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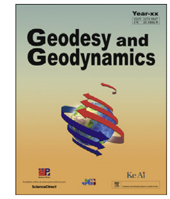

Preliminary study of gravimetric anomalies in the Magallanes-Fagnano fault system, South America

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The main objective of this research is to recognize several geological structures associated with the shear zones of the MFFS (Magallanes – Fagnano fault system) by the analysis and interpretation of gravimetric anomalies. Besides, to compare the gravimetrical response of the cortical blocks that integrate the region under study, which is related to the different morphotectonic domains recognized in the region. This research was developed employing data obtained from World Gravity 1.0, which includes earth and satellite gravity data derived from the EGM2008 model. The study and interpretation of the MFFS from the analysis and processing of the gravimetric data, allowed appreciation of a noticeable correlation with the most superficial cortical structure.

1. Introduction

Tierra del Fuego Island has a complex tectonic situation as it is crossed by the MFFS (Magallanes-Fagnano Fault System), a continental transform margin arranged in an echelon geometry with an E–W direction. MFFS runs through approximately 600 km [1] across the island. This left-lateral strike-slip fault trends between 80°N and 100°N [2].

The MFFS is recognized from the west extreme of the Magellan Strait to the Argentina continental shelf, at the north of the States Island and it continues eastwards along of the North Scotia Ridge, ending at the northern tip of the South Sandwich Islands [3–5] (Fig. 1).

The region under study is poorly covered by terrestrial gravity measurements due the scarcity of handling gravimeters and transport difficulties, fundamentally in those regions that are climatically and topographic inaccessible. Gravimetric data obtained from satellite missions have the advantage that allows viewing underground density variations within a high spatial stability and without disturbances by mathematical approximations.

The present work aims to define the set of geological structures associated to the MFFS and its spatial continuity based on satellite gravimetric data processing and analysis. This fault system is tectonically associated to the largest continental segment of the southernmost boundary between Scotia and South American plates.

Finally, this paper also tries to determine if there is a correspondence between the main morphotectonic units previously recognized in the region [7] and the observed gravimetric potential field.

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2. Geological setting

The southern Andes can be divided into two large sections, one with north-south trend, the Patagonian Andes and a second section with an east-west disposition called Fueginian Andes [8]. The studied area were recognized at least five morphotectonic domains that spread as parallel fringes among each other, and curving eastward in solidarity with the Andes flexure (Fig. 1). The western

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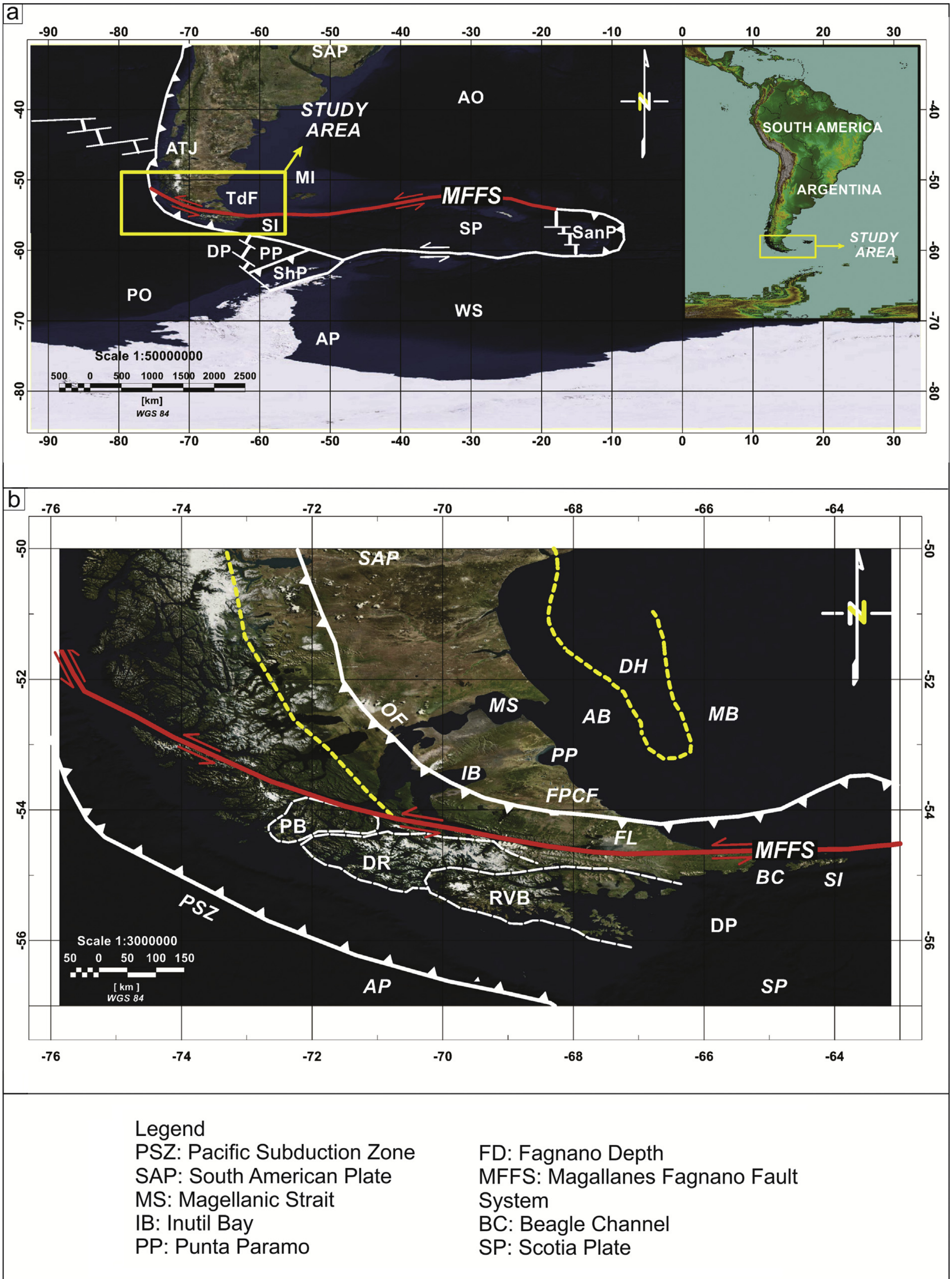

