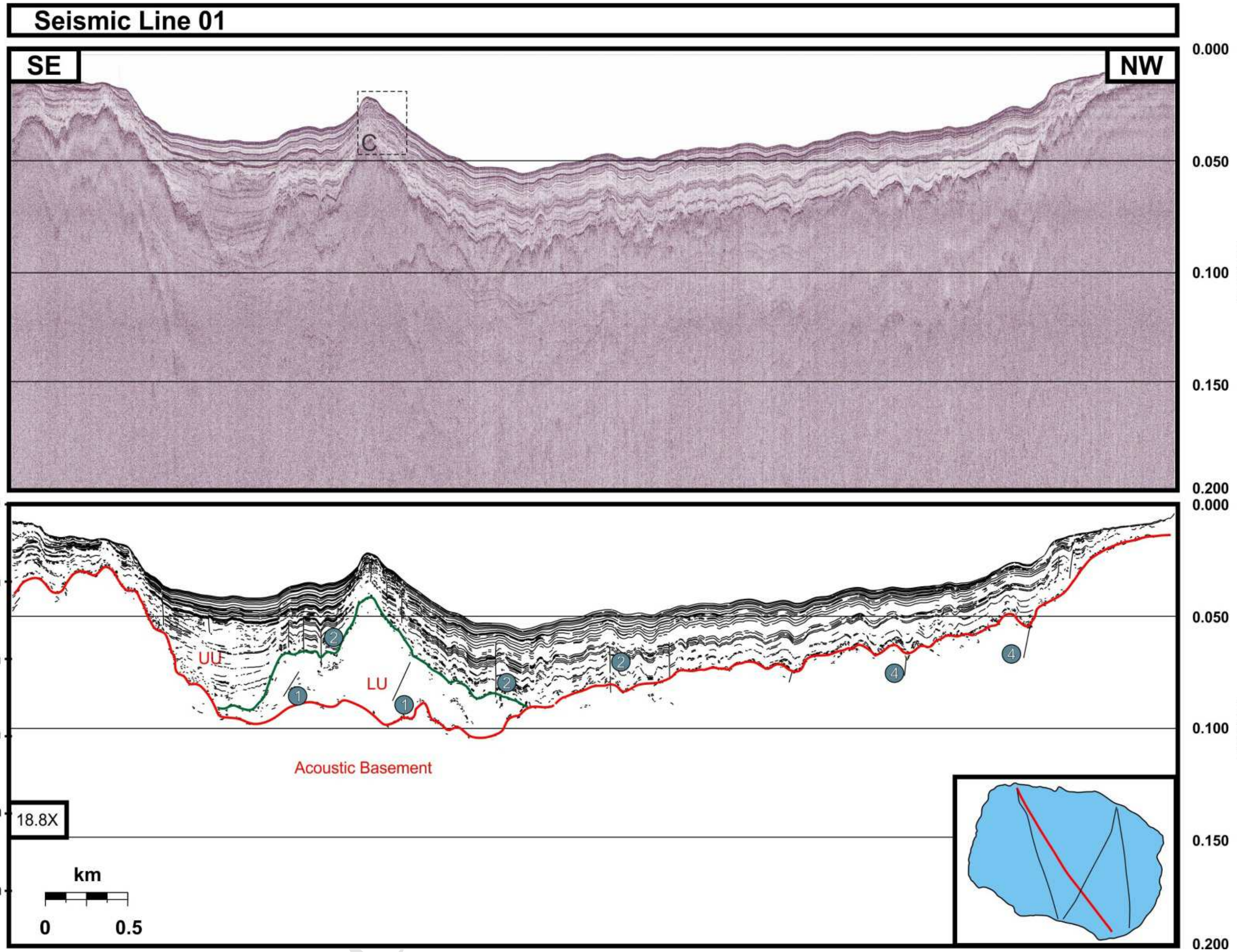

Figure 6. Above, uninterpreted N-S high resolution single-channel seismic profile 01. Below, interpreted sketch with the reflector configuration and lineaments. Depth is given in two-way traveltime (TWT) and converted -only for this figure and as a qualitative measure - to sub-lake level depth (m) based on a P-wave velocity of 1432 m/s. The vertical exaggeration is shown in the lower left side of the interpreted section. The black lines are interpreted as normal faults. Numbers show the group of the faults according to the affected units; LU is the Lower Unit; UU is the Upper Unit. Details of the seismic sections are shown in the Figure 9.

