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Research Article

A Comparative Analysis of Seismological and Gravimetric Crustal Thicknesses below the Andean Region with Flat Subduction of the Nazca Plate

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A gravimetric study was carried out in a region of the Central Andean Range between 28° and 32° south latitudes and from 72° and 66° west longitudes. The seismological and gravimetrical Moho models were compared in a sector which coincides with the seismological stations of the CHARGE project. The comparison reveals discrepancies between the gravity Moho depths and those obtained from seismological investigations (CHARGE project), the latter giving deeper values than those resulting from the gravimetric inversion. These discrepancies are attenuated when the positive gravimetric effect of the Nazca plate is considered. Nonetheless, a small residuum of about 5 km remains beneath the Cuyania terrane region, to the east of the main Andean chain. This residuum could be gravimetrically justified if the existence of a high density or eclogitized portion of the lower crust is considered. This result differed from the interpretations from Project "CHARGE" which revealed that the entire inferior crust extending from the Precordillera to the occidental "Sierras Pampeanas" could be "eclogitized". In this same sector, we calculated the effective elastic thickness (Te) of the crust. These results indicated an anomalous value of Te = 30 km below the Cuyania terrane. This is further conclusive evidence of the fact that the Cuyania terrane is allochthonous, for which also geological evidences exist.

1. Introduction

It is well known that the tectonic features of the Central Andes (Figure 1) are controlled by the interaction of the South American and Nazca plates, and, particularly, by the geometry of the subducted oceanic plate [1–7]. The Andean segment is situated between 28° and 32° south latitudes, where the plate subduction is horizontal along about 300 km of this sector. It then returns to a normal inclination [7], characterized by the absence of active volcanism and, toward the Andean foreland, by a thin-skinned deformation type in the Precordillera and, further eastward, by a thick-skinned deformation type in the Pampean Ranges [2].

The high seismic activity in the crust, not only in the Precordillera but also in the Pampean Ranges, is associated mainly to compression and crustal shortening [8–10].

Fromm et al. [12] calculated the crustal thickness along a cross section from the Andean to the Eastern Pampean Ranges. The 2D seismic model was obtained from the apparent phase velocities of the Pn waves recorded in 8 wide band stations during 16 months of seismic recording. This was a part of the CHARGE project (Chilean-Argentine Geophysical Experiment). Thus the maximum seismic Moho depths obtained were 62 km in the highest Andean altitudes, 60 km in the Precordillera, 55 km in the Western Pampean Ranges, and 36 km in the Eastern Pampean Ranges.

Gimenez et al. [13] made a density model of the crust at a local scale covering the same latitude window. They found a crustal thickness of 55–65 km under the Precordillera and 45–50 km below the Valle Fértil Pampean range. These gravimetric depths were determined while taking into consideration the positive gravity effect of the Nazca plate

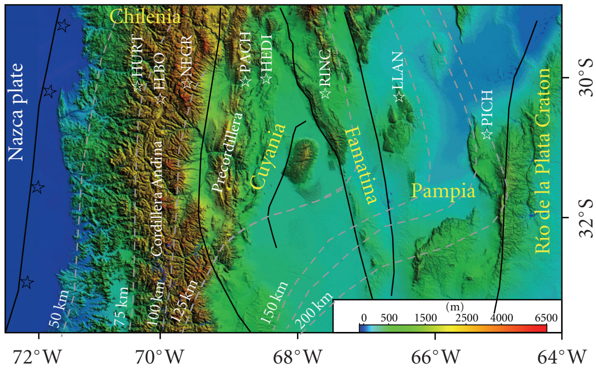


Figure 1: Geological features in the study area. The black triangles show CHARGE seismic stations. Green lines indicate terrane boundaries. Shaded areas indicate major geologic features. Grey lines indicate the contours of the depth to the top of the subducted slab by Cahill and Isacks [3]. Extracted and modified after Heit et al. [11].