Fig. 1. a) Tectonic setting of the Isla Grande de Tierra del Fuego (modified from Ref. [5]); b) Map of the Southernmost Andes showing five main tectonic provinces and their boundaries (after [5,32,33]). The internal domain, with basement-involved contractional deformation, includes the Patagonian Batholith, CD (Cordillera Darwin), and the Rocas Verdes Basin (RVB). The thin-skinned FTB (fold-thrust belt) constitutes the external domain. The MFFS (Magallanes–Fagnano fault system) is the boundary between the South American and Scotia Plates. The orogenic front separates the Fuegian foreland fold-thrust belt to the S–SW from the Austral and Malvinas basins to the N–NE (Modified from Ref. [8]).

unit is represented by a band of archipelagos and fiords which are composed mainly by intrusive rocks belonging to the Patagonian batholith. In the central region, the mountain range shows three tectonic domains: the RVB (Rocas Verdes Basin), eastward the Fueginian Thrust, and between them, the metamorphic basement of DR (Darwin Range) (Fig. 1). The Fueginian Thrust is located south of the Magellan Strait, trending W–E in the southern end of Tierra del Fuego Island. In the eastern region, Patagonian PreAndes are located, mainly raised by the more distal thrusts of the Fueginian thrust and fold belt. Finally, the Cenozoic foreland is located.

During the Cenozoic, a transcurrent tectonic affected the southernmost region of the Tierra del Fuego Island [9,10]. This transcurrent tectonic is characterized by a transtensional regime with extensional faulting and pull-apart basins developed along the mainly fault system.

The region under study includes the boundary of South American and Scotia tectonic plates, which has expression to the west, in the Tierra del Fuego Island, as a regional fault system (MFFS). In the Republic of Chile, the seismic lines show in the Magellan Strait, the existence of a fault zone of significant dimension [11], whereas in the Argentine territory are recognized at least three major systems fault zones: Deseado Lake, Magellan Strait – Fagnano Lake and Carbajal Valley [5].

Based on seismic and gravimetric studies between Fagnano Lake and the Atlantic coast and on the Argentine Continental Shelf, Lodolo E [1] and Yagupsky D [12] established that subvertical fault segments with an overlapping step-over geometry constitute the fault system. These zones are characterized by the development of small asymmetric basins related to transtensional deformation, along the fault system.