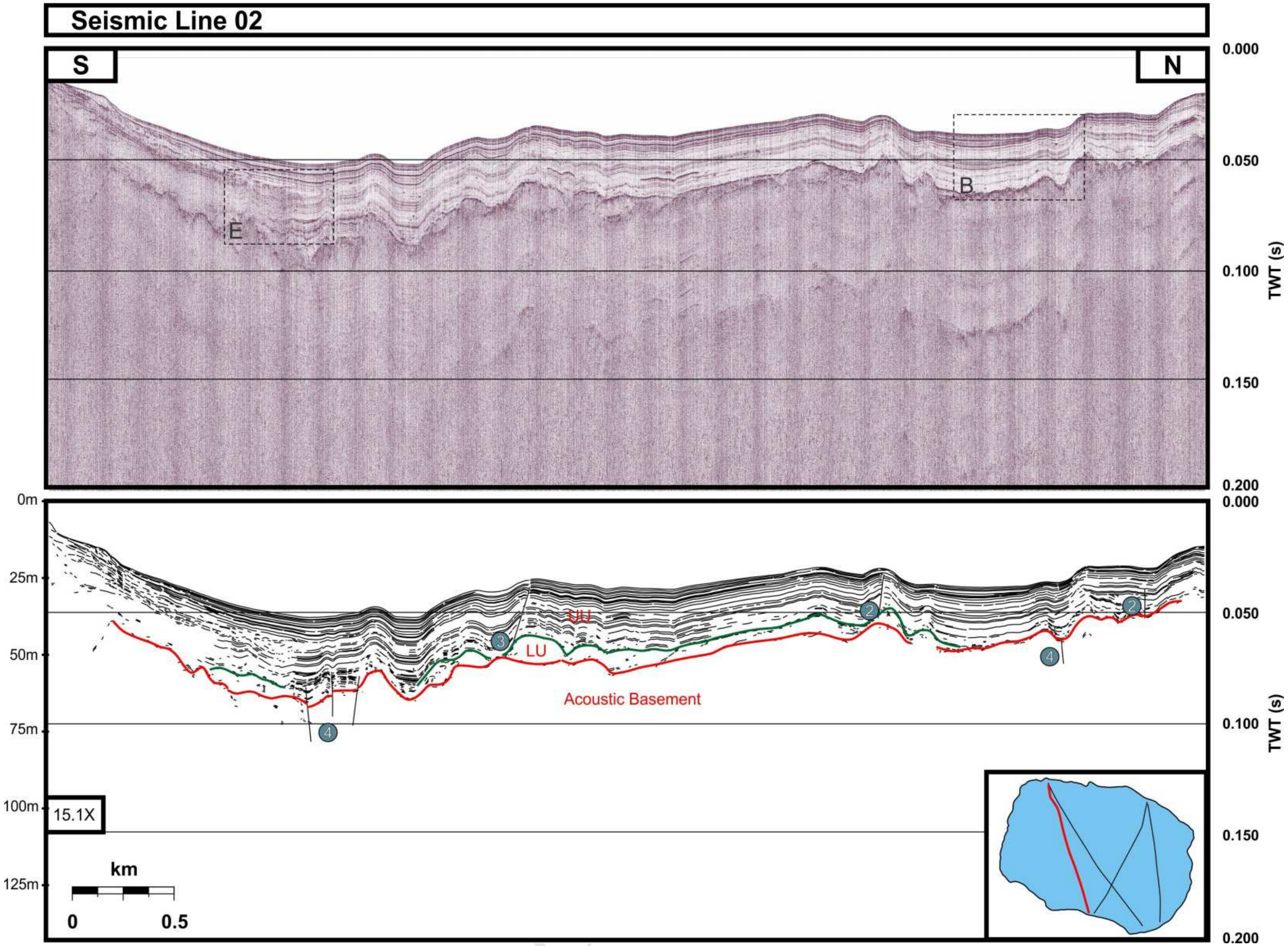

Figure 7. Above, un-interpreted N-S high resolution single-channel seismic profile 02. Below, interpreted sketch with the reflector configuration and lineaments. References same as Figure 6.