(maximum 100 mGal) and the surface geology. They found that the inclusion of the gravity effect of the Nazca plate has the effect of a 10 km increase of the crustal thickness, with respect to an initial model that excludes the effect of the Nazca plate. The density contrast between the lower crust and the upper mantle was equal to $-0.4\,g/cm^3$ [13]. Similar studies which show that the positive gravimetric contribution of the Nazca plate is necessary for matching crustal gravity models and the seismic Moho depths are given by Grow and Bowin [14], Smalley and Introcaso [15], Tassara et al. [16] and Folguera et al. [17].

Gravimetric models of a laterally heterogeneous crust, which take into account the collisional hypothesis and admit the existence of old sutures and a Precambrian basement that represents terranes of different age and composition, have been tested for the Pampean Ranges [18–20] but were unsupported by seismic data.

Alvarado et al. [21] used the inversion of the seismic moment tensor and modeled the components of the seismic displacements using regional data extracted from the CHARGE project. In this way, the authors obtained solutions of focus mechanisms and depths for 27 crustal seisms that occurred between 30° and 33° south latitudes. As a result they found a high seismicity in the Cuyania terrane, and a very limited activity in the Pampia terrane, with average seismic velocities Vp = 6.2 to 6.4 km/s (Vp/Vs = 1.8 to 1.85) and crustal thicknesses from 45 to 52 km for the Western Pampean Ranges. In the Eastern Pampean Ranges the P-wave velocities are lower (Vp = 6.0 to 6.2 km/s), the S wave velocities are higher (Vp/Vs = 1.65 to 1.7) and the thickness of the crust is 27 to 37 km.

The present study aims at giving an explanation to the discrepancy between the depths of the gravimetric and the seismic Moho found mainly below the Cuyania terrane, on the basis of a gravimetric survey, considering the surface geology and the results from seismological investigations. We investigate the crustal structure along an EW-trending profile centered on the Cuyania terrane for which the gravity field and the seismological results are available. We show that under the Cuyania terrane it is necessary to include a layer of high density in the lower crust, in order to match the two types of observations (gravity and seismologic) and in order to allow for the isostatic equilibrium.

2. Regional Tectonic Setting

Geological studies have documented how the major terrane sutures have experienced extensional and compressional deformation since the Jurassic [22–24]. The main geological units are: the Principal Cordillera, which forms the main part of the Andean range (Figure 1); it is composed of Mesozoic marine deposits and the basement is involved in their deformation. The northern and southern parts are characterized by thick-skinned tectonics. The central segment, whose peaks of elevations are higher than 6700 m, is characterized by thin-skinned tectonics [25], where the Frontal Cordillera includes Paleozoic-Triassic magmatic rocks that behaved as a rigid block during the Andean deformation [25]. The Precordillera forms the foothills of the Andes between 29°S and 33°S. It is a fold and thrust belt developed on a Paleozoic carbonate platform [26] (see Figure 1).

East of the Andes, the Pampean ranges province is composed of a series of crystalline basement-cored Precambrian-Early Paleozoic rocks uplifted and tilted by compression during the formation of the Andes and separated by broad and relatively undeformed basins [2, 27–29].

The western Pampean ranges are principally composed of abundant crystalline calcites, amphiboles, basic and ultrabasic rocks, and scarce granitic bodies [30]. In contrast, the eastern Pampean ranges exhibit schists and gneisses of a mainly sedimentary origin, granitic rocks, some of which reach batholitic dimensions, and abundant migmatites and granulites [30, 31]. Proterozoic-Early Paleozoic sutures separate the Río de la Plata, Pampian and Famatina terranes in the eastern Pampean ranges [32] (see Figure 1).

The western Pampean ranges contain rocks as old as 1.1 to 1.0 Ga [33] that correlate in age with the Grenville orogeny. These rocks are part of the Cuyania terrane, which also includes the Precordillera [34–36]. The boundary between the Cuyania and Famatina terranes is interpreted as a major Early Paleozoic suture [23, 34, 37]. However, the origin and evolution of these terranes are still debated [38, 39].

