A Gravimetric Study of Heterogeneities in Intermediate Crust beneath the General Levalle Basin- Córdoba Province– Argentina

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This paper was prepared for presentation during the 12th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 15-18, 2011.

Abstract

We present the results of a gravimetric study carried out in the region of the General Levalle sedimentary basin, Cordoba province, Argentina. We obtained the geometry of the basement roof for the region where the basin is located and the surface of the crust-mantle interface. The latter resulted in a surface of mild slope that deepens to the west. The fact that the interface crust-mantle is rather plane indicate that the sedimentary column has no antiroot that isostatically balances it. Also, the gravimetric effect of the sediments was evaluated and subtracted from the Bouguer anomalies. In the basin area, a positive gravimetric effect was identified, which may be linked to inhomogeneities located in the intermediate crust.

On the basis of the gravimetric results, their comparison with stratigraphic analysis and of basin studies of the region, we propose possible alternatives that consider the presence of thick masses in the intermediate crust: 1)Emplacement of alkaline magmas during the Cretaceous extension, 2) An anomaly in the geometry of the crust, whether by the effect of a thinned crust associated to Cretaceous rifting or to Cenozoic extension or 3) Due to the flexion of the upper crustal layer during the Andean compression.

Introduction

During the Early Cretaceous, tectonic processes that occurred in the South American sector of Gondwana were highly complex (Chebli et al 1999). As a result of the impact of the Paraná-Ethendeka plume, there was a significant phenomenon of oblique extension that resulted in the fragmentation of western Gondwana along the southern Atlantic depression (Chebli et al. 2005). Within the South American continental extensional reactivation of two major suture zones led to the development of two separate rift grooves (called Cretaceous Rifts of central Argentina, Franzese et al. 2003; Rivarola and Spalletti 2006), settled on continental crust with a dominant north-northwest direction, reaching lengths of about several hundred kilometers (Fig. 1). The groove or Eastern Rift System of Central Pampeano (Ramos 1999), is located in the suture zone between the craton of the Rio de La Plata, on the east, and Eastern Pampean field, west (Schmidt et al, 1995). It consists of a set known as Watershed depocenters of Macachín (Salso. 1966), General Levalle (Webster et al. 2002, 2004), The Condor (Ramos 1999) and Sierra Chica (Schmidt, 1995). Further north, the rift system is poorly defined, however, Alvarez et al. (1990) and Ross and Mozetic (1999) have reported the presence of Cretaceous deposits in the basin known as the 'Saliniana'. Thus, and as suggested by Schmidt et al. (1995), Ross and Mozetic (1999), Ramos (1999), Webster et al. (2002, 2004) and Jacques (2003), it is likely to reach the Cretaceous Basin of northwest Argentina (Fig. 1).

This paper aims to study the crust that contains the General Levalle basin based on geological and gravimetric information. This analysis, in addition yields important data about the current state of the crust of the Argentine Plains, in combination with subsurface stratigraphic studies which will aid in understanding the possible causes of the subsidence of the basins developed in the great plain since their early Cretaceous, extensional period to present date.

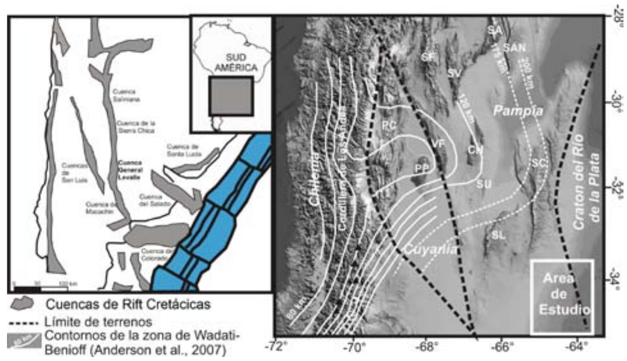


Fig 1: Location of the study area. The map on the left shows the Cretaceous basin system. The graphic on the right, on the digital elevation model of the terrain, was plotted in white contours of the Wadati-Benioff zone in solid lines, black dotted lines show the boundaries of Chilenia, Cuyania, Pampia and river Craton de La Plata. Furthermore, it shows the main geological structures visible: Cordillera de Los Andes, PC: Precordillera, PP: Pie de Palo, VF: Sierra de Valle Fertil, SF: Famatina System, CH: Chepes saw, SU: Sierra Ulapa, SL: San Luis Sierra, SV: sierra de Velasco, SA: Sierra de Ambato, SAN: Ancasti and saw SC: Sierra de Córdoba.

