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Gravity map of the Isla Grande de Tierra del Fuego, and morphology of Lago Fagnano

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ABSTRACT

A complete Bouguer gravity map of the central-eastern part of the Isla Grande de Tierra del Fuego, and a general bathymetric chart of the Lago Fagnano have been realized, on the basis of a series of field geophysical surveys carried out on the Island since 1998. The regional gravity anomaly trend onshore shows a progressive negative gradient from N to S. Distinct, broadly E-W-trending gravity minima are superimposed on this regional negative gradient. They follow the main trace of the Magallanes-Fagnano fault system, which represents the western segment of the left-lateral South America-Scotia transform plate boundary. The gravity minima reflect the presence in the subsurface of restricted and elongated basins developed within the principal displacement zone of the fault system. A relative positive gravity maximum is located just at the SE corner of the Lago Fagnano, and represents the response of a partially exposed crystalline body, occupying an area 3 x 3 km wide. A 2D vertical crustal model has been constructed, combining gravity data inversion and geological information available for the central-eastern region of Lago Fagnano. The bathymetric map of the Lago Fagnano delineates the main morphological features of this 110-km-long, 7-km-wide lake, the largest of Isla Grande. The floor is divided into distinct parts, which suggests that the basin is composed of different sub-basins. In most areas, the basin floor is highly asymmetric in shape, with flat depocentral areas. The most pronounced asymmetry of the basin is seen in the eastern end of the lake, where there is also the deepest depression. The steeper slope of the basin, along the northern shore of the Lago Fagnano, also coincides with the most pronounced regional topographic gradient. The general gravimetric and morphological features of the investigated region are here discussed.

KEYWORDS **Tierra del Fuego Island. Bouguer gravity map. Lago Fagnano bathymetry. Gravity model.**

INTRODUCTION

Five distinct geophysical and geological field surveys were carried out from February 1998 to March 2004 in the central-eastern part of Isla Grande de Tierra del Fuego, and along its Atlantic coast (Fig. 1), in the frame of the TESAC project (Tectonic Evolution of the South America-Scotia plate boundary during the Cenozoic), jointly managed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) of Trieste, and the INGEODAV of the Universidad de Buenos Aires. Acquired data comprise DGPS-fixed magnetic and gravity data points, bathymetric soundings in the Lago Fagnano, and structural geologic studies conducted on the most important outcrops. Integrated analyses with satellite-derived images and aerial photographs have helped the correlation with inaccessible areas, and allowed a homogeneous and clearer picture of the geophysical and geological framework of the studied region.

In this paper, we present the results derived from our gravity and bathymetric surveys, which represent, to date, the first comprehensive study of this kind conducted on this remote region of southernmost South America. The presented maps, which contain the entire gravity and bathymetric dataset acquired in the Isla Grande de Tierra del Fuego and in the Lago Fagnano, and the 2D gravity model realized across the eastern part of Lago Fagnano, integrate the geophysical results published by Lodolo et al. (2002a, 2000b, 2003) and by Tassone et al. (2005), and may be considered as a reference geophysical framework for further studies to be conducted in the region.

GRAVITY MEASUREMENTS AND GRAVITY ANOMALY INTERPRETATION

A total of more than 500 DGPS-fixed gravity data points have been acquired in the central and eastern part of Isla Grande de Tierra del Fuego (Fig. 1), based on the geodetic local net from the Estación Astronómica Rio Grande (EARG). Not more than 20 km of separation have always been kept between reference and measurement stations. The difficulties of access in many sectors of the study areas have prevented the realization of a regular grid with closely-spaced data points. The corrected positions are expressed in the WGS-84 system. All height closures are below 10 cm. The absolute gravity base used is Ushuaia, located close to the harbour. The updated values of this base are given in the International Gravity Standardization Net 1971 (Morelli et al., 1974). Because there is a significant distance between the survey areas of the central part of Isla Grande and its Atlantic coast, and the Ushuaia base, an additional reference base has been linked to the Ushuaia base. This base, named EOLO, is located at the eastern shore of Lago Fagnano (lat = 54° 31' 41.58" S; lon = 67° 13' 50.43" W; height = 39.35 m; g = 981424.50 mGal). Instrument drifts have been corrected for by daily reoccupation of the established base station. A drift correction