3. Methodology

1200 new gravity values were measured in the region of the Central Andes. These values were added to the database of the Institute of Physics of the National University of Rosario, Argentina and of the "Engineer F. S. Volponi" Geophysics and Seismological Institute of the National University of San Juan. A total of 3200 gravimetric data were collected for the study area, all of them linked to the "System IGSN1971". In Figure 2 we show the map of Bouguer anomaly. The gravity stations are indicated as black points. The Bouguer anomaly values were adjusted by the kriging method, with an interval spacing of 5 km.

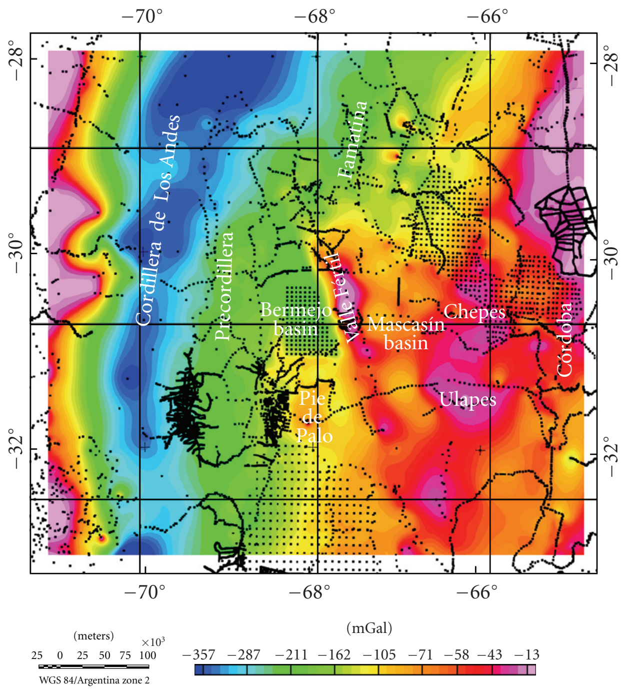


Figure 2: Map of the Bouguer anomaly tied to the IGNS 71 gravity network (data obtained from Instituto Sismologico F. S. Volponi-UNSJ, IFIR-UNR). The gravity stations are indicated as black points.

Classic techniques were used to calculate the anomalies [40]. The normal gradient of 0.3086 mGal/m was used for the free air correction, and the density of 2.67 g/cm^3 for the Bouguer reduction [41]. Thereafter, the gravimetric observations were reduced topographically by means of the Hayford zones up to the circular zones with a 167 km diameter using the Digital Elevation Model obtained from the Shuttle Radar Topography Mission (SRTM) of the US Geological Survey and NASA, based on techniques that combine the algorithms developed by Kane [42] and Nagy [43]. The gravity nets were gridded using the minimum curvature method, which is usually sufficient to regularize field points measured at unevenly spaced stations on a topographic surface [44].

The working tool Lithoflex (http://www.lithoflex.org/) was applied to calculate the gravity forward and inverse modeling, as well as the forward and inverse modeling of flexural rigidity, allowing for high spatial resolution of flexural rigidity. This tool fulfills a series of different functions that are concerned with studying the gravity field as well as the isostatic state.

In detail, the methodologies that have been used are the following.

(1) The gravity forward calculation for a single boundary, defining a density discontinuity as the Moho or the basement, with a laterally variable density difference applied to the Parker-series expansion [45]. This makes use of series expansion up to order 5 of the gravity field generated by an oscillating boundary.

(2) The inverse calculation, which starts from the gravity field and has the goal of obtaining the causative density boundary, uses an iterative algorithm that alternates downward continuation with direct forward modeling (Braitenberg and Zadro [46]). This method has some analogies to the Oldenburg-Parker inversion approach of Oldenburg [47].