Method

To conduct the study in the General Levalle sedimentary basin, the following were used: (1) contour map of the basement of the basin taken from Webster et al. (2004), (2) the sonic profile of the well Hunt City General Levalle x-1, (3) digital elevation model of terrain Etopo2 (Fig 2) and (4) observed gravity values, collected over the years 2004 to 2007 by the Volponi Seismological Institute of Geophysics, from th National University of San Juan and Rosario Physics Institute from the National University of Rosario.

The Bouguer anomaly was calculated in the International System of 1971, and the data refers to the 'Miguelete' base station. The calculation of gravimetric anomalies was carried out by classical expressions, standardized by Blakely (1995). Thus, to reduce 'Free-air', a normal gradient of 0.3086 mGal / m was applied whereas, for the Bouguer reduction, a density of 2670 kg/m3 was used. For topographic reduction, two grids were used, one local and the other regional in the Hayford zone with circular land segments of up to 167km in diameter. Figure 3 shows the Bouguer anomaly chart, with the distribution of gravimetric data.

In order to eliminate the gravimetric effects of short wavelengths, the Bouguer anomaly map was filtered by means of the following techniques such as: 1) ascending prolongation of potential field, extending to altitudes from 20 to 50km (Pacino & Introcaso, 1988, Blakely, 1995) and 2) Butterworth filter with an opening cut of 250 km and order 8. Based on the Pre-Cordillera field work of the different maps of ascending prolongation in the area (Miranda and Introcaso, 1999; Introcaso et al., 2006), the regional anomaly extending to 40 km in height (Fig. 4) was selected, whereby regional anomalies obtained by both techniques are consistent with each other, proffering very similar results.

The residual Bouguer anomaly was obtained by subtracting the regional gravimetric effect (Fig. 4), using the Bouguer anomaly chart. Thus this obtained a residual Bouguer anomaly that responds to gravimetric effects of geological structures developed in the upper crust. Figure 5 shows the contour of the General Levalle basin, with values reaching -16 mGal in the north and -25 mGal depocenter in the southern depocenter, which extends south and southeast of the map.

Density Determinations

In order to determine the densities used in gravimetric models, the sonic interval velocities of the Hunt well profile General Levalle x-1 (see location in Figure 3), were converted, reaching a maximum depth of 5,179 meters, at densities by expression of Gardner et al. (1974):

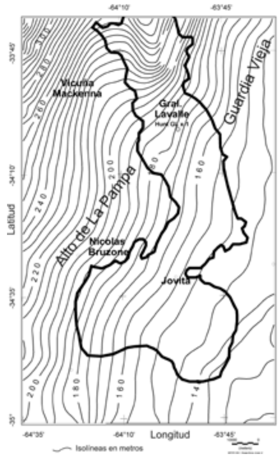
$$\sigma = 0.23V^{0.25} \quad (1)$$

where σ is density expresed in gr/cm^3; V is the velocity expressed in foot/seg.

In this way, density data versus depth for the sedimentary basin General Levalle (Table 1) were obtained. We assumed a value of 2,800 kg/m^3 for the upper crust, as of 5,000 meters of rock density obtained by equation (1) was of 2,790 kg/m^3. The density of the lower crust was considered σ i = 2900 kg/m^3, and the upper mantle σ ms = 3300 kg/m^3, (cf. Woollard, 1969; Pacino and Introcaso, 1988, Watts, 2001, Turcotte and Schubert, 2002).

Gravimetric Inversion Basement Model.

We calculated the geometry of the crystalline basement of the General Levalle basin, from the residual Bouguer anomaly, considering the density profile obtained from borehole sonic Hunt GL x-1, converted to density by Gardner et al. (1974), see Table 1.



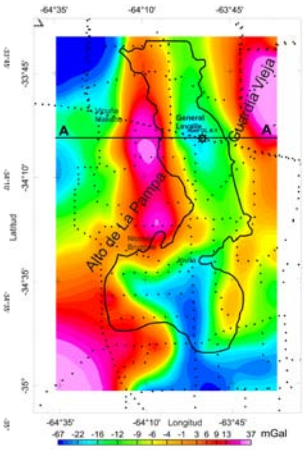
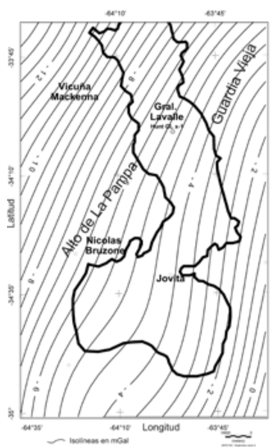


Fig 2: (Left) Model of digital terrain elevation (MED), obtained from the Shuttle Radar Topography Mission (SRTM) of the United States Geological Survey and NASA. It shows limits imposed on the edges of General Levalle basin with a thicker, black solid line.

