

Crustal structure and tectonic setting of the south central Andes from gravimetric analysis

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Resumen

En el presente trabajo, a partir de datos gravimétricos terrestres, se preparó una carta de anomalías de Bouguer, la cual fue adecuadamente filtrada a fin de separar efectos gravimétricos someros y profundos. Con base en un modelo de densidad, mediante de técnicas de inversión gravimétrica, se modeló la discontinuidad corteza-manto y el basamento cristalino, respectivamente. De forma posterior, se evaluó el espesor elástico equivalente considerando la información de la discontinuidad de la corteza-manto y la carga topográfica. Se encontraron valores altos de espesor elástico T_e , al este de la precordillera Andina y al oeste de la sierra Pampeana de Velasco. Estos resultados son consistentes con los valores positivos de anomalía residual de Bouguer e isotáticos, lo que estaría indicando la presencia de rocas de alta densidad en corteza media a superior. Además, los análisis petrográficos y geoquímicos realizados en afloramientos en superficie indican un origen mantélico.

Palabras clave: gravedad, isostasia, espesor elástico equivalente, Andes centrales, modelo cortical, Sierras Pampeanas.

Abstract

Based on terrestrial gravity data, in this paper we prepared a map of Bouguer anomalies, which was filtered to separate shallow and deep gravity sources. Based on a density model and gravimetric inversion techniques, the discontinuous crust-mantle boundary and the top of crystalline basement were modeled. Subsequently, the equivalent elastic thickness (T_e) was evaluated, considering information from the crust-mantle discontinuity and topographic load, finding high T_e values in the eastern Andean foothills and west of the Velasco range. These results are consistent with the positive isostatic and residual Bouguer anomaly values, which suggest the presence of high-density rocks in the mid-to upper crust. In addition, petrographic and geochemical analysis conducted in surface outcrops suggest a mantle origin.

Key words: gravity, isostasy, equivalent elastic thickness, southern Andes, crustal model, Sierras Pampeanas.

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Introduction

The study area at the latitudes between 27°S and 30°S will be referred to as a part of the Southern Andes (Bohm *et al.*, 2002; Tassara and Yáñez, 2003). In this area the flat slab segment (27°S–33°30'S) has a strong active deformation, with a complex High Cordillera, a Precordillera thin-skinned belt and the thick-skinned Sierras Pampeanas (Ramos, 1999). These Sierras Pampeanas basement blocks uplifted during shallowing of the flat-slab since the Late Miocene. It records an initial migration of the magmatic arc by crustal erosion (Ramos, 1988), and a rapid migration associated with the shallowing of the subduction producing a volcanic front as far as 700 km from the trench during Quaternary times (Kay *et al.*, 1991).

The aim of our study is to examine the crustal structure in the research area on the basis of gravity-field modeling. Typically, the modeling of the gravity field involves the construction of a density model of the crust. Combined with the overlying topography, the density model constitutes the load acting on the crust. The internal crustal load is given by the integration along the crustal column of the modeled densities with respect to the reference crustal column. It follows that a density variation within the crust represents a variation in the load, and must be reflected in the isostatic response (Ebbing *et al.*, 2007, Braitenberg *et al.*, 2002).

The study of the isostatic state and of the regional rheological crustal properties is closely related to density modeling. Thus, isostatic modeling is useful for calculation of the isostatic state emplacing an independent constraint upon a given density model. Given the crustal load and the crustal structure, the study of the isostatic state permits modeling the rheological properties in terms of flexural rigidity and by making some assumptions regarding Poisson's ratio and Young's modulus, flexural rigidity can be interpreted in terms of elastic thickness. The flexural rigidity is an important parameter for the characterization of the crust.

Background

The geophysical background for the study area in this work is scarce, and moreover is limited to sparse 2-D seismic data and some deep refraction profiles made by YPF (Yacimientos Petrolíferos Fiscales) in the 1980's in the southeast part of the study region. Cristallini *et al.* (2004) determined the Moho to be 45 km deep, using profound seismic interpretation of parallel 27° South.

Results obtained from Introcaso *et al.* (2000) demonstrated that the shortening value for the present day Andes would be around 200 km, due

to present day compressive stresses and also found that in this region the Andean Cordillera is close to isostatic equilibrium. The CHARGE experiment (Chilean-Argentinian Geophysical Experiment), obtained Moho depths and Vp/Vs south of the study area, on a transect at 30°S, that suggest is a partially eclogitized lower crust under the Famatina and Cuyania terrains. Tassara *et al.* (2006) analyzed the geometry and characteristics of the Nazca plate and continental lithosphere, based on satellite gravity data. Tassara *et al.* (2007) also calculated the equivalent elastic thicknesses of South America using gravity, obtained from GRACE satellite.

In this paper, results of the gravimetric field interpretation are shown for the region between 27° and 30° of south latitude and 71° and 65° of west longitude (Figure 1), with the objective of understanding crustal characteristics and behavior that characterize it.