FIGURE 1 **Shaded-relief Digital Elevation Model of the Isla Grande de Tierra del Fuego, realized on the basis of averaged quotes from the recently released Shuttle Radar Topograpy Mission (SRTM) data. The map resolution is about 7.5 arc seconds in latitude and 10 arc seconds in longitude.**

was applied to intervening observations by linear interpolation. Tidal corrections (related to the combined attraction of the sun and the moon) have also been applied at every gravity measurement. The topographic correction necessary for producing the complete Bouguer gravity anomaly map presented in Fig. 2 has been computed from averaged quotes of the Shuttle Radar Topograpy Mission (SRTM) data (http://www2.jpl. nasa.gov/srtm/). Adopted densities are 2.67 g/cm^3 for land areas, considering an average density for the rock types characterizing the study area, and 1.0 g/cm^3 for areas occupied by lakes. Radius of computation used for each gravity measurement for deriving the topographic correction is 166.736 km.

The analysis of gravity data represents the only useful information to derive the subsurface structure of the geologic bodies in areas where significant outcrops and structural indicators are scarce or absent, as is the case of most of the Tierra del Fuego region. In this study, the gravity map has been used to define possible trends associated with gravity lows and highs, inferred to correspond to sediment-filled basins and anomalous high-density bodies, respectively, and to produce a ~50 km-long, 2D crustal model based on gravity inversion.

The regional anomaly trend is characterized by gravity anomalies ranging from about -10 mGals to -60 mGals, and shows a progressive increase in the negative values from N to S. A broadly continuous, E-W-trending relative gravity minimum, follows the main trend of the Magallanes-Fagnano fault system, a transform-type margin developed on continental crust. This system represents the western segment of the left-lateral South America-Scotia plate boundary, and extends for over than 600 km across the Isla Grande de Tierra del Fuego in both the Argentinean and Chilean territories. It runs from the western arm of the Magallanes Strait to the Isla Grande Atlantic offshore (Winslow, 1982; Cunningham, 1993; Klepeis, 1994b; Klepeis and Austin, 1997; Lodolo et al., 2002a, 2003). The linear relative gravity minimum is superimposed on the regional negative gradient, and presents diverse gravity lows. Two principal lows (-56 mGal) are centred on the western and eastern part of Lago Fagnano; a less pronounced, relatively narrow minimum is located along the linear valley occupied by the Rio Turbio, the eastern tributary of Lago Fagnano; then, toward E, the gravity low presents a minimum of about -55 mGal in correspondence of a morphological depression occupied by a small lagoon; from this location, the gravity low broadens toward E and reaches the Isla Grande Atlantic coast. In this sector, the extent and the surface geometry of the gravity lows are less constrained with respect to the central-eastern part of the Island, because the low density of measurements. Here, we analyze the results in a qualitative way, to associate the gravity anomalies to sub-surface features like in the case of sedimentary basins. Along the coast, the gravity trends sharply towards negative values, apart a restricted area where a relative minimum of about 3 mGals with respect to the surrounding area (inside a radius of 25 km), is found. This gravity anomaly is located within a peat-covered valley that ends at the estuary of Rio Irigoyen, and occupies a 2.5 km wide area (Fig. 3). The valley trends broadly EW, like the Rio Turbio valley. These two valleys may be considered as

