Bathymetric map of Lago Fagnano (Tierra del Fuego Island)

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ABSTRACT We present a general bathymetric map of Lago Fagnano, the largest ice-free lake of the Southern Hemisphere, located in the central part of the Tierra del Fuego Island. The map has been obtained compiling all the available bathymetric soundings and depth-converted high-resolution seismic profiles, collected in the course of several geophysical campaigns. The lake occupies a 110-km long, E-W trending tectonic depression within the southernmost tip of the Andean Cordillera, where the South America-Scotia plate boundary traverses the Tierra del Fuego Island. The map allows us to identify the main morpho-bathymetric features of Lago Fagnano. The lake floor is divided into two principal sectors of different water depths, separated by a main shoal located in the central part of the lake. Maximum water depth (206 m) is found in the eastern part, whereas water depths in the western half do not exceed 165 m. In this paper, we describe the geometry and the general morphological characteristics of the basin, which was generated by a combination of distinct tectonic processes, and later superposed by Late Quaternary glacial and glacio-lacustrine dynamic events.

1. Introduction

Lago Fagnano (or Lago Khami, as originally called by the native inhabitants), located in the central part of the Tierra del Fuego Island (54°26'-54°37'S, 66°42'-68°35'W; 26 m AMSL, Plate 1), is the southernmost and largest ice-free lake of the Southern Hemisphere. The basin trends roughly E-W, is more than 105 km long, and its width varies from 2.8 to 9.7 km. The total area of the lake is 596 km^2. Only its westernmost tip (about 15 km) is part of the Chilean territory. Lago Fagnano occupies a segment of the Magallanes-Fagnano fault system (Lodolo *et al*., 2002, 2003), which is part of the South America-Scotia transform plate boundary crossing the Tierra del Fuego region (Fig. 1). The shape and lake morphology is strongly conditioned by tectonic processes; later its shape was mainly controlled by Late Quaternary glacial dynamics, as testified by the geometry and sedimentary architecture of the sequences filling the basin, and by the widespread glacial landforms surrounding the lake coastline. A bathymetric map of the entire Lago Fagnano, derived from sounding profiles and digitized high-resolution seismic lines acquired in several geophysical campaigns, is presented here (Plate 1), along with three representative high-resolution seismic profiles

showing the main morphological and sedimentary characteristics of the different sectors of the basin.

2. Materials and methods

The bathymetric map of the Lago Fagnano is derived from a large data set comprising bathymetric soundings and depth-converted, high-resolution seismic profiles acquired during several campaigns in the Tierra del Fuego region. These geophysical and geological surveys were conducted in the frame of the TESAC (Tectonic Evolution of the South America-Scotia plate boundary during the Cenozoic) and FORTE (Fueguian Orogen Tectonic Evolution) scientific projects (from 1999 to 2004), partly funded by the Italian "Programma Nazionale di Ricerche in Antartide" (PNRA), and in the frame of a Italian-Argentinean project financed by the Italian Foreign Ministry. To produce the bathymetric chart, TESAC data have been integrated digitizing a high-resolution seismic grid acquired in March 2005 by Waldmann *et al*. (2008) in the Lago Fagnano. Measurements collected by the TESAC group, some of them already published in literature (Lodolo *et al*., 2003, 2007; Menichetti *et al*., 2007), comprise 43 DGPS-fixed bathymetric profiles acquired with a 200 kHz echo-sounder, and 27 depth-converted, high-resolution single-channel seismic profiles acquired in November 2009 using a Boomer seismic source and a solid-state, 10 m long streamer. Sampling rate was 0.05 ms, 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 (with an average ship speed of 4 knots). To convert the two-way travel time of the high-resolution profiles in water depths, the following formula was applied (Marczak, 1997):

$$c = 1.402385 \times 10^{3} + 5.038813\,T - 5.799136 \times 10^{-2}\,T^{2} + 3.287156 \times 10^{-4}\,T^{3} - 1.398845 \times 10\text{-}6\,T^{4} + 2.787860 \times 10^{-9}\,T^{5}$$

where c is the sound velocity in water, and T is the temperature in degrees Celsius. In the case of Lago Fagnano, the average temperature is 6°C, as measured in different sectors of the lake through vertical profiling in November 2005 (Waldmann *et al*., 2008). The formula gives a sound velocity for the conversion time-depth of 1432 m/s.