Geologic Setting

The complex history of the Andes started in the Palaeozoic with the accretion of Pacific micro-continental blocks to the western margin of Gondwana. At that time, the south-western coast of Gondwana was not far from the present-day Sierras Pampeanas in Argentina. The accretion of the terranes, with a new subduction zone forming along it is western margin, belongs to the early Palaeozoic Famatinian tectonic cycle of Andean evolution. This subduction zone left a large accretionary prism preserved along the Pacific margin of Chile south of 25°S (Hervé *et al.*, 1981). In the second Gondwana tectonic cycle, the magmatic arc composed of granitoids and rhyolitic volcanic rocks was developed within this accretionary prism and in adjacent areas eastwards of it. The last evolutionary stage, the Andean tectonic cycle (Mesozoic to Cenozoic), is characterized by a major palaeogeographic change. The complex of backarc basins are associated with the arc developed on late Palaeozoic basement during the Jurassic–Early Cretaceous.

Subsequent subduction erosion removed large amounts of the accumulated Palaeozoic forearc. The Mesozoic–Cenozoic Andes, in contrast to the Palaeozoic Andes, lack evidence for the collision of major terranes and appear to be related to the tectonic erosion of the continental margin. The extraordinary feature of the Mesozoic evolution of the Andean orogen is the along-strike tectonic segmentation.

There are differences in the geological evolution, structural styles and behavior of the related magmatic arcs of various segments, as well as changes in the nature of the backarc basins (Mpodozis and Ramos, 1989 and references

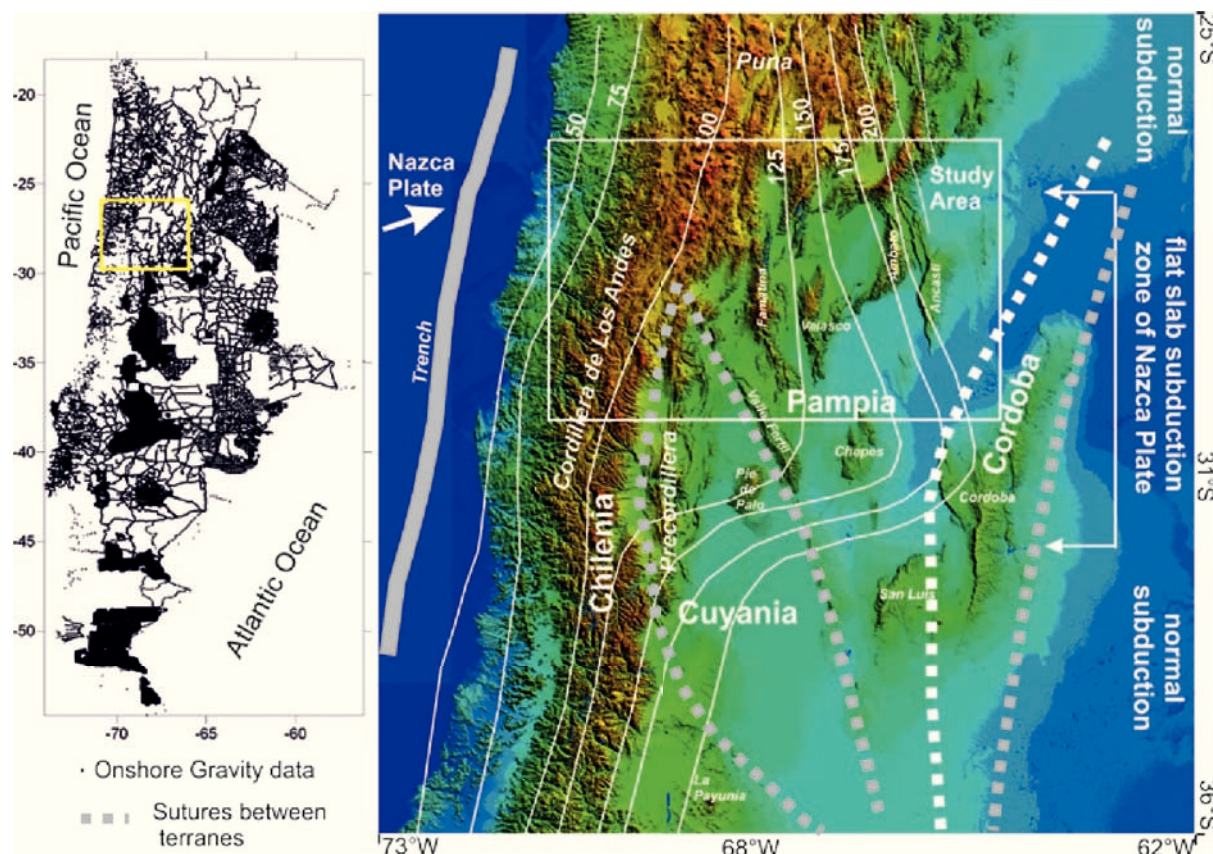


Figure 1. Location map of the study area. Solid lines show depth to the subducting Nazca plate. On the left the dots show locations of the gravity stations.

therein). Therefore, there must be two significant controls on the tectonic segmentation: the plate interactions and the pre-existing inhomogeneities of the South American plate (e.g. Jordan *et al.*, 1983). Thus, the Andes offer a great opportunity to understand and study the coupling of subduction and continental orogenesis. As proposed by various authors (e.g. Barazangi and Isacks, 1976; Jordan *et al.*, 1983; Mpodozis and Ramos, 1989; Cahill and Isacks, 1992), the Andes can be subdivided into several segments.