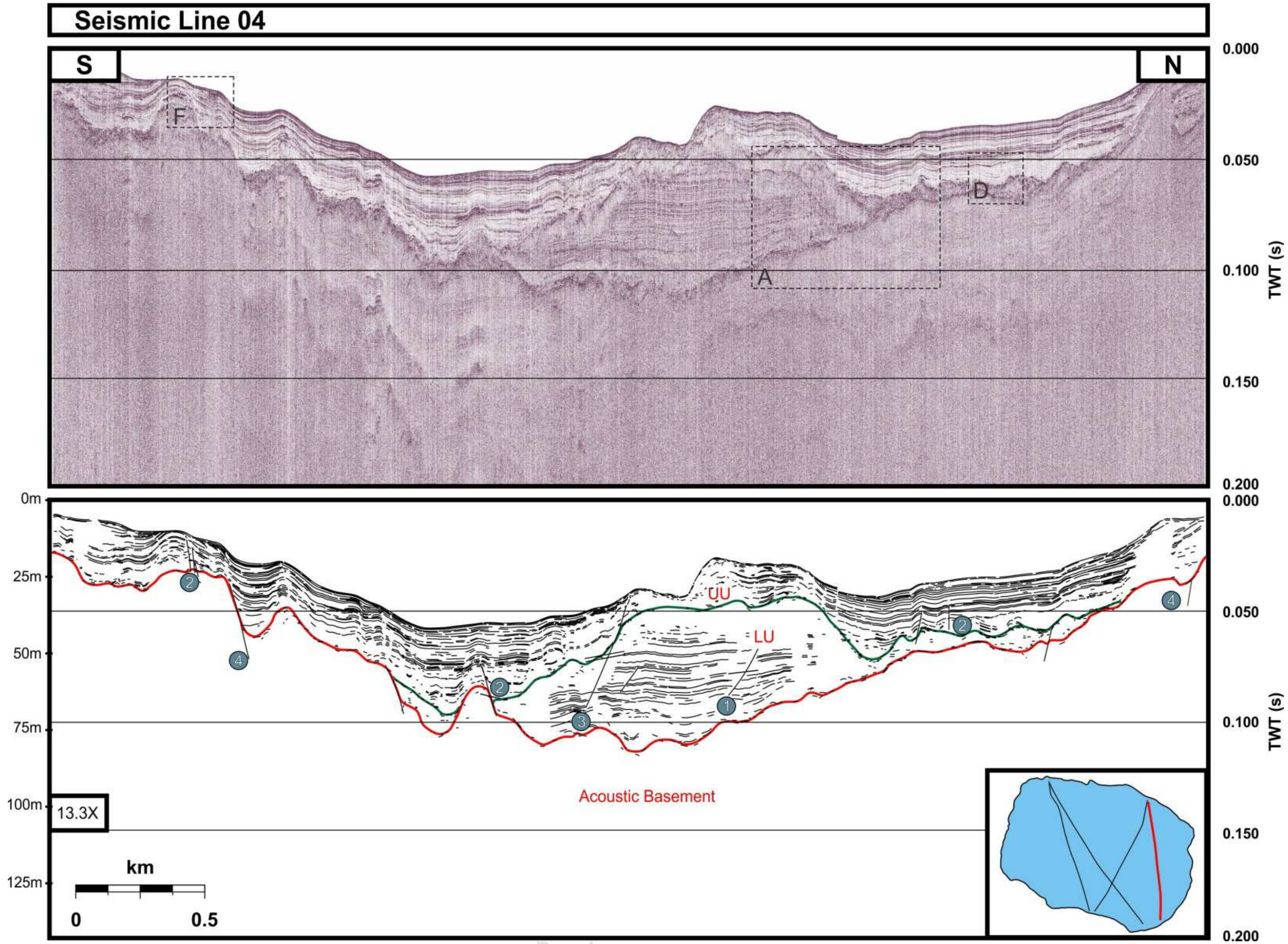

Figure 8. Above, un-interpreted N-S high resolution single-channel seismic profile 04. Below, interpreted sketch with the reflector configuration and lineaments. References same as Figure 6.

The Lower Unit (Figure 9A) rests over the acoustic basement and is chiefly developed in the eastern half of the basin reaching a thickness of up to ~80 m in the central basin. For the time-depth conversion, a sound velocity of 2600 m/s was assumed (see Pugin et al., 1999). Overall the Lower Unit displays a mound-like geometry, grouped in three small mounds (Figure 5B). It is composed by seismic reflectors which include low-amplitude, high to medium intensity, discontinuous with a parallel to subparallel configuration, sometimes chaotic and with transparent intervals.

The Upper Unit (Figure 9B) comprises the sedimentary record between the lake bottom and the top of the Lower Unit. For the time-depth conversion, a sound velocity of 1600 m/s was assumed for this unit. It is mainly characterized by layered and continuous reflectors with a draped distribution which fills the depressions of the underlying unit. The maximum thickness of almost 40 m is reached near the southern margin; the center of the basin has an average of 40 m. The Upper Unit becomes thinner towards the eastern and northern margins. In addition, there is a poorly defined NE trend for the distribution of this unit in the southern margin (Figure 5C).

There are a few variations in the reflector geometries within this unit. The parallel intervals sometimes appear to be truncated by erosive unconformities. In other cases, the reflectors become chaotic with no internal arrangement, evidencing disturbed zones. The upper parts of the unit show wedging reflectors to the margins.

Both seismic units make up a total sedimentary package within the Lago Chepelmut basin of almost 90 m of thickness in the deepest part of the basin (Figure 5D). The deposits appear to be distributed along a NE direction.