Lake Fagnano (or Khami) in Argentina is located in the central section of the Magallanes Fagnano Fault System, with approximately 100 km of east-west maximum extension. The Lake Fagnano area has been affected by two tectonic phases: (I) The Andean compression phase, with a prevailing ductile deformation during Upper Cretaceous; and (II) the Oligocene-Quaternary strike-slip phase, where the deformation is essentially brittle [13–15]. The evolution of the fault system has a close relationship with the complex tectonic events responsible for the ocean bed development at the west of the Scotia Sea during the Late Oligocene; events which led to the definitive separation of the Antarctic Peninsula from the South American continent [16].

3. Material and methods

In order to achieve the MFFS recognition, we made a geophysical characterization from Free Air, Bouguer and Isostatic anomaly charts.

A hydrostatic Moho model based on the Airy – Heiskanen hypothesis was determined; in calculation, the gravity effect due to the root of the topographic load associated to with the Fueguino orocline as well as the anti-root associated with the paleogenic Magallanes foreland basin and the surrounding ocean basins, was considered. The calculated hydrostatic Moho shows a good correlation with the cortical thicknesses values derived from seismic data, which were interpreted in the different geotectonic environments of the under study area by Chulick G.S [6].

3.1. Data and gravity anomalies

The area under study was covered by an extensive gravity database obtained from the WGM 1.0 (World Gravimetric Map). Gravity information used in WGM 1.0 is derived from the EGM2008 global gravity model, which was developed in spherical harmonics up to 2160 by the NGAI (National Agency of Geospatial Intelligence) [17]. EGM2008 model includes surface gravity measurements (from terrestrial, marine or aerial studies), satellite altimetry and satellite gravimetry (GRACE Mission).

Free Air and Bouguer Anomalies were obtained from the WGM 1.0, (Fig. 2a and b). The charts were gridded according to the minimum curvature method with a 5 km grid pass. Gravity data covers the analyzed region and its boundary sectors. In order to eliminate edge effects a data expansion was performed. Theoretical gravity was calculated according to the closed Somigliana expression, for 1980 reference ellipsoid parameters (GRS80, Geodetic Reference System 1980). A density of 2.67 g/cm^3 was considered for the upper crust rocks according to the proposal by Hinze [18]. For every station the complete Bouguer anomaly through Free Air (FAC = 0.3086 h), Bouguer (BC = 0.11118 h) and Topography corrections was calculated, where h is the height of the station in meters concerning to the mean sea level.

Terrain corrections were computed according to the algorithms developed by Kane [19] and Nagy [20]; considering a local elevation model (1 km × 1 km) and a regional elevation model (10 km × 10 km); both elevation models were obtained from the Global elevation model ETOPO 1 [21]. Due to the study area extension the terrestrial curvature correction according to La Fehr [22] expression was applied.

3.2. Sedimentary fill gravity effect calculation

The Bouguer anomaly chart corrected by topography even contains the gravity effects generated by Magellanes basin and surrounding oceans sedimentary filling. The 3D gravity effect by direct modeling using the Parker algorithm [23] was calculated. Sediment thickness for Atlantic and Pacific Ocean basins [24] were obtained from the NOAA (National Environmental Information Center). Database was gridded by using the minimum curvature method with a 10 km grid pass. A density of 2.0 g/cm^3 for marine sediments and 0.85 g/cm^3 density contrast for marine sediment-oceanic crust interphase were considered. The gravimetric effect related to Magellanes basin sedimentary fill was obtained considering a density of 2.2 gr/cm^3 and a density of 0.25 g/cm^3 for the sediment-basement basin interphase.

Finally, a geological correction to the Complete Bouguer anomaly chart was applied; it represents the gravimetric response generated by all those masses located below the sedimentary depocenters.

3.3. Topographic gravity effect calculation

A 3D hydrostatic Moho model was constructed (Fig. 3), considering a compensation model based on the Airy hypothesis [25–27]. For this analysis, the region under study in a set of parallelepipeds with a 10 km width of the topography data derived from the ETOPO 1 model was attached. Furthermore, the reference cortical thickness of 17.5 km was obtained as an average of the Moho depths proposed by Chulick G.S [6].

The gravimetric effect produced by the hydrostatic Moho model, resulting from the combination of roots and anti-roots was calculated. The analytical expression that links the root depth with elevations and topographic densities is $\Delta R = \frac{\sigma_t}{\Delta\sigma} h$, being $\sigma_t = 2.7$ g/cm^3 the land density above the mean sea level; h the topographic altitudes and $\Delta\sigma = -0.4$ g/cm^3 is the upper crust-mantle density contrast. The anti-root value from the following analytical expression, is obtained: $\Delta R' = \frac{\sigma_{cs}-\sigma_c}{\Delta\sigma} {}_s$, where $\sigma_{cs} = 2.7$/cm^3 is the upper crust density or basement; is $\sigma_s = 2.2$ g/cm^3 the sedimentary fill density, hs is sedimentary thickness and $\Delta\sigma = -0.4$ g/cm^3 is the upper crust-mantle density contrast.