The resulting bathymetric map, superposed on the Digital Elevation Model of the surrounding region (SRTM data: http://dds.cr.usgs.gov/srtm/), is presented in Plate 1. More than 350,000 data points (70% of them resulting from digitalization of seismic profiles) have been used to produce the map, contouring the data with a triangulation algorithm imposing a forcing factor along the E-W direction. This map represents an updated and complete version of parts of Lago Fagnano bathymetric maps published in previous papers by Lodolo *et al*. (2002, 2003, 2007).

3. Geological setting of Lago Fagnano

Lago Fagnano is located in the mountainous area of Tierra del Fuego, within the southernmost tip of the Andean Cordillera. The geological setting of the region is described in several papers (Olivero and Malumián, 1999; Menichetti *et al*., 2007, 2008 and references therein), and so we

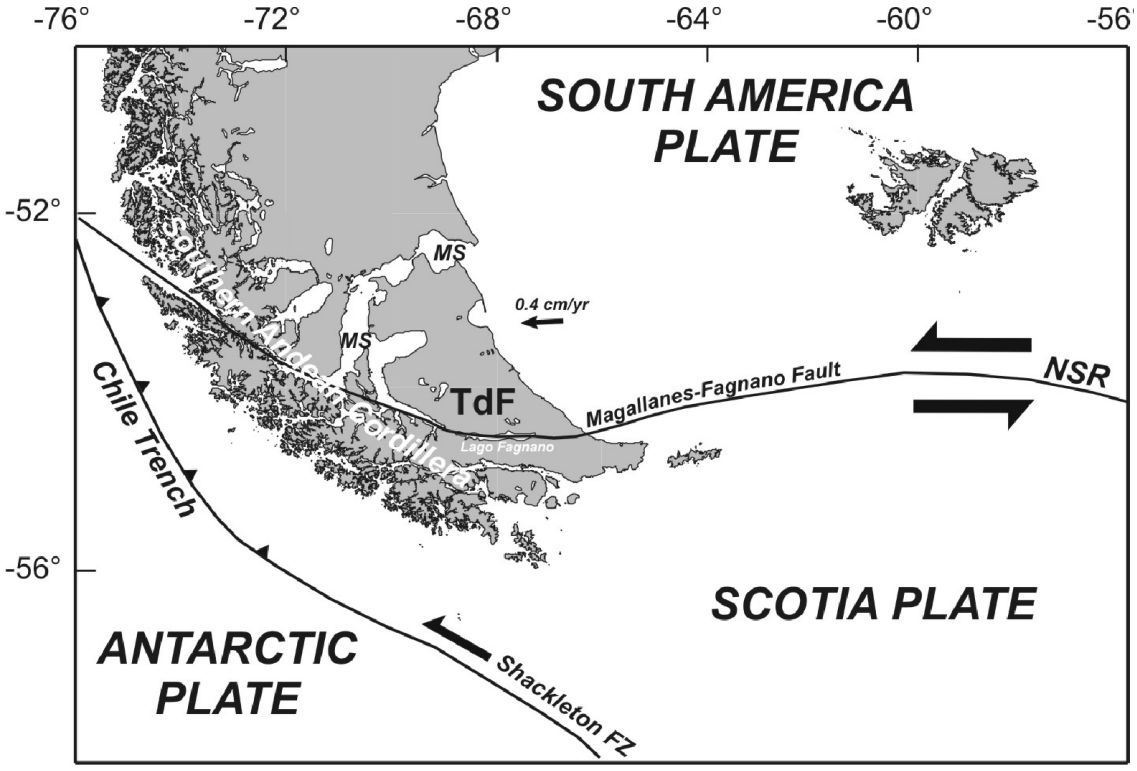

Fig. 1 - Simplified tectonic sketch of southernmost South America and Tierra del Fuego Island (TdF). Abbreviations are as follows: MS, Magallanes Strait; NSR, North Scotia Ridge.

describe only the principal geological formations surrounding Lago Fagnano and the general tectonic context (Fig. 2).