Fig 3: (Right) Bouguer anomaly map and the distribution of measured gravity points.



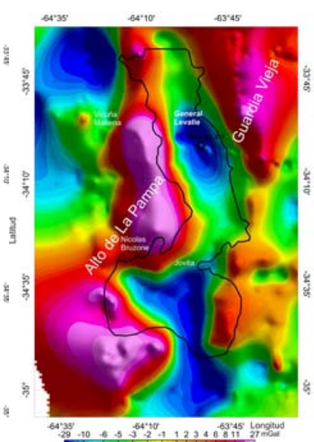


Fig 4: (Left) Regional Bouguer anomaly.

Fig 5: (Right) Bouguer residual anomaly map.

The 3-D model consisted of two layers, the topography and the crystalline basement. Calculations were made by fixing the topographic surface, considering a variation in density with depth (see Table 1) and 2,800 kg/m3 for the crystalline basement. The gravitational field was draped at a constant height of 320m above the highest point of land. The draping technique uses the algorithm known as Cordell (1985), which is applied to calculate the upward continuation of gravity field obtained on rough surfaces to a plane of constant height. The inversion is adjusted to

the Bouguer residual anomaly following Popowski et al., (2006).
The result was a surface that can be interpreted as corresponding to the substrate of crystalline basement of the basin, whose depths were determined from the topographic level (Fig. 6). It is observed that the southern depocenter is the deepest, reaching a depth of 7,200 meters and continuing south to the map, possibly reaching Macachín basin. The depocenter northern sector (where the well Hunt GL x-1 was made) is more shallow, developing to 6,000 meters.
The flanks of the Levalle General basin are found to be non-outcropping basement highs, which correspond to the Alto de La Pampa in the west and the Old Guard base in the east (see also Chebli, et al., 2005 .)

Gravimetric Inversion Mantle-Crust Interphase Model

We calculated the depth to the surface of the crust-mantle interface from gravimetric inversion of the Bouguer anomaly map extended to 40km in height (Fig. 4). For the calculation, an average crust thickness 35km, a density of 2,900 kg/m^3 for the lower crust and 3,300 kg/m^3 for the upper mantle were used. In this way, the interface crust - mantle gravity inversion was obtained (Fig. 7) yielding a deepening gently-sloped area to the northwest. This result is consistent with other regional characteristic studies such as those by: Introcaso and Huerta (1972); Introcaso et al., (1992), Miranda and Introcaso (1999) and Gilbert et al. (2006).

These results indicate that the sedimentary column would not have an anti-root and would not be hydrostatically compensated, since the crust-mantle discontinuity shows no evidence of anti-root.

To analyze the deeper gravimetric effects, the effect of gravity produced by sediments of the General Levalle basin were used, employing a direct gravimetric modeling based on the technique developed by Parker (1973). To calculate the crystalline basement, isobaths obtained from gravimetric inversion (Fig. 6) were used. From the well information Hunt GL x-1, we calculated a weighted average density for the entire sedimentary package, resulting in 2,370 kg/m^3. Figure 8, presents the map of the sediment gravity effects. The gravity effect of sedimentary package was deducted from the Bouguer anomaly (Fig. 3) and Figure 9 shows the Bouguer anomaly chart corrected for the effect of sediments, and responds to gravity effects produced by bodies with density variations located at greater depths. The map in Fig. 9, shows the area of the basin revealing an observable positive Bouguer anomaly, a relatively short wavelength. This infers the presence of dense masses, which by its median wavelength, and the absence of anti-root (see Figure 7), should be located in the middle crust. Similar events are seen in Lyngsie et al. (2007).
This suggests that although the basin originated in the Mezosoic through a continental rift system, this structure was attenuated during the Andes phase in tectonic regime change (Ramos, 1999, Gómez et al. 2005; Mpodozis et al. (2005).

2D Gravimetric Model

A 2-D gravimetric model was prepared, based on existing geological and geophysical information, to analyze whether it is possible to adjust the Bouguer anomaly curve observed with the inclusion of an attenuated middle crust.