4.3. Unconformities

Several unconformities were recognized in the seismic profiles. Some of them are recognized in the whole basin while others are of limited extension, mostly restricted to basin margins. The identified unconformities are six. From the base to the top, the first one is located at the top of the acoustic basement, and is defined by a continuous and high amplitude reflector, U0 (Figure 9D) corresponding to an erosive surface extended in the entire basin. Upwards, another unconformity, U1, of regional extension within the Lago Chepelmut basin is defined by an erosive truncation of the underlying reflectors and onlap configuration of the overlying seismic reflectors (Figure 9D). It separates the Lower Unit from the Upper Unit. The other four unconformities are located within the Upper Unit, affecting the parallel reflectors. The U2 unconformity is an erosive truncation restricted to Lago Chepelmut margins which becomes a paraconformity in the central basin (Figure 9D). A clear erosive truncation is found along the southern margin of Lago Chepelmut basin, U3, which separates folded underlying reflectors from the downlap overlying reflectors (Figure 9E). A local angular unconformity, U4, is identified by an acoustic fabric characterized by the overlying reflectors downlapping against the underlying reflectors (Figure 9F). U4 is located only in the shallower zones of the northern and southern margins. The uppermost unconformity, U5, is a slight angular unconformity located through the entire basin. The overlying reflectors wedge through the deepest zones, while the underlying reflectors are strongly parallel (Figure 9F).

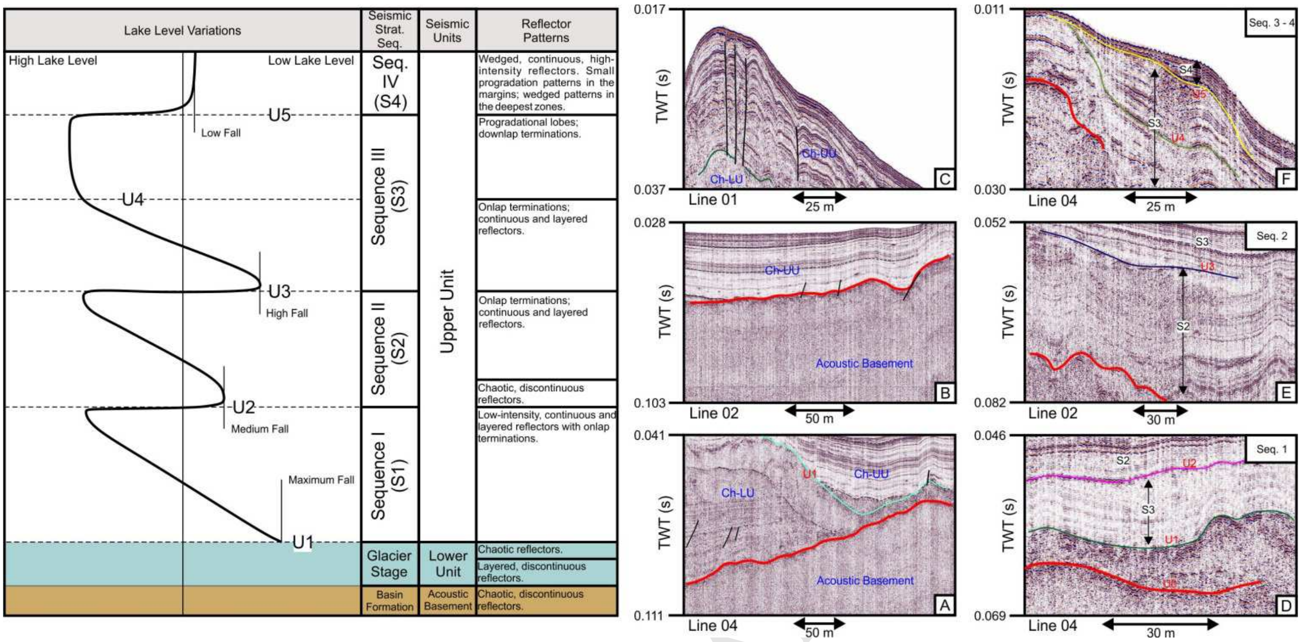

Figure 9. Lake level curve including the correlation with the seismic units and the main reflector patterns between the unconformities. Except U4, the unconformities were assigned with a qualitative lake level fall based on the extent and depth reached by each erosional surface. The location of the inset is displayed in the Figures 6, 7 and 8; the continuous lines represent the discontinuities interpreted as normal faults; colored lines are the six recognized unconformities.

4.4. Interpretation of structure from seismic images

Several sub-vertical to oblique discontinuities were recognized in the seismic records (Figure 9C). These discontinuities of seismic reflectors show an average time shift of 0.002 TWT s (an offset of 1.5 m) and affect mainly the sedimentary infill. The slip of the reflectors is downslip; therefore, they are interpreted as normal faults.