(3) The forward modeling of the gravity field produced by a sedimentary basin, for which the sediment thickness is known, is made by allowing different density variations with depth, either as a sediment compaction model (e.g., Sclater and Christie [48]) or as a linear sediment density increase with depth.

(4) The basin is discretized into a series of thin sheets, for each of which the gravity effect is evaluated. The load of the sediment basin is also calculated, and refers to the integrated load with respect to the standard reference crust and given as output. Isostatic modeling adopts the isostatic lithospheric flexure model (e.g., Watts [49]) and calculations are fulfilled with a convolution approach with the numerical (Braitenberg et al. [50]) or with the analytical flexure response functions (Wienecke et al. [51]). This evaluation method allows a relatively high spatial resolution, superior to the spectral methods. In the forward flexure calculation application, typically the crustal load is given, as it has been obtained from the gravity modeling. Then the expected Moho or basement undulation can be calculated assuming isostatic equilibrium. When using the inverse flexure calculation application, a crustal load is required, which can be obtained from the density model and the amplitude of the crustal flexure is retrieved from the Moho undulations. In the latter situations the crustal flexural rigidity is obtained from the condition that the flexure model with the known loads matches the known crustal thickness model. By means of this procedure it is possible to divide the crust into different areas, which can be geologically significant.

The densities used in the calculations are standard values already used by Woollard [52], Introcaso and Pacino [53] and Martinez et al. [54] and are as follows: for masses above sea level, density equal to 2.67 g/cm^3; upper crustal density: 2.7 g/cm^3; lower crustal density: 2.9 g/cm^3; upper mantle density: 3.3 g/cm^3. The gravimetric effect of the Nazca plate was evaluated assuming a constant thickness of 80 km [13, 53]. The density contrasts used to calculate the gravity effect of the subducted plate were +0.05 g/cm^3 in the western and eastern portions [14] and +0.02 g/cm^3 in the central section of the subduction. The positive gravity anomaly of the Nazca plate was incorporated as an additional correction of the Bouguer anomaly. The Bouguer anomaly, corrected for the gravimentric effect of the Nazca plate, was inverted considering a normal crust thickness of 35 km.

Using the Bouguer anomaly field for the gravity inverse calculations, we obtained a gravimetric Moho undulation, using standard parameters as normal crust thickness Tn = 35 km, and a crust-mantle density contrast of $-0.4\,g/cm^3$. In order to model the gravity Moho in terms of an isostatic model, the effective elastic thickness (Te) is allowed to vary in the range $1 < Te < 35$ km. The elastic thickness is constant over moving windows of 50 km × 50 km size. The window size was chosen by evaluating the wavelength of the main visible, geological structures.

The results were then compared with the seismological Moho depths along a section coincident with the CHARGE project, defined by the locations of the seismologic stations used by Fromm et al. [12]. Their geographic distribution can be observed in Figure 1.

4. Data Analysis

From top to bottom, the following quantities are shown in Figure 3: the upper part of the graph (Figure 3(a)) shows the topographic profile, obtained from the digital terrain model (Shuttle Radar Topography Mission; URL: http://srtm.usgs.gov/), entirely covering the Andean Cordillera, the Precordillera and the Pampean Ranges. Then (Figure 3(b)) the gravity effect of the Nazca plate is shown, which has been calculated with the Grow and Bowin [14] densities. Figure 3(c) shows the gravity field corrected for topography (Bouguer anomaly) and the gravity effect of the isostatic root according to the Airy model. In Figure 3(d) the Moho undulation obtained from the gravimetric inversion, the isostatic root according to the Airy hypothesis (considering normal crustal thickness Tn = 35 km, lower crustal density $2.9\,g/cm^3$ and mantle density $3.3\,g/cm^3$) and the Moho depths obtained from Fromm et al. [12] are compared. Corona [55] found the predictive topography that would isostatically respond to the geometry of the seismic Moho. This topography fulfills the requirement for the load so that the seismic Moho depths are fitted with the Airy isostatic model. The load is calculated by inverting the Airy isostatic linear relation, when the isostatic root and the crustal and mantle density are known. The isostatic root is set equal to the seismic Moho. This calculated topography, as observed in Figure 3(a), is much higher with respect to the real topography, mainly in the Cuyania region. Finally, in the lower part of the graph (Figure 3(e)) the effective elastic thickness is shown.