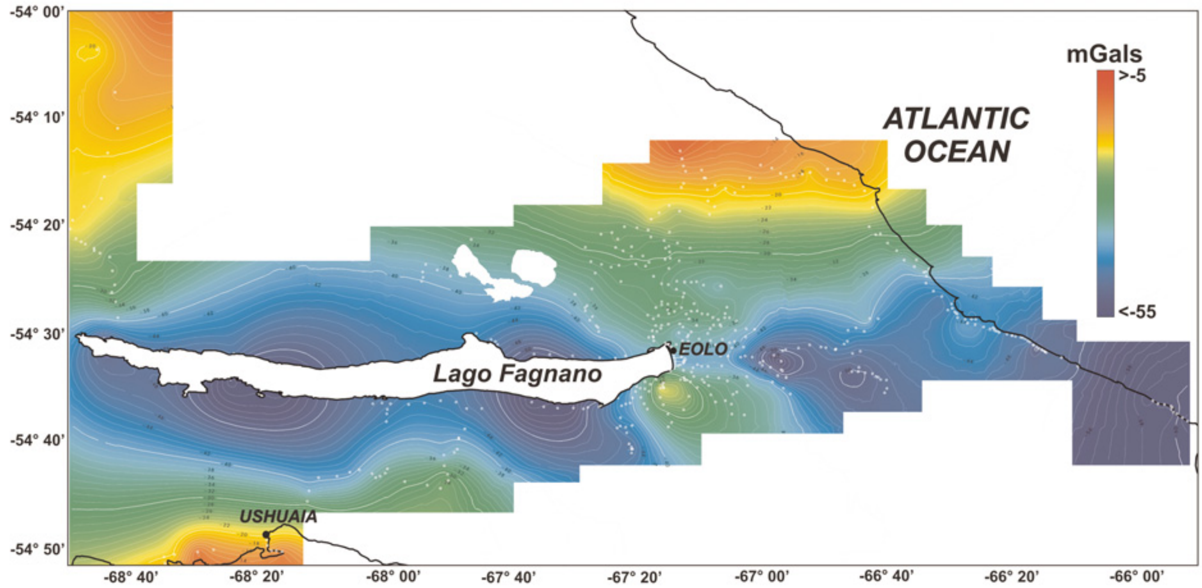

FIGURE 2 | **Complete Bouguer anomaly map of the Isla Grande de Tierra del Fuego, computed from a total of more than 500 DGPS-fixed gravity measurements. The difficulties of access in most of the study areas have prevented the realization of a regular grid of data points. The reference base located at the eastern shore of Lago Fagnano (EOLO base) has been linked to the Ushuaia base. Small white dots indicate the gravity mesurements.**

the morphological expression of the diverse segments constituting the Magallanes-Fagnano transform system, along which restricted and narrow sedimentary basin has been formed, as revealed from the localized gravity anomalies (Lodolo et al., 2003). The relative positive gravity anomaly (-24 mGal) located just at the SE corner of Lago Fagnano represents the response of a partially outcropping monzodioritic body (Cerro Hewhoepen) that occupies an area approximately 3 x 3 km wide, and which coincides with an isolated topographic high rising about 750 m above sea level.

A 2D vertical gravity model was performed along a SSW-NNE transect located close to the Lago Fagnano eastern shore where available geological information are quite well constrained (Fig. 4). This gravity model represents an updated version of the 2D model presented by Tassone et al. (2005), and integrates new field geological information and structural constraints. In the same Fig. 4, a simplified geological map of the region surrounding the eastern part of Lago Fagnano is displayed. It has been used to analyze the rock distribution in the study region, and to assign the rock density of each geologic unit. The two main structural features are represented by the master fault of the Magallanes-Fagnano system and by the Cerro Hewhoepen crystalline body, in correspondence of which a positive gravity anomaly was found.

In order to isolate more clearly the smaller gravity features from the observed gravity map, the regional gravity effect was removed applying the second vertical derivatives technique (Elkins, 1951). This method is generally used to enhance the local anomalies obscured by broader regional trends and to aid in the definition of the edges of the source bodies. A shallow geologic feature of limited lateral extent, such as a sediment-filled basin developed within a principal displacement zone of a transform system, will typically have a gravity anomaly with greater curvature than the regional field (which probably originated from deeper sources) on which it is superimposed. Plotting a map of second vertical derivative values will have the effect of making the gravity anomaly from the local feature stand out more conspicuously. In definitive, vertical derivatives can be regarded as types of high-pass filters that enhance anomalies caused by small features while suppressing longer wavelength regional trends. Figure 5 shows the results of the application of the second vertical derivative method on the area located just to the E of Lago Fagnano, which emphasizes the local gravity anomalies associated with sediment-filled basins that are obscured by the broad Bouguer regional gradient. The map of Fig. 5 allows the definition of the lateral extent of the source bodies and their edges. The gravity anomaly located in correspondence of the Río Turbio sag pond is elongated EW and apparently continues toward W within the easternmost part of Lago Fagnano. This anomaly is about 10 km long and about 6-7 km wide, and may correspond to a localized, shallow sedimentary basin. The gradient of the northern edge of this anomaly is steeper than the southern one, indicating a possible asymmetry in the source body. The local minima continue to the E along the valley occupied by the Río Turbio, and seem to terminate at a localized, pronounced gravity low, that corresponds to the western termination of the Río Turbio valley. This gravity low is areally smaller than the minimum at the Río Turbio sag pond, and hence may be associated to a smaller basin.