The faults can be divided in four groups based on the affected seismic unit. The first group (see faults in Figure 6) is composed by a few short normal faults that affect only the Lower Unit. The angles of the fault planes vary from 4° to 9°. The second group includes normal faults that are affecting only the Upper Unit. This group is composed by faults with an average dip of 15°, extended from the top of the Lower Unit to the upper part of the Upper Unit (Figure 7). A few faults are vertical to sub-vertical (Figure 9C). The third group is characterized by a few faults only found in the center of the lake basin (Figure 8), affecting the entire sedimentary package (Lower and Upper units). The angles of these faults are low, between 10° and 13°. The fourth group is composed by vertical to sub-vertical faults that are affecting the acoustic basement. Mainly found in the southern margin (Figure 6, 8) these faults are associated with a stepped morphology of the substratum. In this group of faults, the time shift reaches 0.007 TWT s (almost 5 m offset).

5. Interpretation of the data

5.1. Seismic units

Lower Unit

This seismic unit includes layered strata and continuous internal reflectors. These types of units have been interpreted in other periglacial lakes (Eyles et al., 2000; Waldmann et al., 2008, 2010a, 2010b; Pinson et al., 2013) as till deposits. The geometry of the Lower Unit (Figure 5B) suggests mound-like morphology, which can be interpreted as a moraine deposit, based on the similarity with glacier deposits studied, for example, in Bahía Inútil and Estrecho de Magallanes (Chile), or Oak Ridges Moraine, in Canada (Pugin et al., 1999; Fernández et al., 2017). The distribution of the deposits in top view shows a NE orientation (Figure 5B). The onland moraine arcs (i.e. Chepelmut, Indiana or Hantuk moraines) along with this new submerged moraine ridge complete the recessional path of the Ewan ice lobe along the Ewan river valley (Figure 2). Therefore, we interpret the mound shaped deposits of this unit as part of the Ewan ice lobe terminal moraines.

Upper Unit

The Upper Unit is essentially composed by layered and continuous reflectors of varied reflectivity. The well-defined geometry, continuity and extension of the reflectors suggest lacustrine sedimentation. However, a detailed analysis of the geometries and their terminations, supported by a comparison with other studies (i.e. Lyons et al., 2011; Scholz et al., 1998), indicates variations in the sedimentation rate and local presence of erosion. A sequential stratigraphic analysis was made by the observation of the geometric patterns of the reflectors.

5.2. Seismic sequence stratigraphy of the Upper Unit

The stratal architecture of the Lago Chepelmut as revealed from seismic data analysis reflects changing rates between the accommodation space and the sedimentation rate of the basin. Following the principles of seismic sequence stratigraphy (Vail et al., 1977; Vail 1987; van Wagoner et al., 1987; Scholz, 2001), the deposits of the Upper Unit within the Chepelmut basin can be divided into four seismic stratigraphic sequences. These sequences are defined and separated on the basis of erosional surfaces and angular unconformities, interpreted to have been formed during major drops in the lake level.

S1 (Figure 9D), the oldest sequence, begins with a lowstand marked after the deposits of the seismic unit interpreted as glacier till (Lower Unit). The general retreat of the glacier lobe resulted in an increase in the water input to the system. Then, a transgressive system tract due to the lake level rise is represented by the first lacustrine deposits of the base of Upper Unit, with onlap terminations. No high-stand system tract is recognized after the transgression as no progradational pattern is observed in the reflectors. The upper boundary of the sequence is marked by an erosive truncation (U2), and may represent a falling stage of the lake level.

S2 (Figure 9E) represents the lake change level after the first lake-level fall. Near the lowermost part of this sequence, the Upper Unit is composed by chaotic reflectors with a lenticular geometry, which may represent a small delta or fan sedimentation located in the southwestern and northeastern basin margins. The presence of these deposits is the result of the sedimentation after the erosive conditions which generated the boundary between sequence I and sequence II. Over the fan sedimentation, the continuous, layered and medium to high reflectivity reflectors with onlap terminations, are interpreted as a transgressive system tract marked by a lake level rise.

The sequence S3 (Figure 9F) is bounded at the base by another erosive truncation (U3). The erosional relief of U3 is the most notable and accentuated in comparison with the other unconformities. Therefore, it represent the highest lake level fall. The lower part of this sequence is interpreted as a transgressive system tract, while the upper part represents a high-stand system tract composed by wedged and downlap reflectors. The base of these reflectors, therefore, are interpreted as a maximum flooding surface (U4), which marks the highest lake level during the lifetime of the sedimentation of the S3.

The sequence S4 (Figure 9F), the youngest sequence of the Chepelmut basin, is bounded at the base by an important erosive truncation (U5) which can be recognized at the northern and southern margins of the lake. The continuous, layered, high reflectivity and, slight-wedged reflectors may be interpreted as a lowstand system tract. The wedged reflectors and the progradational lobes on the southern margin suggests that the lake level was low enough to give this type of depositional structures, with a sediment bypass towards the deepest sectors of the basin.