Between the seismological stations NEGR and RINC (see Figure 3(d)) a positive difference (less than 10 km) between the gravimetric and seismic Moho depths is observed. In the same segment, the isostatic Moho is considerably shallower than the seismologic Moho (more than 10 km). In order to minimize this difference from the gravimetric perspective, in addition to the gravimetric effect of the Nazca Plate and the inhomogeneities in the upper crust, it is necessary to incorporate a layer of high density with a wavelength similar to the distance between the seismological stations (NEGR-RINC). The high density layer will have the effect of allowing a deeper gravimetric Moho, and an extra load that will produce a deeper isostatic Moho. Thus a forward gravity model was formulated that contemplates the subducted Nazca Plate, the inhomogenieties in the upper crust [13] and a high density layer ($3.075\,g/cm^3$). The lower crust high density layer could be interpreted as eclogitized lower crust, as suggested by Gilbert et al. [56], or in more general terms as underplating. They found, however, that the amplitude of the P to S conversion was diminished in the western part of the profiles and have attributed it to a reduction of the impedance contrast at the Moho due to lower crustal eclogitization. Figure 4 shows a crustal model which fits the Bouguer anomaly well, with an upper crustal density of $2.7\,g/cm^3$, a lower crust of $2.9\,g/cm^3$, an upper mantle of $3.3\,g/cm^3$ and which incorporates the upper crustal inhomogenieties after Gimenez et al. [13]. The upper crustal model is based on geological constraints and structures such as the sedimentary basins (orange) are well constrained. The sediments of the basin wedge below the Valley Fertil range justify the strong anomaly gradient which is found at the contact between the two structures (mountain and basin). Finally, between the crust-mantle interface we incorporated a layer of high density ($3.075\,g/cm^3$) or eclogitized crust below the Cuyania terrane, in accordance to the observations regarding the mismatch of the isostatic and gravity Moho with respect to the seismic Moho. In potential field modeling the models are not unique, but the variety of models can be greatly restrained if some hypothesis on the densities can be made. In the case of the eclogitized crust, we have adopted a density increase of $0.175\,g/cm^3$. A lower density contrast would lead to a linearly proportionally increased layer thickness. Alternative crustal models have been tested, as the one proposed by Heit et al. [11], which presents the Moho geometry obtained along the CHARGE profile, but examining the receiver function of the S wave. Unfortunately the results are geologically and gravimetrically inconsistent, such as the 73 km Moho-depth under the Precordillera.

5. Results

The analysis of Figure 3 shows that the Andean Cordillera seems to be in isostatic equilibrium whereas the Precordillera and Pampean Range regions are isostatically unbalanced. For the same section the Moho depths obtained by gravimetric inversion, isostatic modeling, and by seismologial investigations (depths given by the apparent phase velocities Pn [12]) were compared. It is evident, that the biggest difference between the depths obtained by the different techniques is found beneath the Cuyania terrane. In particular, the biggest difference is found between the seismic Moho and the isostatic Moho according to the Airy compensation model [13]. The misfit between the three Mohos is due to one cause: the neglect of buried mass in the lower crust. The buried mass generates a positive gravity signal, which produces an apparent shallowing of the Moho in the gravity inversion process if neglected. The neglect of the buried mass in the isostatic model leads also to an apparent shallowing of the Moho, because the load of the buried mass is not considered