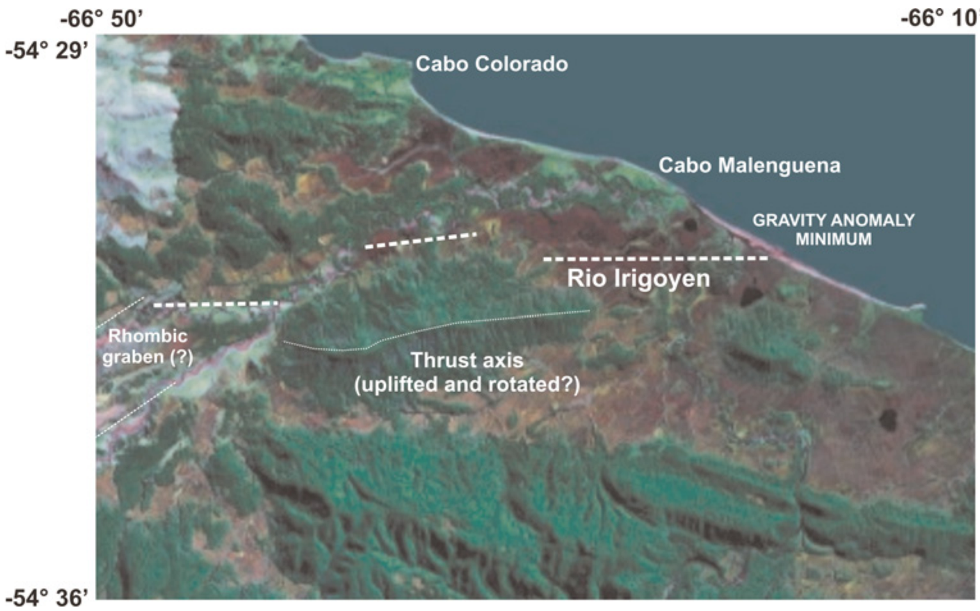

FIGURE 3 | **SPOT image of the eastern termination of the Rio Irigoyen valley. Here the underlapping segments of the Magallanes-Fagnano fault system are arranged in an-echelon geometry. The location of the gravity minimum along the coast, and centered in correspondence of the Rio Irigoyen estuary, is also indicated.**