Methodology

The onshore gravity data set used for this work consists of a compilation of more than 7,500 gravity stations from several different sources. The observations were carried out over the past 20 years by the "Instituto Geofísico y Sismológico Volponi (IGSV)". Data of industry were provided through agreements with YPF (Argentina). Additional data was taken from: Araneda *et al.* (1999), Götze *et al.* (1990) and Chile.

This data compilation resulted in a rather inhomogeneous data set with large data gaps in some parts of the modeled region (Figure 2a). These gaps are mostly due to difficult access to

some of the areas under study. The complete Bouguer anomalies were calculated using a spherical Bouguer cap with a radius of 166.7 km, and densities of 2.67 g/cm³ (Hinze, 2003).

We used the ETOPO2 (<http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html>), for the digital elevation model. The normal gravity formula of 1967 was used and observations were tied to the IGSN71 gravity datum, which is still in use in South America. The Bouguer anomaly has an estimated accuracy of 2–5 mGal.

Separation of Gravimetric Sources

It is well known that the Bouguer anomaly contains the sum of gravimetric effects of different sources and there are many techniques that allow for a proper separation of such. Different frequency techniques were applied: band pass filter, upward continuation, surface trends, Butterworth filter (e.g. Blakely, 1995). Nevertheless, due to the powerful influence of the Andean root, the filter that proved to be most efficient, was obtained by a Butterworth filter with a cutoff of 300 km and filter order 8 (Blakely, 1995). Regional and residual gravity anomaly maps are presented in Figures 2a and 2b respectively.