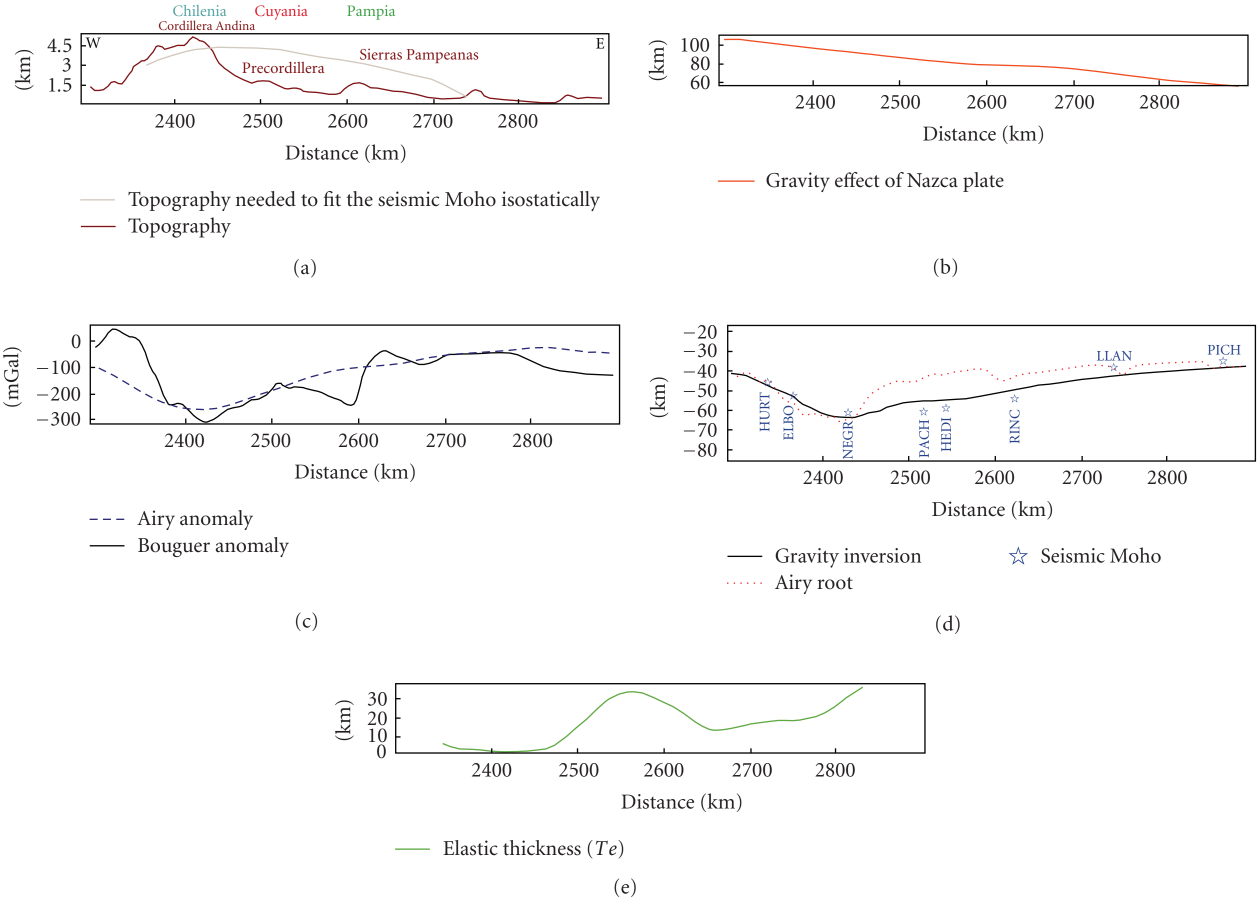


Figure 3: East-west section between latitudes 30° and 31° south, coincident with the CHARGE project seismic stations, with the results of the gravimetric and seismic modeling. (a) The present day topographic elevation (brown) and the elevation predicted from the seismic Moho (grey). (b) The gravimetric effect of the Nazca plate (red) calculated from the Grow and Bowin densities [14]. (c) The gravimetric Bouguer anomaly corrected for the gravimetric effect of the Nazca plate and the gravity effect of the Airy isostatic root. (d) The gravimetric inversion (full black line), the isostatic roots (red dotted line), and the seismic depths obtained from Fromm et al. [12] are represented by blue colored diamonds. (e) The effective elastic thickness calculated according to Braitenberg et al. [50], Wienecke et al. [51].