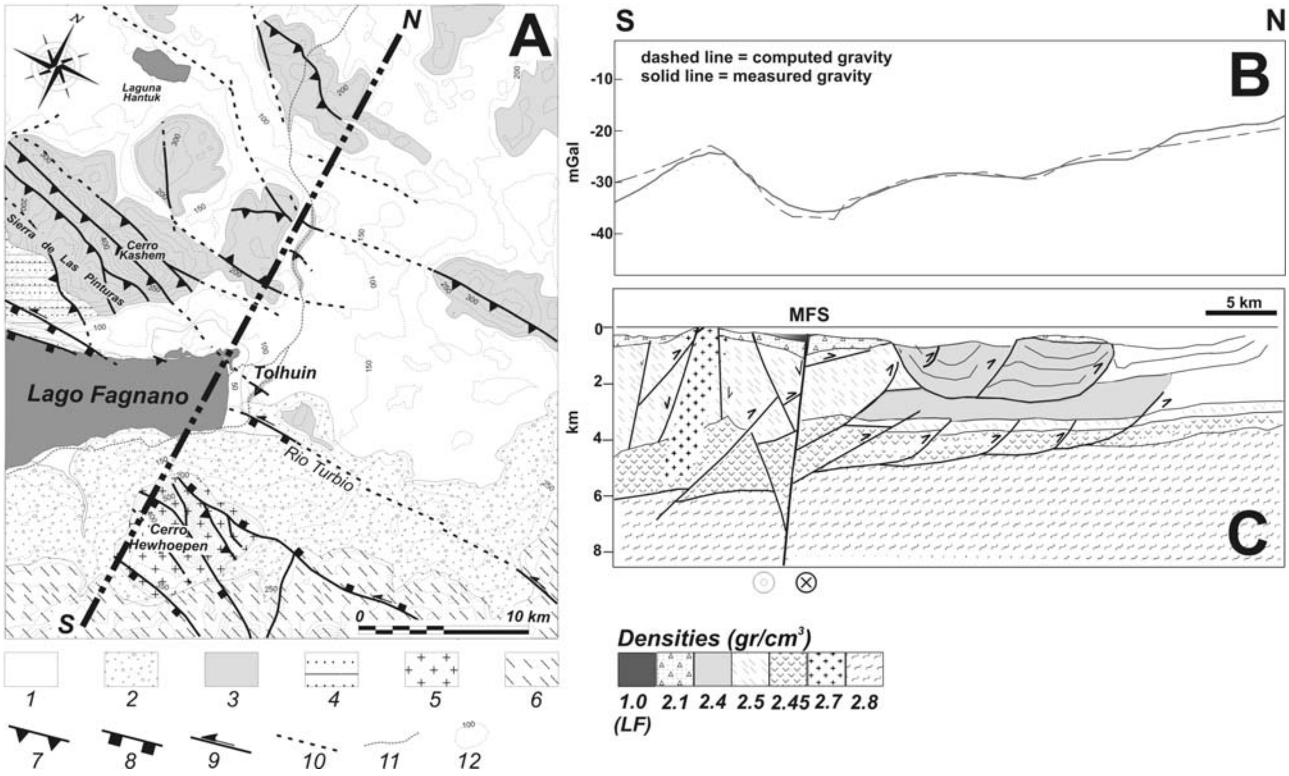

FIGURE 4 | **A) Simplified geological map of the eastern Lago Fagnano area and surroundings (modified from Lodolo et al., 2002b). Location of the 2D vertical cross-section is also indicated. 1: Undifferentiated lacustrine and glacio-lacustrine deposits (Quaternary); 2: Glacio-lacustrine sequences (Pleistocene); 3: Fine-grained sandstone and marl (Tertiary); 4: Feldspatic wackes and conglomerates (Early Cretaceous); 5: Monzodioritic plutonic rocks; 6: Dark mudstone and limestone (Early Cretaceous); 7: Thrust faults, barbs in the hanging-wall; 8: Normal faults, barbs in the hanging-wall; 9: Strike-slip faults; 10: Inferred tectonic lineaments; 11: Ruta Nacional N. 3; 12: Elevation contour lines (in meters). B) Computed and measured Bouguer gravity anomaly across the N-S section located on the geological map (modified from Tassone et al., 2005). C) 2D vertical cross section, constructed on the basis of numerical inversion of gravity data and geologic information (modified from Tassone et al., 2005). Applied densities are also indicated. LF: Lago Fagnano; MFS: Magallanes-Fagnano transform system**

BATHYMETRIC MAP OF LAGO FAGNANO: LINKING MORPHOLOGY AND GRAVITY FEATURES

Lago Fagnano, the southernmost lake of our planet (if we do not consider the sub-ice lakes in Antarctica) occupies an important segment of the Magallanes-Fagnano continental transform system. The lake, trending broadly E-W, is about 110-km-long, with average width of about 7 km. Only its westernmost tip (about 15 km) is part of the Chilean territory. In order to analyze the morphological expression of the submerged segment of the Magallanes-Fagnano fault system, and correlate the gravity features to possible morphostructural trends, a bathymetric map of the entire Lago Fagnano was for the first time derived from data collected along DGPS-fixed transversal profiles and longitudinal tie-lines. A total of forty-three profiles were acquired (Fig. 6), in spite of the often prohibitive meteorological conditions, with a 200 kHz echo-sounder installed on a Zodiac boat from the Prefectura Naval – Dpto. Lago Fagnano. The resulting bathymetric map, superposed onto the Digital Elevation Model of the surrounding region, is presented in Fig. 7. This bathymetric map has also been used to compute the complete Bouguer gravity anomaly map in Fig. 2. Terrain correction, in fact, is highly sensitive when significant contrasts in densities occur, like in the case of water bodies (shape and geometry of water-covered areas as a lake) and rocks.