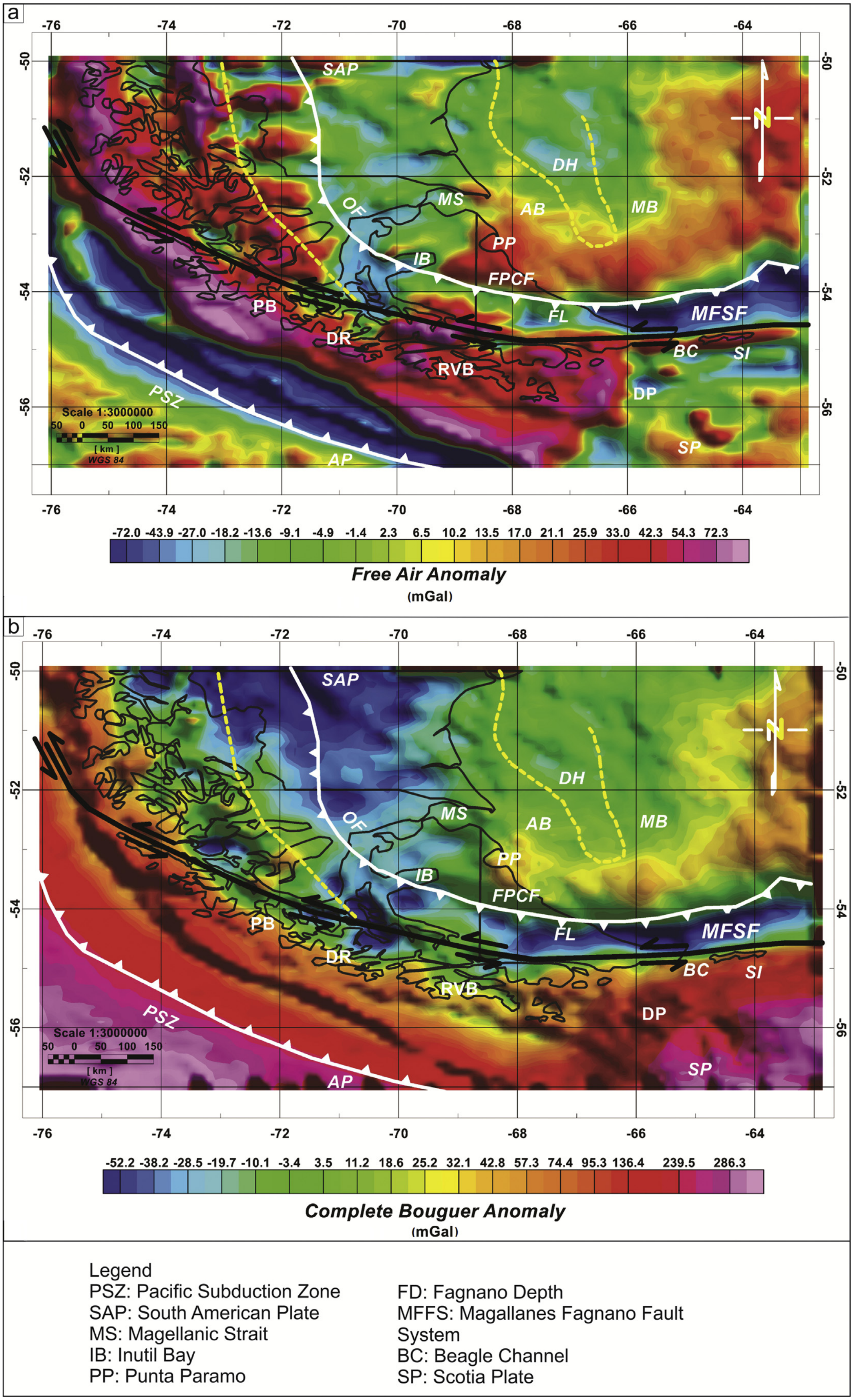

Fig. 2. a) Free air anomaly map; b) Bouguer anomaly map corrected by topography.