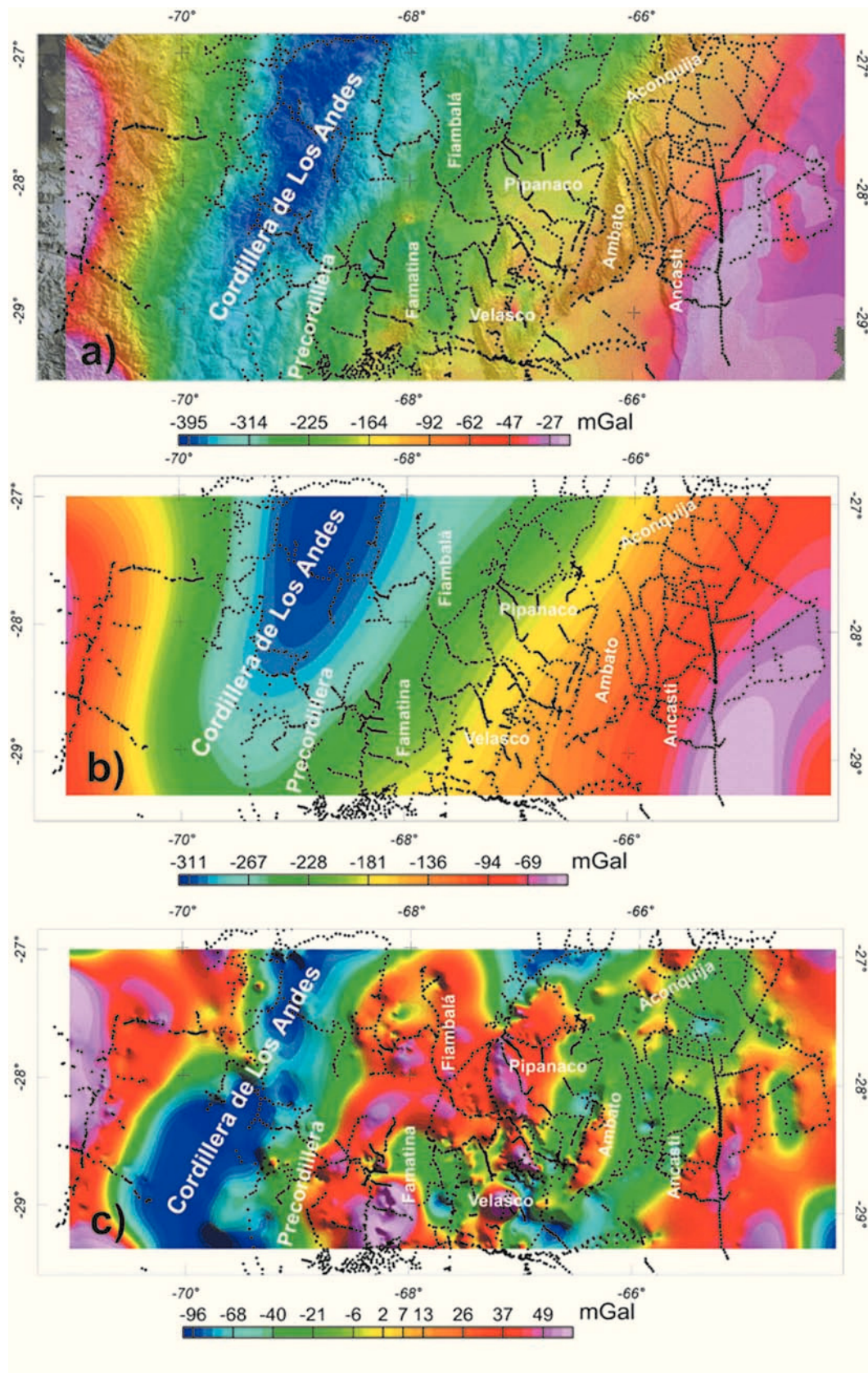


Figure 2. a) Bouguer anomaly map with the gravimetric stations, drawn on the digital elevation model. b) Bouguer regional anomaly, obtained through band pass filter. c) Bouguer residual anomaly obtained from the difference between a) and b).

Basement by Gravity Inversion

To estimate the depth to the crystalline basement, we calculated an inversion of the Bouguer residual anomaly (Figure 2c). Gravity modeling requires knowledge of densities of subsurface bodies, which can be approximated by using standard relationships between densities and seismic wave velocities of igneous and metamorphic rocks (Ludwig *et al.*, 1970; Brocher, 2005) or similar velocity-density relationships. Gardner *et al.* (1974) derive an empirical relationship between densities of commonly observed subsurface sedimentary rock and the velocities of propagation of seismic waves through the rocks. There are no deep boreholes in the area of study, so we used the "geological standard model" (Table 1), available seismic velocity model for the wells near the area of study and previous papers from: Götze and Kirchner, (1997); Ruíz and Introcaso (1999); Introcaso *et al.* (2000); Cristallini *et al.* (2004); Fromm *et al.* (2004); Gilbert *et al.* (2006); Giménez *et al.* (2006); Tassara *et al.* (2007); Giménez *et al.* (2009).

Table 1. Parameters of reference crustal model

Parameters	Values
Topographic Density	2.67 g/cm ³
Sediments Average Density	2.3 g/cm ³
Top Crust Density	2.7 g/cm ³
Medium Crust Density	2.8 g/cm ³
Lower Crust Density	2.9 g/cm ³
Lithosphere Mantle Density	3.3 g/cm ³
Crust Normal Thickness	35 km

We employ a software that uses fast Fourier transform (FFT) to compute the geological model response (Popowski *et al.* (2006). For this, all grids must be expanded in size and filled so they are periodic and eliminate edge effects (Blakely, 1995). Each layer is assigned density values (Table 1). The basement was assigned a value of 2.7 g/cm³ by extrapolating values obtained from seismologic studies by (Regnier *et al.*, 1994) for the Pie de Palo Range and the San Juan Precordillera. The values used for the crust and upper mantle are standard values used in previous studies by: Introcaso and Pacino (1988); Introcaso *et al.* (1992); Martinez and Introcaso (1999); Giménez *et al.* (2000).

When the area has rugged topography, care must be taken to ensure the depths to horizons of interest are reported relative to the datum of interest (Cordell, 1985). The topographical surface is the most practical frame of reference for measuring depths to density changes. Inversion

of the gravity field is calculated relative to a horizontal plane. In this work, the plane was at 7,000 m above sea level. The result of gravity inversion of the Bouguer residual anomaly calculated with GMSYS 3D and transformation to the depth below the topographic surface is the map of the top of the crystalline basement shown in Figure 3a.

Crust–Mantle discontinuity by Gravity inversion

To estimate the depth to the crust–mantle discontinuity we calculated an inversion of the Bouguer regional anomaly (Figure 2b), assuming a single boundary, with a density discontinuity across the Moho. The inverse calculation starts from the gravity field and attempts to obtain the causative density boundary, using an iterative algorithm developed by Braitenberg and Zadro, 1999. This method is analogous to the Oldenburg–Parker inversion approach of Oldenburg (1974). We used the parameters shown in Table 1. The density contrast between lower crustal and upper mantle was -0.4 g/cm³ (Woollard, 1959; Introcaso *et al.*, 1992; Introcaso, 1993; Giménez *et al.*, 2000). The result of the inversion model for the crust–mantle discontinuity is shown in Figure 3b.