The rocks located along the northern shore (Beauvoir range, with a maximum elevation of 1050 m AMSL) and eastwards, belong to the Beauvoir Formation (Camacho, 1967), of Albian-Cenomanian age. These are mainly composed of dark mudstones, shales and tuffs, with intercalations of fine sandstones and layers of marl (Menichetti *et al*., 2007). The Las Pinturas range (with a maximum elevation of 660 m AMSL), lies to the NE, and is composed of yellowish brown-to-greenish grey, fine-to-very fine sandstones, with intercalations of shelly limestones, mudstones and conglomerates of Danian-Palaeocene age [Río Claro Formation of Camacho (1967) and Martinioni *et al*. (1999)]. The bedrock of the Alvear and Lucio López ranges (with maximum elevations of 1300 and 1490 m AMSL, respectively), located in the southern sector of Lago Fagnano, is composed of rhyolitic and dacitic lava and tuffs, frequently of ignimbrite type, with sandy and sometimes conglomeritic inter-bedding (Caminos *et al*., 1981), corresponding to the Lemaire Formation of the Late Jurassic (Borrello, 1969). To the west, Lago Fagnano is bordered by the eastern scarp of the steep and narrow Monte Hope, and to the east by a curved gravel barrier forming the eastern shore of the lake and closing the sag pond of the Rio Turbio to