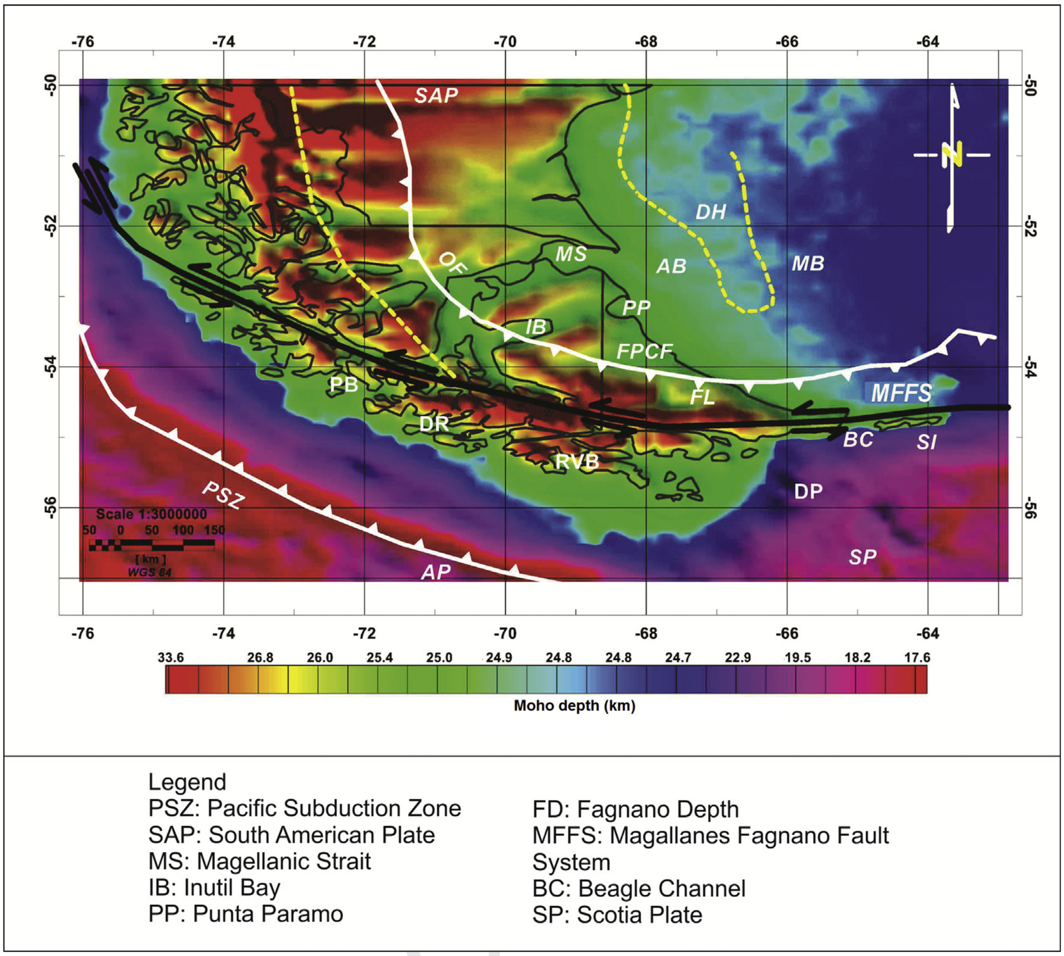

Fig. 3. A 3D hydrostatic Moho model, considering a compensation model based on the Airy hypothesis. Moho depth map shows maximum depth values beneath the Andes range, minimum values are located below the oceanic crust.

Finally, the Isotactic correction to the Bouguer anomaly chart corrected by topography and sedimentary fill effect was applied, obtaining in this way the Isotactic Residual Anomaly chart (Fig. 4).

4. Results and discussion

The free air anomalies (Fig. 2a) contains the gravity effect from all mass anomalies, so they replicate the bathymetry, the bathymetric gradients and seabed configuration quite faithfully. In this case the deviation observed in the free air anomalies respect to seabed topography is due to the heterogeneity within the subsurface sediment and crustal layers. The free air anomaly chart shows high negative values for the study region, over −70 mGals, related to PSZ (Pacific subduction zone). Other relative minimum anomaly values are associated to ocean sedimentary basins like Malvinas basin (−45 mgals) and Magallanes basin (−20 mGals) and to the Andean foreland basins (−15 mGals). In addition, high positive anomaly values are related to the Andes range and limited by the orogenic front, reaching values over 70 mGals for this zone.