Airy Isostatic Crustal of Model

Isostatic compensation requires that all topographical masses above the geoid height must be compensated, in accordance with the Airy hypothesis. To do this, we calculated the topographic load model from the digital terrain elevation averaged in blocks of 30 km x 30 km, in order to minimize short wavelengths. The parameters considered are the same as those used in the gravimetric inversion model (Table 1). The normal crustal thickness (T_n) considered was 35 km, the topographic load density was 2.67 g/cm³ and the crust–mantle density contrast was -0.4 g/cm³. The surface that hydrostatically compensates the masses located above the geoid can be seen in Figure 3c.

Airy Decompenated Isostatic Anomaly

Isostatic corrections can be used to remove the effect of roots or anti-roots of the crust produced by topographic heights or sedimentary basins, but do not solve the problems of crustal regions with high density. The reduction of this gravity field by the Moho for isostatic decompenating (Cordell *et al.*, 1991) is an attempt to remedy this.

The calculation of the decompenated isostatic gravity residual (Cordell *et al.*, 1991) was based on the local isostatic anomaly map (Figure 3c), continued upward to 40 km above sea level, resulting in a map showing long wavelength

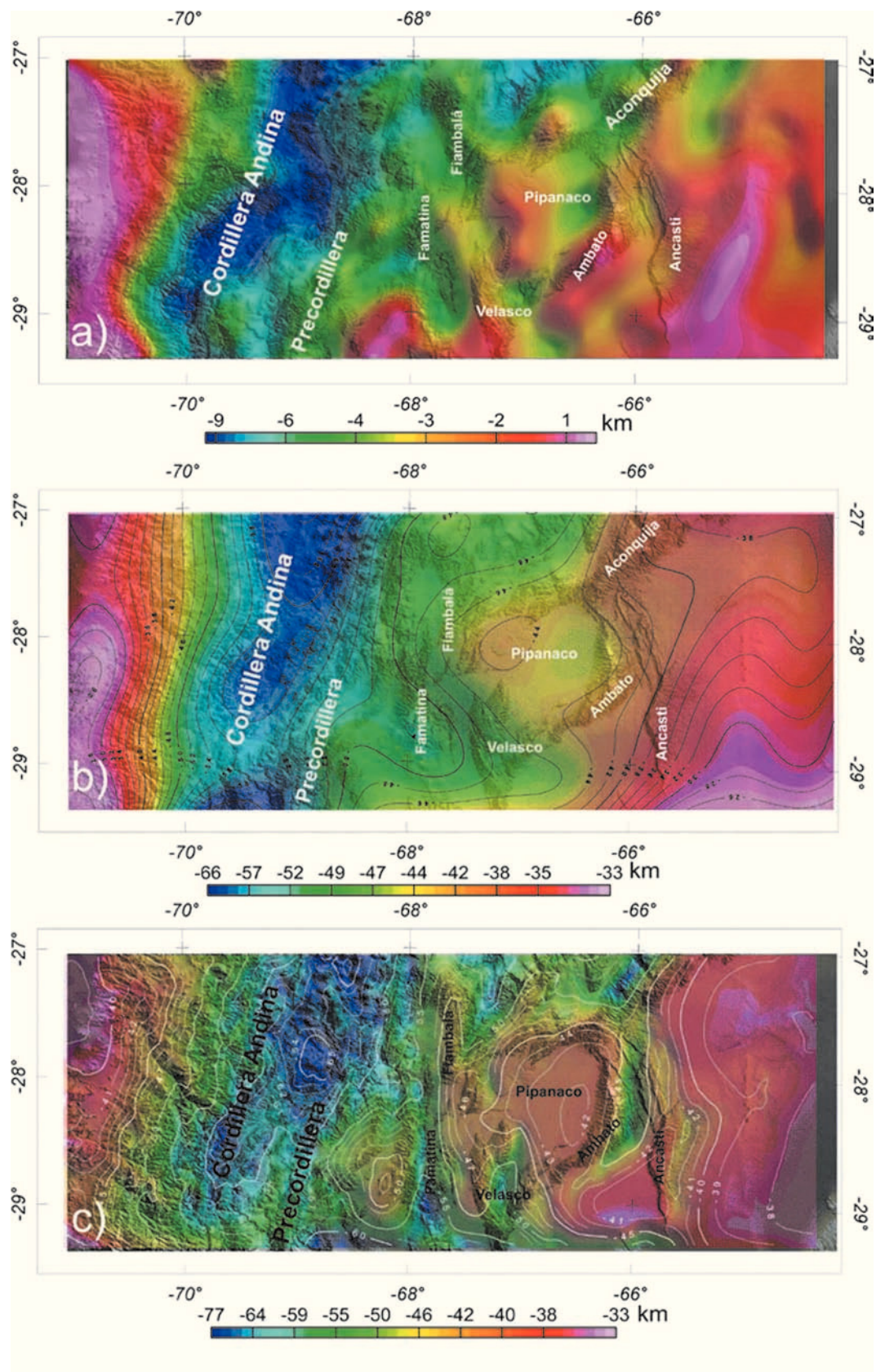


Figure 3. a) Top of basement, obtained by gravimetric inversion of the Bouguer anomaly map, based on the parameters in Chart 1. b) Crust-mantle depth obtained by gravimetric inversion of Bouguer regional anomaly. c) Isostatic model compensated on the Airy hypothesis of the crust-mantle boundary.

effects, which were subtracted from the isostatic anomaly itself (Figure 3c), in order to obtain the uncompensated isostatic anomaly (Figure 4a).