The described sequences reflect changing conditions in the lacustrine sedimentation within the basin. The Figure 9 shows a schematic qualitative curve with the inferred lake level changes and a correlation with the main events in the zone and with the previously defined seismic units.

6. Discussion

The glacial history of the central region of Tierra del Fuego has been documented both near the Lago Fagnano (Bujaleski, 2011; Caldenius, 1932; Coronato et al., 2008a, b; 2009; Meglioli, 1992; Waldmann et al., 2008; 2010 a, b) and near the Lago Yehuin and Chepelmut (Meglioli, 1992). Fuego and Ewan glacier tongues, which were two diffluent ice lobes of the Fagnano glacier (Waldmann et al., 2010), flowed northward and north-eastward, traversing both the Yehuin and Chepelmut basins (Lozano et al., 2018). The exposed moraine deposits were mapped and dated in the Fuego and Ewan river valleys. In the Fuego river valley, the Buenos Aires, Miramonte and Penny moraines can be correlated with the stage B of the LGM (Coronato et al., 2008a), dated at 25.2 – 23.1 kyr B.P (McCulloch et al., 2005). The Yehuin moraine is correlated with the stages C or D, of 21.7 – 20.3 kyr B.P. or older than 17.5 kyr B.P. In the Ewan river valley, the Indiana and Hantuk moraines are also correlated with the stage B, while the Chepelmut moraine (Figure 3A) is correlated with the stages C or D (Coronato et al., 2008b). Multiple advances/stillstands of the Fagnano glacier lobe were evidenced by moraine crests preserved in the Fagnano lake basin (Waldmann et al., 2010). These oscillations probably had an effect on the retreat of the Ewan lobe. However, the final retreat of the glaciers from Tierra del Fuego's lowlands towards the Cordillera Darwin occurred during later stages of the Younger Dryas, at 11 to 10 kyr B.P. (Boyd et al., 2008).