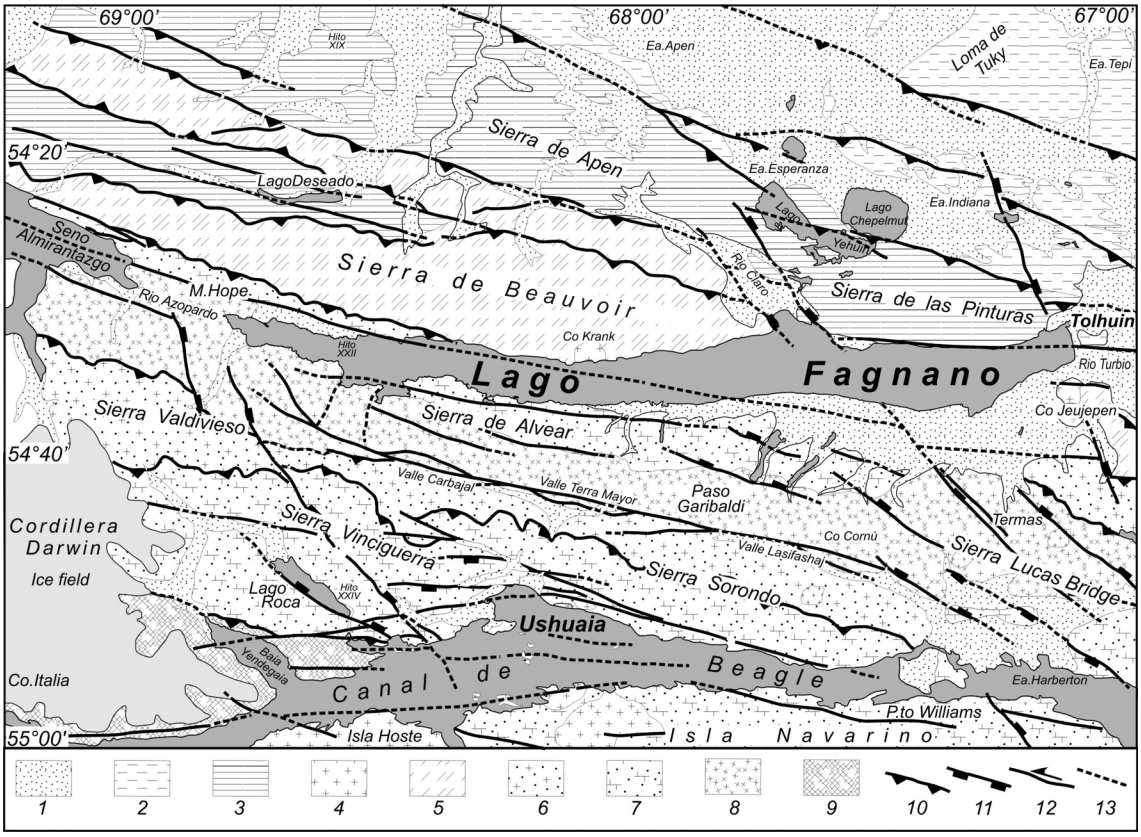

Fig. 2 - Geological and structural map of the central sector of the Tierra del Fuego Island and Lago Fagnano area. Legend is as follows: 1. glacial and fluvio-glacial sediments (undifferentiated moraine systems and till) and debris (Pleistocene); 2. sandstones, marls and conglomerates, Rio Claro Group (Lower Paleogene); 3. slaty marls, meta sandstones and siltstones, Cerro Matrero Fm. (Upper Cretaceous); 4. plutonic rocks, syenites and monzodiorites (Upper Cretaceous); 5. dark slates, metamarls and tuffs, Beavouir Fm. (Lower Cretaceous); 6. metasandstones, dark shales and metatuffs, Yaghan Fm. (Lower Cretaceous); 7. submarine volcanoclastic metasediments with basalts, Alvear Fm. auct., Lemaire or Tobifera Fm. (Upper Jurassic); 8. volcanoclastic metasediments with rhyolites and quartz porphyres, M.te Buckland Fm. Auct., Lemaire or Tobifera Fm. (Upper Jurassic); 9. metasediments with fine-grained quartz-sericite-garnet schists, Lapataia group Auct. (Middle Jurassic); 10. thrust faults, triangles in the hanging-wall; 11. normal faults, barbs in the hanging-wall; 12. strike-slip faults; 13. inferred faults (from Menichetti *et al.*, 2010).

the west. The lowlands that characterize the eastern sector of Lago Fagnano are mainly covered by peaty zones and widespread forests. Coastal cliffs formed by glacial and glacio-deltaic sedimentary strata are mainly found along the south-eastern shore, and deposited during an ice advance prior to the Last Glacial Maximum (Bujalesky *et al*., 1997). The Claro, Milna, Valdez, Tuerto and Turbio rivers are the principal inputs of Lago Fagnano, whereas the Azopardo River at the western extreme of the lake is the only outlet towards the Pacific Ocean through the Seno Almirantazgo in the Strait of Magallanes.

Lago Fagnano occupies a significant part of the Magallanes-Fagnano left-lateral fault system, an E-W trending depression traversing the whole Tierra del Fuego Island in both the Argentinean and Chilean territories (Lodolo *et al*., 2002, 2003; Menichetti *et al*., 2008). To the west, the Magallanes-Fagnano system impinges with the southern Chile Trench, and to the east it connects

with the system of shallow banks and submarine ridges constituting the northern margin of the oceanic Scotia plate. This transform system accommodates the relative movements between the South American and Scotia plates (Pelayo and Wiens, 1989); earthquake data and global plate circuits show that in the Scotia Sea region, the Antarctic plate is slowly moving (1.7 to 2.0 cm/yr) easterly relative to the South American plate (Smalley *et al*., 2007). Recent fault scarps and displacement of glacio-lacustrine sediments along the transform lineation in the eastern part of the lake indicate ongoing tectonic activity (Menichetti *et al*., 2008). Moreover, fluvial drainages in the same region are clearly influenced by the presence of E-W striking structures related to the fault system.

4. Morpho-bathymetry of Lago Fagnano

The origin and development of Lago Fagnano are due to a combination and superposition of tectonic and glacial dynamic processes. During past glacial periods, a glacier originating from the Cordillera Darwin has expanded eastwards through the Fagnano basin, with its external front reaching a maximum advance identified at about 35-40 km east of the present-day eastern shore, where a typical ice-disintegration landscape has been documented (Coronato *et al*., 2009). Glacial sediment accumulation probably covers the entire Holocene and may date back even to the Last Glacial Maximum (Bujalesky *et al.*, 1997). Based on lake depth and altitude of the erosional glacial features along the valley slopes, a maximum ice thickness for the Fagnano paleoglacier was crudely estimated at 1000 m (Coronato *et al.*, 2009). Currently, the climate of this region is Alpine, with a strong winter sub-polar Antarctic influence and is under the south-westerly wind effect during austral summers, which brings moisture and humidity to the region.