Elastic Lithospheric Thickness

The parameter that characterizes the apparent flexural strength of the lithosphere is the flexural rigidity (D), which is commonly expressed through the elastic thickness of the lithosphere (T_e). The flexural rigidity of the plate is defined in terms of Young's modulus (E), Poisson's ratio (ν), and the elastic thickness (T_e), with the following equation:

$$D = \frac{ET_e^3}{12(1 - \nu^2)}$$

In order to study the lithospheric properties in this region, elastic thickness (T_e) was estimated (Figure 4). We used the Lithoflex software (Braitenberg and Zadro, 2007) to calculate flexural rigidity by inverse modeling, allowing for high spatial resolution.

For the inverse flexure calculation application the following are required: a crustal load and the crust-mantle discontinuity. The crustal flexural rigidity is then obtained from the condition that the flexure model with the known loads matches the assumed crustal thickness model. By means of this procedure it is possible to divide the crust into areas of differing T_e , which can be geologically significant.

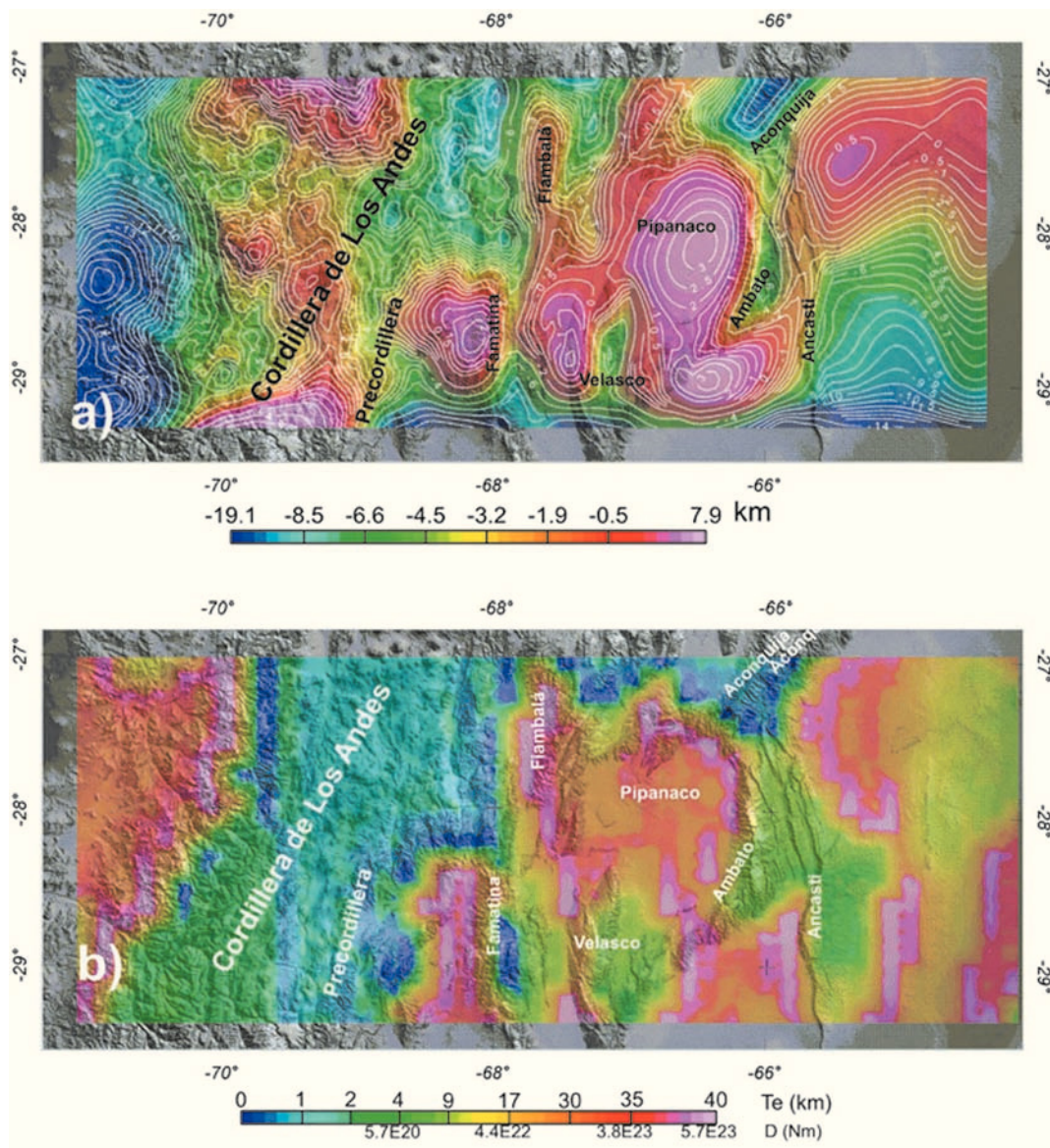


Figure 4. a) Isostatic anomaly. b) Effective elastic thickness map (T_e) and flexural rigidity (D).