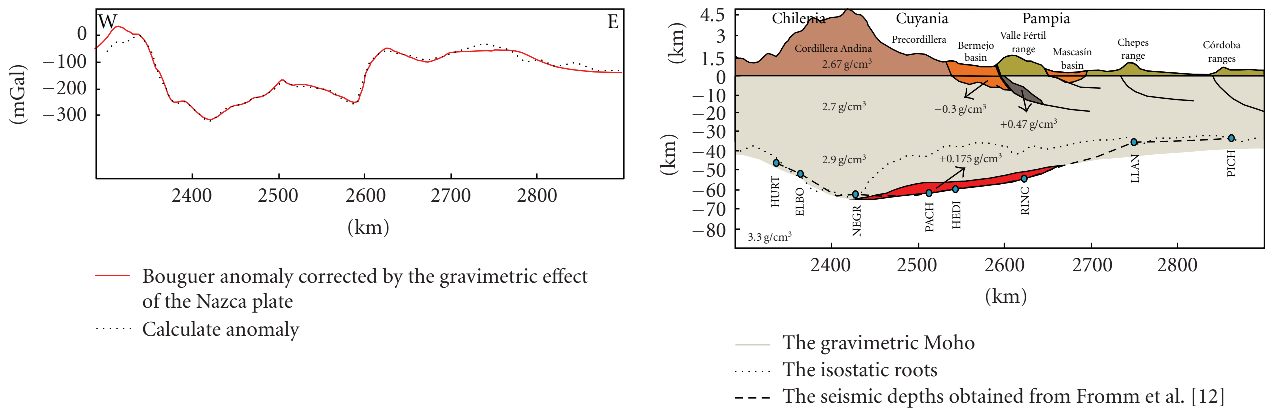
correctly in calculating the isostatic root. We can see that the comparison of the seismic, gravity and isostatic Moho is a general means to detect buried unknown masses. The deeper the buried mass is, the smaller is its gravity signal, and the smaller is the discrepancy between the gravity-inversion Moho and the seismic Moho. The depth of the buried mass has no influence on the misfit of the isostatic root, because be it shallow or deep, the load of the mass which has been neglected is the same. It follows that a greater misfit of the isostatic root with respect to the gravity root, is an indication of a deep seated mass. Vice versa, when the isostatic misfit is smaller than the misfit of the gravity root, we may suspect a superficial buried mass.

We find that the gravity Moho can be made to match the seismic Moho by introducing a 5 km thick slab with a density of 3.075 g/cm^3 beneath the Cuyania terrane. A slab of higher density would lead to a proportionally thinner slab. This result is in good agreement with the seismological observations, as it could justify the increase in the value of the apparent phase velocity [12] in the Precordillera to 8.0 km/s, compared to the velocity under the Andean Cordillera of 6.0 to 7.0 km/s.

Beneath the same region, Gilbert et al. [55], by using the receiver function technique applied to the data from the CHARGE project, found anomalous values for the Vp/Vs ratios, in particular they found Vp/Vs = 1.8 in the lower crust of the Cuyania terrane. This brought them to the hypothesis that the anomaly could be interpreted as an indication of an eclogitized crust.