The Bouguer anomalies identified in this study have high positive and negative values, reflecting high-density contrasts to a cortical and lithospheric scale, as well as possible isostatic disequilibrium (Fig. 2b). The largest Bouguer anomalies in the oceanic crust of the South American plate relative to the Scotia plate are the result of its higher density and age, due to their different origin and tectonic evolution.

In the Bouguer Anomaly chart (Fig. 2b), high positive values are related to the oceanic crust of the Antarctic plate (280 mGals) that decrease along the subduction zone between Antarctic plate and South America plate to 50 mGals over the Chilean trench region. Furthermore, relative minimum values are located over the Andean foreland basins, which appear to be caused by the presence of thick sediments on the back arc and the continental slope and shelf.

The Moho Depth Map (Fig. 3) shows maximum depth values beneath the Andes range. In this region, Moho values are higher than 30 km, which is consistent with the highest topographic heights. In addition, minimum values are located below the oceanic crust; values around 17 km could be recognized below the Antarctic plate. In the Atlantic Ocean, Moho depths vary from 25 km over the Argentinian continental shelf to 20 km near the Atlantic mid ocean ridge.

The Isostatic Anomaly Chart (Fig. 4) would show the influence of the superficial structures in the study region, like the existence of a shear system associated to the MFFS.

The analysis and interpretation of the MFFS would show, from the analysis and processing of the gravimetric data, a remarkable correlation with the most superficial cortical structure (Fig. 5a and b).

Towards the Andean foreland region, the anomalies charts show the existence of relative gravimetric minimums with a SW orientation, in the order of 25 mGals, which have been interpreted as sedimentary depocentres limited by structural highs (−5 to 10 mGals) acquiring a typical structural configuration of grabens and horsts. These depocentres are limited to the west by the Andean orogenic front, evidenced by relative gravimetric highs of the order of 30 mGals and to the east, over the Argentinian continental

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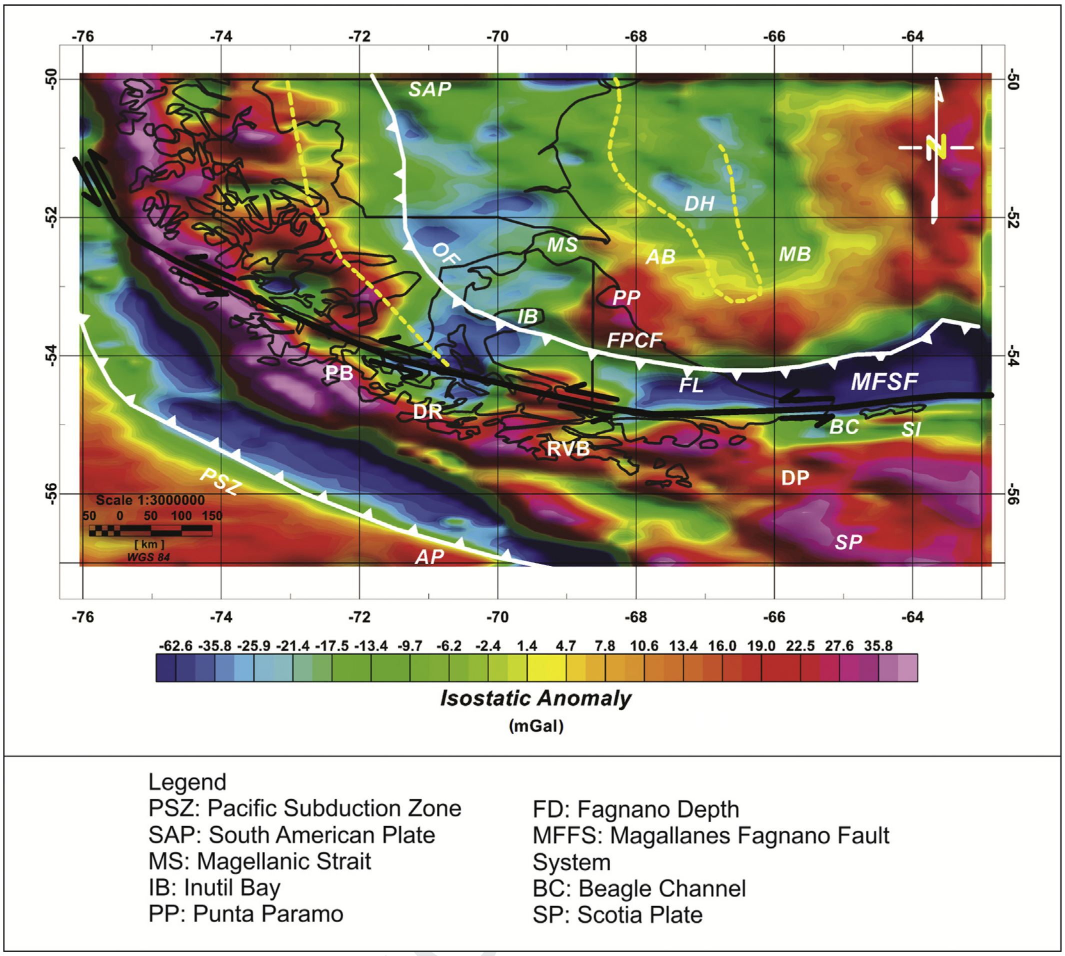