The densities used in the calculations are (Table 1), for masses above sea level, density equal to 2.67 g/cm³; upper crustal density: 2.7 g/cm³; lower crustal density: 2.9 g/cm³; upper mantle density: 3.3 g/cm³. The Bouguer anomaly was inverted considering a normal crust thickness of 35 km.

Using the Bouguer anomaly field for the gravity inverse calculations we obtained a gravimetric crust–mantle discontinuity (Figure 3b). In order to model the gravity crust–mantle discontinuity in terms of an isostatic model, the equivalent elastic thickness (T_e) is allowed to vary in the range $1 < T_e < 40$ km. The elastic thickness is constant over moving windows of 35 km x 35 km size. The window size was chosen by evaluating the wavelength of the main visible geological structures.

The flexure was calculated with standard values of Young's modulus (10^{11} N/m²) and a normal Poisson's ratio of 0.25; crust and mantle densities were 2.9 g/cm³ and 3.3 g/cm³ respectively (Figure 4b).

Results

The Bouguer anomaly map (Figure 2a) shows the influence of the Andean root that causes a negative gradient centered on the Andes Cordillera axis. Filters were applied to separate the different wavelengths of gravity features. We obtained two maps, 1) a regional trend map (Figure 2b) that would respond primarily to the crust–mantle discontinuity geometry, and 2) a residual Bouguer anomaly map, linked to short and medium wavelengths (Figure 2c) that could be related to the middle and upper crustal densities.

Considering that we used a 2.67 g/cm³ density for the Bouguer correction, the positive values of Bouguer residual anomaly observed (Figure 2c); indicate the presence of denser bodies than the reference value. Negative values would correspond to lighter rocks. The Precordillera area and the northeast (Figure 2c) reveal positive anomalies. In general, positive residual anomaly values suggest the presence of mantle involvement in the generation of felsic rocks from parental magmas (Dahlquist *et al.*, 2010). This model supposes the fusion of continental lithosphere by intrusion of asthenospheric magma.

These dense bodies could be layered residual crustal melts or remnants of asthenospheric material (which led to the melting of the continental lithosphere).

The upper crust base model (Figure 3a) clearly shows the existence of dense bodies located a few kilometers from the surface, as interpreted

in the residual Bouguer anomaly map (Dahlquist *et al.*, 2010).

Figure 3b reflects the geometry of the crust–mantle interface, which presents maximum values below the Andean axis (66 km), close to 35 km on the eastern edge of the study area. The Cordillera de Los Andes is associated with a pronounced crustal "root", whereas beneath the range of the Sierra de Famatina and Sierras Pampeanas, the crustal thickness decreases significantly.

The Airy isostatic model (Figure 3c) indicates a hypothetical surface of the crust–mantle interface, produced by assuming that the topographic masses are in local hydrostatic equilibrium. Results obtained by the inversion of the regional Bouguer anomaly gravimetric model (Figure 3b), are significantly different from the isostatic model (Figure 3c) especially in the regions of: Fiambalá, Más, Aconquija ranges and Pipanaco basin.

To verify this isostatic imbalance, we calculated the decompensated isostatic anomaly (Figure 4a) in which the long-wavelength isostatic anomaly effects were removed (Cordell *et al.*, 1991). The obtained results respond to heterogeneities located in the upper crust. We observed that this map shows optimal consistency with the residual Bouguer anomaly.

On the other hand, the results obtained in the calculation of equivalent elastic thickness (T_e) indicate those as Tassara and Yanez (2003), expected from previous work: Stewart and Watts (1997); Sá (2004); Pérez-Gussinyé (2004); Tassara *et al.* (2007); Sacek and Ussami (2009). The Andean domain values are lower than 10 km, indicating that the crust that contains the Andean Cordillera has a low flexural rigidity, close to local compensation. On the contrary, there are high values of T_e on a strip that extends from the Western edge of the Sierra de Velasco to the North of the Sierra de Tinogasta (across the regions of Vinchina, Villa Castelli, Jagué and Los Pozuelos) and to the East, under the Ancasti Sierras and Pipanaco basin. These high values of T_e and D , are consistent with the positive residual anomalies observed in Figure 2c and Figure 4a which favors the hypothesis with areas of high density and higher flexural rigidity.