The acquired bathymetric profiles have delineated the main morphological features of the Lago Fagnano. The floor is divided into distinct parts, which suggests that the basin is composed of different sub-basins. In most areas, the basin floor is highly asymmetric in shape, with flat depocentral areas. The most pronounced asymmetry of the basin is seen in the eastern end of the lake (see, for example, profile LF-13 in Fig. 6), where there is also the deepest depression (maximum water depth of 206 m). The steeper slope of the basin, along the northern shore of the Lago Fagnano, also coincides with the most pronounced regional topographic gradient. The total throw along the northeastern shore of the Lago Fagnano, considering also the submerged part of the lake, is about 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

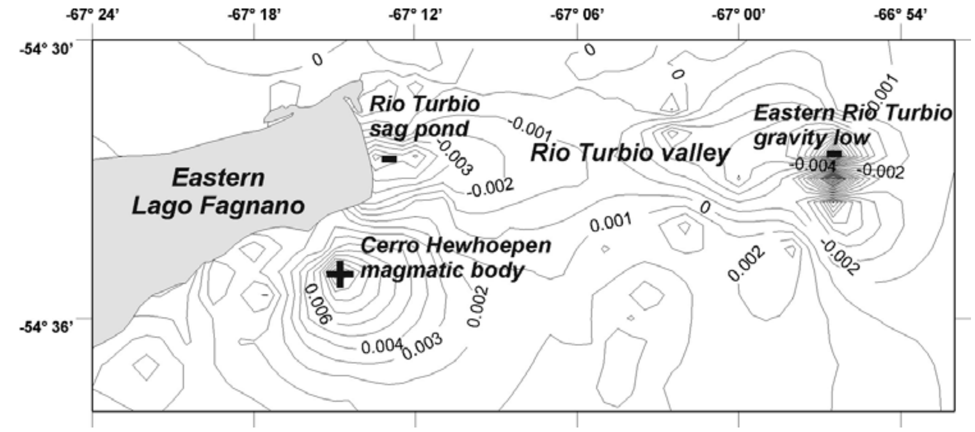

FIGURE 5 | **Second vertical derivative of the Bouguer gravity field of the eastern part of the Lago Fagnano area and Rio Turbio valley. The map enhances anomalies caused by small features. The relative maxima of the Cerro Hewhoepen are also delineated in detail. A smoothing filter has been applied to dampen noise. Contour interval is 0.001 mGal/km²**

separation boundary paralleling the shoreline and running along the ridge summit. This anomalous stream network configuration was possibly generated by the action of the fault strand in this sector of the Lago Fagnano, with rapid uplift of the hanging wall of the ridge as a consequence of isostatic rebound. A prominent secondary fault (the Río Claro fault), forming an angle of about 130° with the master segment of the eastern Lago Fagnano, laterally offsets the principal fault. This splay fault aligns with the eastern flank of a wedge-shaped, graben-like depression occupied by the Río Claro river, and it is very clear in the remote-sensing maps (Lodolo et al., 2003). Strands of the transform on both sides probably border the central, symmetrical part of the lake floor. The eastern-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. Along the westernmost part of the Lago Fagnano, two major, sub-parallel tectonic lineaments control the shape of the floor, as seen on the bathymetric profile LF-24 in Fig. 6. Onshore, those lineaments define large graben structures, and bound on both sides a tilted sliver of crust (Monte Hope). An elevated area (about 35 m below the lake level) is found in the central part of the Lago Fagnano, morphologically separating the western and eastern part of the lake. This structure may represent a pressure ridge formed within the principal displacement zone of the Magallanes-Fagnano fault system.

The peculiar morphology of Lago Fagnano, and its location within the principal displacement zone of the Magallanes-Fagnano fault system contrast in part with the postulated glacial origin for the lake as proposed by some authors (see discussion in Bujalesky et al., 1997). However, the glacial activity, in combination with the tectonic activity, has played an important role in shaping the morphology of the Lago Fagnano basin. The general morphology of Lago Fagnano is clearly controlled by the tectonic activity along the Magallanes-Fagnano fault system and its geometry most probably reflects its sub-bottom structure. It represents the surface expression of at least two large pull-apart basins, formed by strands of the Magallanes-Fagnano fault system. This is confirmed by the presence of two relative gravity minima which align broadly E-W. However, the low density of gravity data points in the areas adjacent to the Lago Fagnano shores does not allow a precise definition of the geometry and shape of these gravity features.