Fig. 4. Isostatic anomaly map. The isostatic anomaly chart shows the influence of the main superficial structures in the under study region.

platform, by the Dungeness height, which shows a gravimetric response of the order of 10 mGals.

At the Chilean trench region it is possible to recognize irregularities in the surface of the ocean floor in the anomalies charts, (Fig. 5a and b). They are evidenced by gravimetric minimums in the order of −50 to −60 mGals. The high gravimetric gradient associated with a topographic high observable in this region, would suggest the existence of an accretion prism with considerable dimensions.

Finally, the interpretation of the free air and isostatic anomalies charts allowed the recognition and delimitation of two main transcurrent faulting systems: 1-the Magellan Fagnano strike-slip fault system, with E–SE orientation and 2-a subparallel fault system located at the south of the Beagle Channel. The two fault systems are defined by the existence of strong horizontal gravimetric gradients, both recognized in the free air anomaly chart and in the isostatic anomaly chart. Associated with these shear systems appear relative gravimetric maximums and minimums which would correspond to the typical alternation of shear systems with the development of depressed and elevated blocks. That is, the shear zone originated by these two main parallel structures would give rise to minor transverse faults, in an echelon array, which would have an opposite sense to that of the main shear, with the possible rotation of small blocks (or highs) within these main structures.

On the other hand, it is also possible to recognize transpressive and transtensive systems associated with shear systems towards the Chilean trench area, being as in the case previously described, because of the existence of strong horizontal gravimetric gradients and the alternation of continuous gravimetric maximums and minimums to the transcurrent structure.

The MFFS shows, along the entire Tierra del Fuego island area, several characteristic morphotectonic features, all of them typical of transcurrent faults, as fault scarps, linear fault ridges, displaced and parallel river patterns and aligned ponds [28]. As was mentioned in Ref. [29], several authors like Lodolo [1,12] and [30] interpreted the MFFS as conformed by several left lateral segments with an echelon pattern along which pull-apart depocenters arose. Besides [31], interpreted the Fagnano depression (where Fagnano lake is located) as a pull-apart basin. Eastwards the Fagnano depression, the neotectonic activity of the MFFS forced the formation of south-facing scarps that show a higher elevation along the northern block, corresponding to the South American Plate. These hills have rocky cores, a mean elevation of 200 m and rounded summits. They are limited by glacio fluvial valleys, later in filled by peatlands [28]. The hilly landscape of endogenous origin was affected by glacial activity throughout the Middle Pleistocene. This morphostructural arrangement could be projected in depth from the interpretation of the gravimetric data. It is recognized for the entire MFFS (Magallanes-Fagnano fault system), as well as for the structures located in the Beagle Channel to the south and the Magellan Strait to the north of the Island (Fig. 5).

Finally, from the analysis of Fig. 5a–b, it is also possible to identify structures trending SE defining a depressed area in the Inútil Bay and PenínsulaPáramo.