Previous studies suggested the presence of dense bodies in the crust, which could be interpreted as eclogitized crust (Ramos, 2009). However, those studies put the eclogite at the base of the crust, but in this interpretation, dense masses would be located within the middle to upper crust. Another alternative was proposed by Astini *et al.* (2009), focusing on Central Andes rifting stage in the early Carboniferous

to late Permian. Crustal extension with rotated basement blocks, rift sedimentation and thinning associated with differentiated rhyolitic and basandesitic magmatism (are associated with a more basic residue deposited in the lower crust). Astini *et al.* (2009) point out that during the early Carboniferous, the Sierras Pampeanas area contained numerous Type A granitic bodies with mantle contamination, implying that on a regional scale, asthenospheric ascent could be explained by rifting, which would have obscured Sanrafaelic shortening (Figure 5). We believe that this model of tectonic evolution is compatible with the results obtained from gravimetric analysis.

Conclusions

The gravity models presented in this paper show that the crustal structure in the southern Central Andes is not homogeneous. The observed gravity

anomalies are interpreted to be produced by medium to short wavelength bodies, which are interpreted as intrusions placed in the middle to upper crust. Isotopic results in the region also suggest the presence of mantle source magmas that could be remnants of asthenospheric material fused with continental lithosphere, generating granitic magmas that are presently exposed on the surface. Dense material from the mantle (magma type A) would have been intruded during crustal stretching in the Early Carboniferous. Associated thinning and differentiated rhyolitic and basandesitic magmatism, leaving the denser bodies in the lower crust. The configuration of granitic bodies with mantle contamination might have been obscured during the Sanrafaelic shortening. Some of these bodies are visible on the surface and others can be identified by their high density.

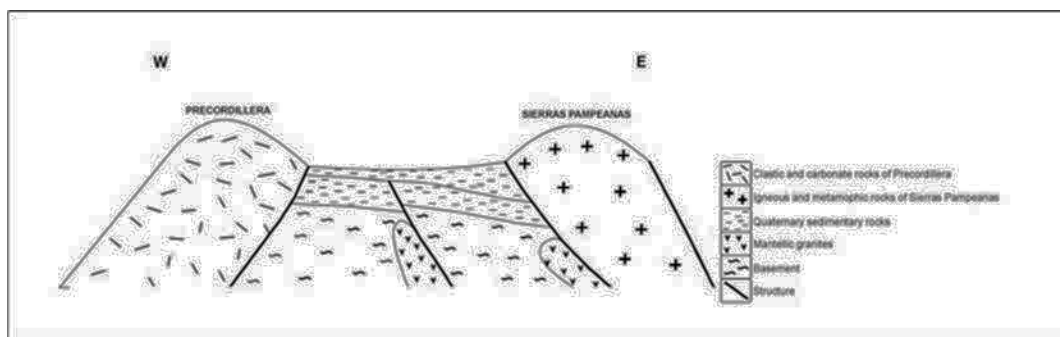


Figure 5. Schematic profile of the crust.

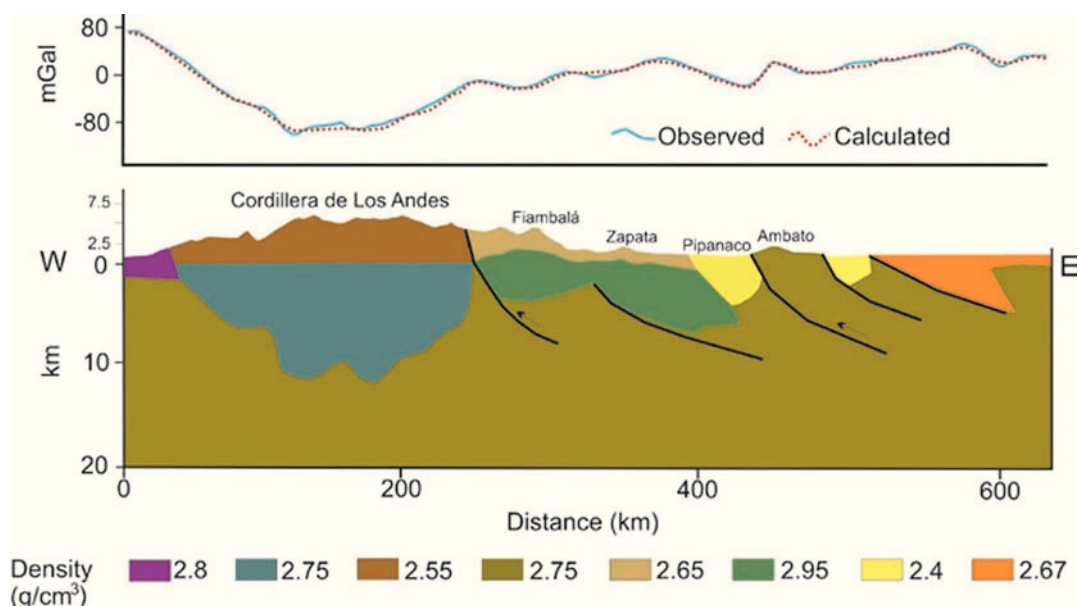


Figure 6. 2D density model.

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