The most widely accepted models to explain the tectonic development of pull-apart basins suggest that such basins are formed at places where bends or step-overs occur along the trace of strike-slip faults, leading to *en-echelon* segmentation of the faults. In this case, the two longitudinal sides of such basins would be bounded by strike-slip faults, while the transverse faults, which trend diagonally to the strike-slip faults, are predominantly normal faults (Aydin and Nur, 1985). These transverse faults may be considered secondary features forming the complementary sides of a bend or step-over across which the basin was extended. In real cases of strike-slip environments, such as the Dead Sea rift system and the Gulf of Elat (Aqaba) (Ben-Avraham et al., 1979), bathymetric and seismic records have shown that the asymmetry is generated when only one side of the basin is bounded by the transform segment (master fault), and the asymmetry is towards the transform fault. Comparable features have been imaged by seismic profiles in the Lago Izabal, a pull-apart basin developed within the continental Polochic transform system of eastern Guatemala. Other important structural features in strike-slip environments are represented by the obliquely-oriented cross faults (transverse faults) which bound different pull-apart basins. Well known examples have been reported in the Gulf of Elat (Ben-Avraham et al., 1979) and eastern Sinai

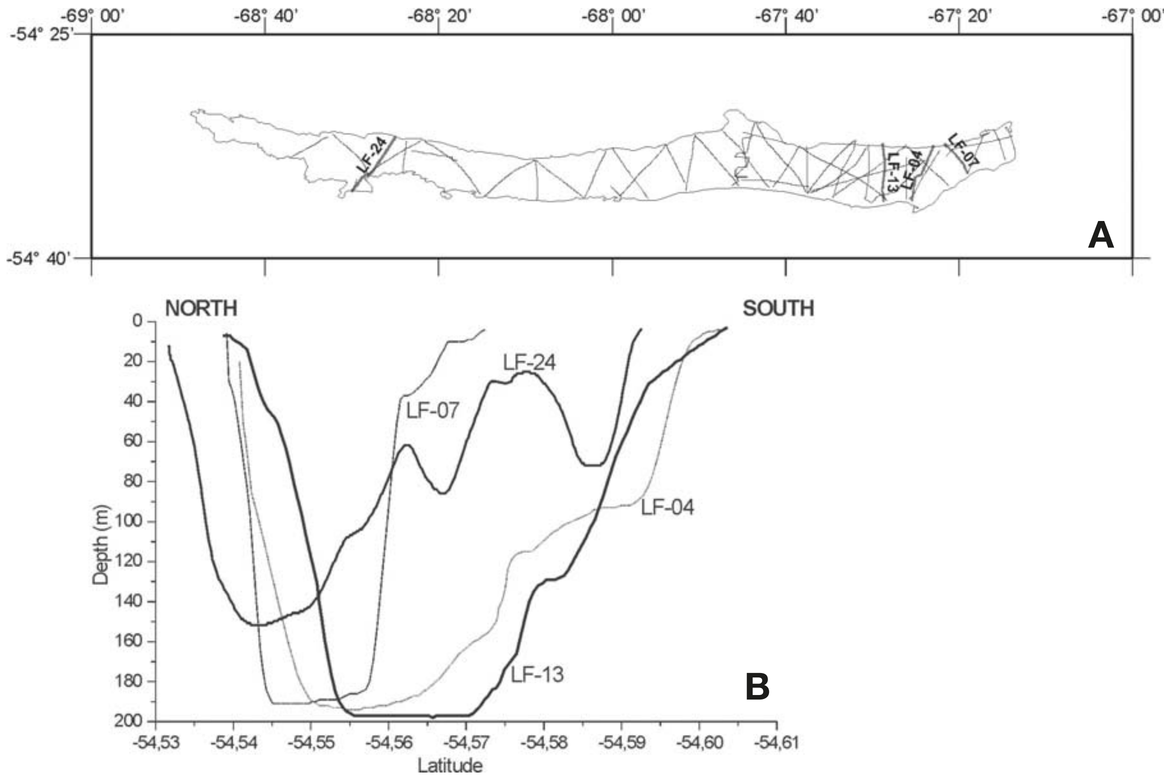

FIGURE 6 **Bathymetric tracks acquired in Lago Fagnano (A), and representative profiles (B).**

(Eyal et al., 1986). The fault-related Río Claro wedge-shaped depression, forming an angle of 130° with the eastern Lago Fagnano master fault, may be considered an example of transverse fault, which separates the highly asymmetric basin of the eastern Lago Fagnano from the central, symmetrical part of the lake. The observation that the basin asymmetry is toward the transform fault, suggests that subsidence was mostly governed by extension in a direction normal to the regional strike of the transform, at the same time that strike-slip motion is taking place (Ben-Avraham, 1992; Ben-Avraham and Zoback, 1992).