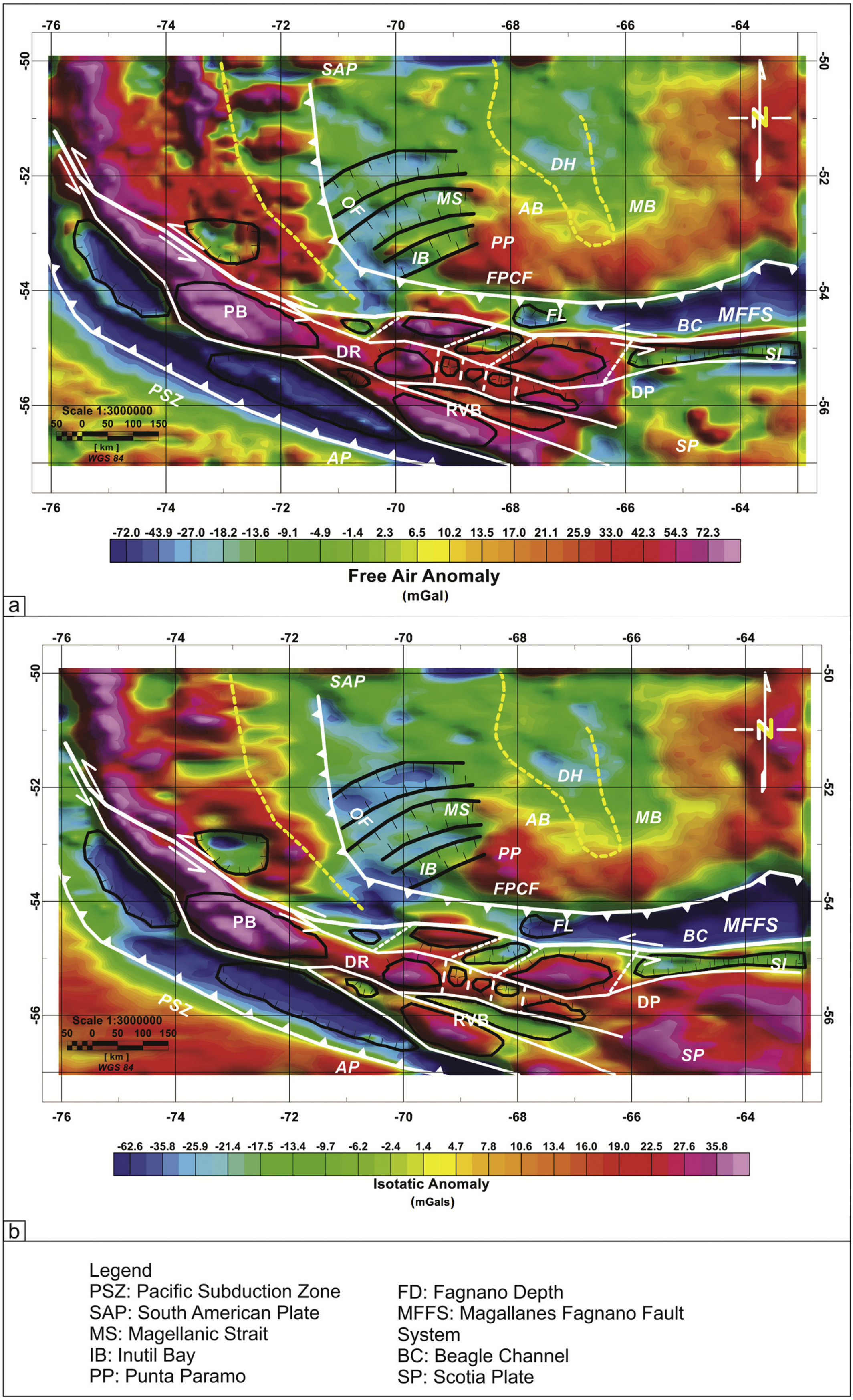

Fig. 5. Interpretation of the structural setting of the Isla Grande de Tierra del Fuego from the analysis of the Free air anomaly map (a) and isostatic anomaly map (b).

5. Conclusions

The use of satellite gravity data derived from the EGM2008 global gravity model made possible to obtain the free air, complete Bouguer and isostatic anomaly charts for the Magallanes-Fagnano fault system region.

The analysis of complete Bouguer anomaly chart shows a decrease in gravity values along the oceanic crust of the Antarctic plate up to South American Plate, clearly delimiting the geometry of the subduction zone over the Chilean trench region and allowing to recognize the ocean floor irregularities. We observe a high horizontal gravity gradient associated with a topographic high in this region, which would suggest the existence of an accretion prism.

The interpretation of the free air and isostatic anomalies charts allowed the recognition and delimitation of two main transcurrent faulting systems: 1-the Magellan Fagnano strike-slip fault system, with E–SE orientation and 2-a subparallel fault system located at the south of the Beagle Channel.

The gravimetric analysis of the Magallanes Fagnano fault system zone and surroundings areas shows relative lows and highs of gravity, which are topographically related to depressed and raised sectors. These morphotectonic features are typical of transcurrent faulting and could be recognized along the entire Tierra del Fuego Island. In this way, we have interpreted the depressed areas as pull apart basins, in which glacial valleys were developed; on the other hand, the raised areas would represent push up geometries, corresponding to the highest mountain peaks of the region.

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