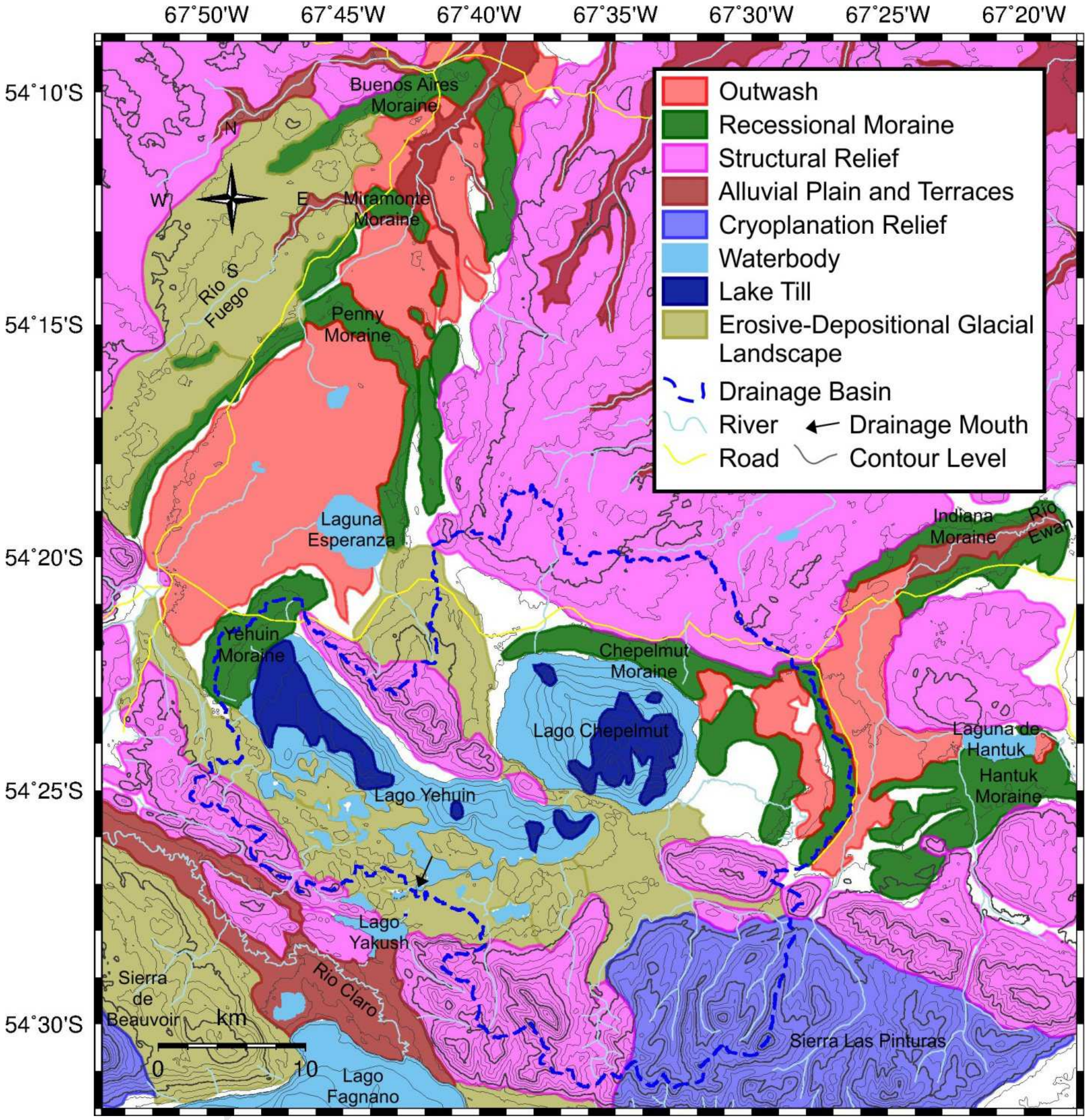

Figure 10. Geomorphologic map of the Lago Yehuin and Lago Chepelmut area. The moraine arcs are displayed through the Fuego and Ewan river valleys. Additionally, the moraines within both lakes are also displayed. The blue dashed lines show the boundary of the drainage basin which is mainly controlled by the moraine arc at the western and eastern sides. The northern part is limited by a structural relief. The waters of the entire system output through the south,

toward Lago Fagnano. The glacial activity modeled the landscape and at present day, the glacial deposits control the drainage.

A map with the geomorphology and the position of the moraines is presented in Figure 10. As in the case of the Lago Chepelmut, submerged moraine ridges were interpreted in the sedimentary record of the Lago Yehuin (Lozano et al., 2018). The Lago Yehuin shows thick deposits of glacial origin located mainly in the western side, while in the eastern side are scarce. The differences in thickness between the two sides of the Lago Yehuin are related with the two glacier lobes that move through the area: the Fuego glacier lobe to the west and the Ewan glacier lobe to the east. In addition, the difference in thickness could be due to the fact that the two glaciers (Ewan and Fuego) were different in size and in sediment load, or maybe that the two glaciers melted in different times (Lozano et al., 2018). The thickness of the glacial till of Lago Chepelmut is comparable with the glacial till of the western side of Lago Yehuin.

The evidence of glacier dynamics and their deposits are mirrored in the sedimentary infill of the Lago Chepelmut. The seismic analysis of the acquired profiles and the sedimentary architecture of the lake fill suggests that the origin of the lake is due by the ice-carving of the Ewan glacier. However, a primary control in the morphology could be due by the pre-existing structural setting of the area. The Late Cretaceous compressive tectonics of the Magallanes fold and thrust belt developed a system of W-NW thrust faults which is well represented in the relief and river valleys, mainly in the Sierra de Beauvoir and Sierra Las Pinturas (Figure 2). It is well recognized that glaciers preferentially use already formed structures as corridors for the ice flow. As an example, some studies show that there is a close relationship between the structures related to wrench tectonics and the orientations of the fjords in the southern Andes (Glasser and Ghiglione, 2009; Breuer et al., 2013). In other zones of Tierra del Fuego, like the Lago Fagnano or the Canal de Beagle, a structural control is reported for the glacier discharge patterns (Bujaleski, 2011; Lodolo et al., 2002, 2003). In the Ewan and Fuego river valleys, existing structures related with the Jurassic transfer faults (Ghiglione et al., 2013) seem to be related with the glacier path of the two glacier lobes. The strike-slip tectonics reactivated these older NE Jurassic transfer faults and left their imprint in form of NE valleys like Fuego and Ewan river valleys (Lozano et al., 2018). Finally, the glacier activity modeled the relief and later deposited the moraine arc, locally changing the drainage net. The geomorphological map shows that there is a quite close relationship between structural lineaments and the general trend of the rivers and valleys. A sub-parallel to sub-dendritic drainage pattern is recognized in the area. The drainage basin observed in Figure 10 shows that there is a main control from the glacier forms with the boundaries located in the western and eastern areas of the lake. These depositional forms separate Ewan and Fuego river valleys from the Lago Yehuin and Chepelmut.

The sedimentary patterns in lakes are controlled by allogenic factors such as tectonics and climate through interactions of four main variables: sediment supply, water supply, basin-sill height (spill point), and basin-floor depth (Bohacs et al., 2000; 2003). Erosional surfaces are best developed on areas where relatively slow rates of subsidence limit accommodation space (Scholz et al., 1998).