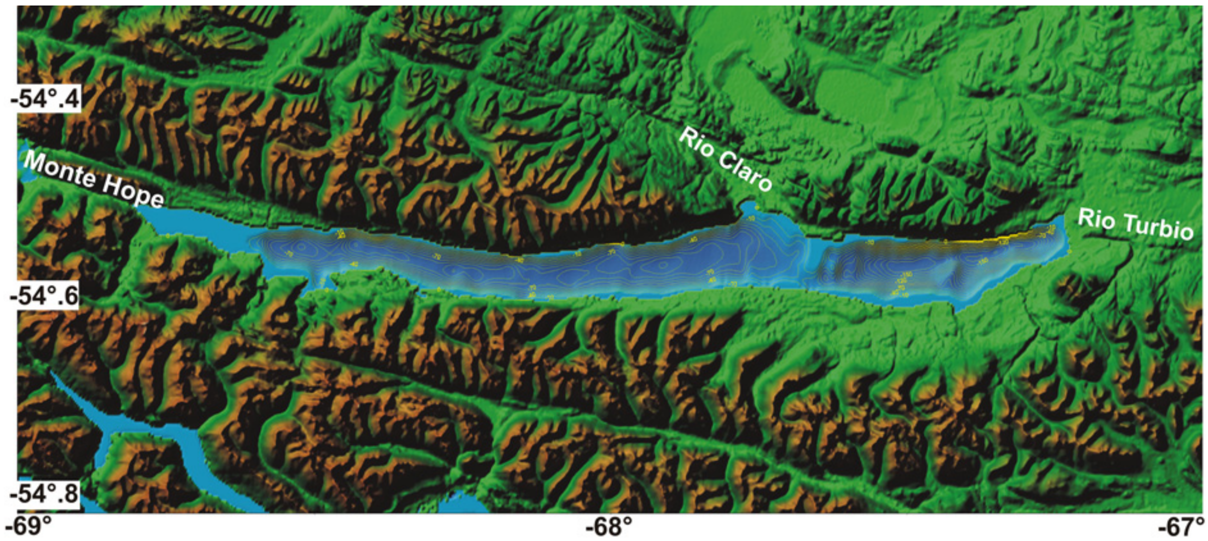

FIGURE 7 **Shaded-relief bathymetric map of the Lago Fagnano, derived from data collected along DGPS-fixed transversal profiles and longitudinal tie-lines, for a total of more than 600 km of acquisition tracks, and Digital Elevation Model of the surrounding region.**

CONCLUSIONS

We have presented a complete Bouguer gravity anomaly map for the central and eastern part of the Isla Grande de Tierra del Fuego, and a bathymetric map of Lago Fagnano. Moreover, a 2D crustal model across the eastern part of Lago Fagnano has been constructed, on the basis of gravity data inversion and available geologic information.

The gravity map has shown that, superimposed on a regional N-S negative gradient, is present an EW-trending gravity anomaly low, which is composed by various and distinct relative minima, and is interpreted as the expression of elongated and narrow sedimentary basins formed within the principal displacement zone of the Magallanes-Fagnano transform system. This fault system represents a major segment of the South America-Scotia plate boundary and traverses broadly E-W the entire Island.

The complete bathymetric map of Lago Fagnano, the largest lake of Isla Grande de Tierra del Fuego, was for the first time realized. It shows that the basin, which presents a maximum depth of 206 m, is remarkably asymmetric in shape, particularly for the eastern half of the lake. The central part of Lago Fagnano presents a relative high in the morphology, and the western half of the basin is generally symmetric in shape. The whole morphological setting of the Lago Fagnano suggests that it is composed by different sub-basins, as is the case of similar pull-apart features developed within transform systems.

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