In the lower part of Figure 3, the effective elastic thickness is shown, which was calculated according to the above mentioned methodology. It is observed that under the Andean range, Te is low, as was expected if this area is in isostatic balance. In the Precordillera, specifically in the Cuyania terrane region, an important increment in Te (with a maximum value of 30 km) was found. This value decreases eastward to 12 km and then increases again in the Pampian terrane. This increase of the elastic thickness indicates that this eastern region shows higher rigidity.

The above given values are consistent with: (1) the anomalous density ($\rho = 3.075\,\mathrm{g/cm^3}$) at the base of the Cuyania region, necessary for adjusting the seismic and gravimetric Moho depths and, (2) the high seismicity typical for this region [3, 8, 9, 21, 57].



(a) (b)

Figure 4: Crustal model where the gravimetric effect adjusts to the Bouguer anomaly. This model considers an upper crust with a density 2.7 g/cm^3, a lower crust with the density of 2.9 g/cm^3, the upper mantle with a density 3.3 g/cm^3 and incorporates the inhomogeneities interpreted by Gimenez et al. [13]: the most occidental structure represents the suture zone between the Chilean and Cuyania Terranes. The Bermejo Basin is located in the central zone, with a density-contrast of −0.3 g/cm^3, and with a depth of approximately 10 km. The incorporation of a dense positive mass below the Valley Fertil range, with a density contrast of 0.47 g/cm^3, justifies the positive anomaly in Valley Fertil. This also represents the suture zone between the Cuyania and Pampean Terranes [13]. The sediments of the Bermejo basin, wedged below the Valley Fertil range, justify the strong gradient in the Bouguer anomaly which exists between both structures. Finally, at the base of the crust, within the Cuyania region, the layer of high density or eclogitized crust is seen in the model.

In recent research, Wagner et al. [58], looking at the elastic properties of cratonic xenoliths, indicate that a low Vp, high Vs, and low Vp/Vs signature is indicative of cratonic lithosphere. This suggests that the material above the flat slab may be ancient Laurentian lithosphere, or other melt-depleted, dry lithospheric material.

This would indicate that not only, beneath the Cuyania region, it is necessary to consider the effect of the Nazca plate for the adjustment of the seismic and gravimetric inversion depths but also that, at the base of the crust, a high density layer about 5 km thick should exist which, in view of its high density, could be made up of eclogite.

This result could be justified if Cuyania was an exotic terrane with specific physical and geologic features, different from other terranes, as proposed by some authors [22, 34, 36, 59].

6. Conclusions

In the Central Andes, between 28° and 32° south latitudes and 72° to 66° west longitudes, the Moho depth was obtained by inversion of the Bouguer anomaly, corrected for the positive effect of the Nazca plate with flat slab subduction. The depths from the gravimetric inversion were compared with the Moho depths given by the analysis of the apparent phase velocities at eight seismolgical stations of the CHARGE project, along a transect situated at about 31° south latitude. From this comparison, discrepancies between the seismological and the gravimetrical Moho depths below the Cuyania terrane were observed. An isostatic study showed that in the same area also the isostatic Moho did not fit the seismic Moho. We have shown that the introduction of a zone of high density located at the bottom of the crust of this terrane allows to match the gravity Moho to the seismic Moho. We have constructed a constrained crustal model that includes upper and lower crustal inhomogeneities. The upper part of the model (up to 10 km depth) relies on previous density models that used geological and geophysical constraints to produce the correct density model. The deeper part of the model relies on the recent results of the seismological CHARGE project.

Our study shows that in the Cuyania terrane, the Nazca plate gravity-correction is insufficient to adjust the depths of the seismic and gravimetric Moho. Rather, it is necessary to assume an anomalous lower crust in this region. An alternative interpretation could be that the lower crust high density layer is underplated material. This could be related to the melt-products produced by the subducting Nazca plate.

A notable increase of the flexural rigidity to about Te = 30 km was found for this area, correlating with anomalous seismic wave velocities obtained by receiver function studies. These evidences, in addition to the many known geological ones, support the allochthony of the Cuyania terrane.

Acknowledgments

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