The lake level curve (Figure 9) shows a progressive increase in the lake water level, which can be inferred as the result of the enormous water input due to the melting of ice lobes and permafrost during the climate warming after the LGM (Del Valle et al., 2007). The record of the changing lake level is also evident from lake terraces located in the eastern margin of the Lago Chepelmut (Figure 3B). The decrement of the lake level, which left an evidence of three erosive unconformities (U2, U3 and U5) within the lacustrine deposits (Upper Unit) can be correlated with the three terraces levels recognized along the Fuego river valley (Coronato et al., 2008a) and the three to four terraces levels in the Ewan river valley (Coronato et al., 2008b). However, at present day, the Lago Chepelmut is disconnected from the valley due to the low lake level (Figure 10). The youngest sequence IV, therefore, represents a stage where the hydrology was characterized by drainage to the south, through the Lago Fagnano. The change in the hydrology of the Lago Chepelmut from the Atlantic water drainage to a drainage to Seno Almirantazgo (Estrecho de Magallanes, Chile) was established 7.8 kyr B.P., when the Paleolago Fueguino – a water body which includes the present day Lago Fagano, Yehuin and Chepelmut – decreased their water level after the LGM. This decrease could be associated to a seismic event in the area, which caused the broke of the moraine barriers of the lakes and led to a loss of the water of the system (Del Valle et al., 2007). The unconformity U5 can be correlated with this event and may be assigned an age of 7.8 kyr B.P.

The several faults recognized within the seismic sections, in particular, groups 1 to 3, are characterized by low angles of 5° to almost 20° with a low offset. This deformation within the sedimentary record can be treated as a result of a gravity collapse, given its low angle, low offset and their presence confined only within the sedimentary package. However, it cannot be excluded that these may have been generated by earthquakes. Seismological data of the Tierra del Fuego show a great variety of seismic events that comprise earthquakes of low to medium magnitude, with the majority of the events between 2 and 4 Mm, with 50% of them located in the uppermost 10 km. In addition, seismicity shows that the zone is active at the present day (Buffoni et al., 2009; Sabbione et al., 2007, 2016) and recent GPS studies conducted along the Magallanes-Fagnano Fault System indicate that the principal strain components define two deformation styles: a zone with predominant shortening of the crust to the west, and significant stretching to the east (Mendoza et al., 2011). NW-SE extensional components and a subordinate contraction component with a SW-NE trend have been reported for the Lago Yehuin area (Mendoza et al., 2011, 2015). Therefore, the Yehuin and Chepelmut basins are located within an area dominated by transtensional, left-lateral deformation.

The fault group 4, characterized by vertical to sub-vertical normal faults which affect the basement of the lake, could have a tectonic origin, so we cannot exclude *a priori* the occurrence of tectonic factors which partly influenced the genesis and evolution of the Lago Chepelmut. A fault zone analogous to the Deseado Fault Zone but located between Lago Yehuin and Chepelmut (Lozano et al., 2018) could be the responsible of the normal faulting of the basement and the trigger for the gravity collapse of the lacustrine sediments.

7. Conclusions

- Analysis and interpretation of single-channel seismic records, coupled with information derived from outcrops, have allowed to produce for the first time a bathymetric map of the Lago Chepelmut and analyze the sedimentary architecture of the depositional cover.
- The Lago Chepelmut, a small basin located in the central part of Tierra del Fuego Island, is filled with sediments grouped into two units: a Lower Unit, consisting of glacial deposits, is found in the deepest part of the lake, near the eastern margin. These till deposits were correlated with onland moraine ridges to reconstruct the recessional path of the Ewan ice lobe. The Upper Unit, interpreted of lacustrine origin, drapes the entire basin and represents the sedimentation which occurred after the glacier retreat.
- After the moraine deposition in the Lago Chepelmut basin, the lacustrine stage was marked by variations in the lake water level. At least three lake level falls were recognized from the analysis of the sedimentary infill. However, the exact magnitude and the age constraints of these variations remain difficult to determine.
- Data suggest that the origin of Lago Chepelmut basin is mostly due to ice-carving by glacier lobes dynamics. However, the presence of a few vertical to sub-vertical faults affecting both the basement of the Lago Chepelmut and part of the sedimentary cover testify that tectonic activity has contributed to shape the lake.
- There is a tight correspondence between structural lineaments and ice flow paths of the Ewan and Fuego glacial lobes. These structural-controlled corridors of ice discharge were later reshaped by glacier activity.
- Several low-angle normal faults occur in the sedimentary infill of the Chepelmut basin which can be related to gravity collapses. The Lago Chepelmut zone is located in a seismically active area, where a complex array of left-lateral, strike-slip lineaments is developed. A fault zone analogous to the Deseado Fault Zone, located between Lago Yehuin and Chepelmut, could be the responsible of the normal faulting of the basement and possibly the trigger for the gravity collapse of the sediments.

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- We present a study of a seismic survey in Lago Chepelmut basin, located in Tierra del Fuego.
- Two seismic units are recognized within the basin, a glacial-related lower unit and a lacustrine upper unit.
- The basin is interpreted mainly as an ice-carved basin by the glacier lobes.
- We suggest that three major drops in the lake levels are evidenced in the stratigraphic record.