The acquired soundings and high-resolution seismic lines, and the derived bathymetric map, have delineated the main morphological features of the Lago Fagnano. The basin floor is divided into two principal parts, separated by a morphologically complex, shallow relief located in the central part of the lake in correspondence of the Rio Claro outlet. This structure may represent a pressure ridge related to the principal displacement zone of the Magallanes-Fagnano strike-slip fault system (Lodolo *et al*., 2003; Menichetti *et al*., 2007), but geomorphological studies lead to an alternative proposal that this threshold may represent a rocky outcrop, a remnant of glacial erosion generated by a tributary ice tongue flowing northward through the Rio Claro valley (Coronato *et al*., 2009). This morphologic peculiarity suggests that the basin is composed of two different sub-basins. The deepest depression, with a maximum water depth of 206 m, is found in the eastern sub-basin, which presents a flat depocentral area. The flanks are highly asymmetric in terms of slope gradient; the steeper slope of the basin runs along the northern shore of the Lago Fagnano, and coincides with the most pronounced regional topographic gradient. The total throws along the north-eastern shore of the Lago Fagnano, considering also the submerged part of the lake, is of the order of 600 m. The drainage system in this area, as seen on the Digital Elevation Model, shows a peculiar pattern: a very short surface stream system flowing toward the lake, with the separation boundary paralleling the shoreline and running along the ridge summit. The western-half of the lake presents a maximum water depth of 165 m. This part of the basin is

broadly symmetric in shape and, like the eastern part of the lake, presents a relatively flat depocentral area. A NE-trending ridge, about 4 km long, is found just off the Kosovo lagoon. It can be alternatively interpreted as a bedrock threshold or as a submerged frontal moraine.

The peculiar shape and morphology of Lago Fagnano, and its location within the principal displacement zone of the Magallanes-Fagnano fault system, clearly suggest that the tectonic activity along this lineament has conditioned the formation and development of this basin at least in its early times. Moreover, its geometry most probably reflects its sub-bottom structure. Lago Fagnano represents the morphological expression of at least two large pull-apart basins, generated by a progressive migration of a restraining bend along the strands of the Magallanes-Fagnano fault system (Menichetti *et al.*, 2007). However, the Late Quaternary glacial activity has played an important role in shaping the bottom morphology and the surrounding landscape.

The first seismostratigraphic study for the Lago Fagnano sediments was conducted by Waldmann *et al*. (2008). Data show that the entire sedimentary record reaches a thickness of more than 100 m in the eastern basin; it reaches only 60 m in the western basin. This thickness discrepancy suggests either different sedimentation rates in the sub-basins or a longer temporal record in the east. Three main seismic units within the lake basin were recognized, based upon their seismic facies differences: (a) a bedrock complex at the base, overlain by (b) ice-contact glacier-derived deposits, which in turn are superimposed by (c) glacio-lacustrine successions infilling topographic lows. A multi-proxy study of selected cores of the uppermost sedimentary cover of the Lago Fagnano, have allowed the characterization of a Holocene sedimentary record (Waldmann *et al*., 2008, 2009). Petrophysical, sedimentological and geochemical studies of a complete lacustrine laminated sequence revealed variations in major and trace elements, as well as an organic content, suggesting high variability in environmental conditions.

In Plate 1, we present three representative, high-resolution seismic sections acquired in November 2009 to show the geometry and morphology of the lake floor in its western, central and eastern sectors. We refer to the two articles by Waldmann *et al*. (2008, 2009) for more details on the depositional and stratigraphic characteristics of the Lago Fagnano glacio-lacustrine sediments.

5. Conclusions

The bathymetric map of Lago Fagnano presented in this paper illustrates the principal morphological characteristics of the basin, formed within the principal displacement zone of the South America-Scotia transform plate boundary traversing the Tierra del Fuego Island. Lago Fagnano represents the surface expression of at least two large pull-apart basins: the eastern part presents the deepest water depths (206 m), and shows a peculiar asymmetry, the western part is shallower (maximum water depth of 165 m), and is relatively symmetric. The steepest slope runs along the north-eastern shore of the lake. A shoal located in the central part of Lago Fagnano, in correspondence of the Rio Claro outlet, divides the two basins. Repeated glaciations that occurred in the Late Quaternary have played an important role in shaping the basin and featuring the landscape surrounding Lago Fagnano. The glacial and

glacio-lacustrine deposits present both at the lake shorelines as coastal cliffs and filling the basin floor, testify the effects of these dynamic processes. Therefore, Lago Fagnano sediments represent an invaluable archive that record past tectonic events and climatic changes occurred in the Late Quaternary.

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