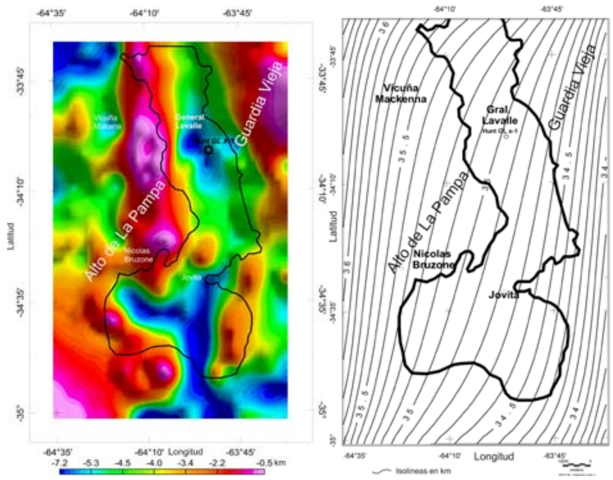


Fig 6: (Left) Basin Basement Map, obtained through Bouguer residual obtained by gravimetric inversion.
Fig7:(Right) Mantle-Crust surface interfase through gravimetric inversion of Regional Bouguer Anomaly Map.

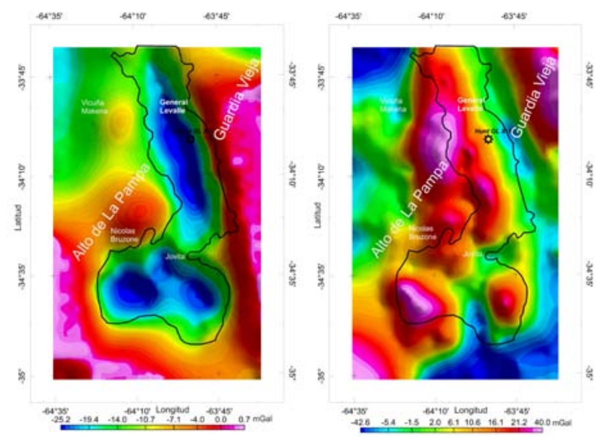


Fig 8: (Left) Gravimetric effect of sediments
Fig 9: (Right) Bouguer anomaly without the gravimetric effect of sediments.

With this aim, section AA '(Fig. 3) to latitude 34 ° S was drawn, which divides the basin of General Levalle at its maximum depth, resulting in the gravity profile observable in Figure 10. The densities for the sediments in the basin are the same as those used in the calculation of the base inversion 3-D model, which are summarized in Table 1. The densities used were: 2,730 kg/m^3 upper crust, lower crust 2,900 kg/m^3 and upper mantle 3,300 kg/m^3, respectively. The cortical model that adjusts the Bouguer anomaly is shown in Figure 10. This model shows the mantle-crust interface gently tilted to the west, without major changes under the General Levalle basin. It would be necessary to incorporate dense masses in the intermediate cortex to achieve a gravimetric adjustment in the anomaly curve between what is observed and what is calculated.

This result would support the idea of stretching under the basin formation, allowing the rise of lower crustal materials to upper crust, due to crustal thinning by stretching or normal faulting, preserved to the present day and registered by the gravity measurements.

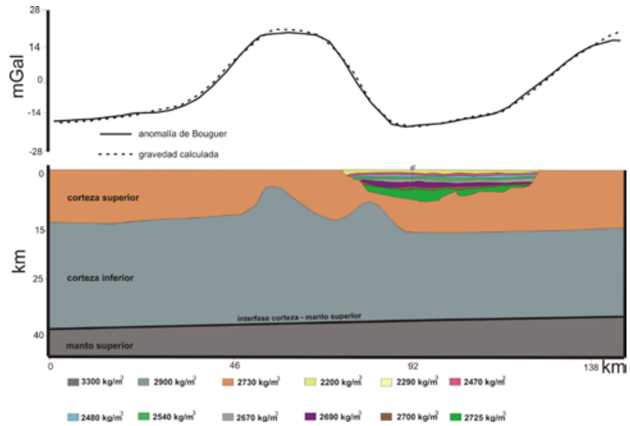


Fig 10: Upper Crust model of section A-A´ to 34° of South latitude

DISCUSSION

The objective of this study is to furnish independent control of the gravimetric data. This analysis herein contemplated the stratigraphy of the General Levalle basin. Based on this information as a starting point, which originated from the stratigraphic well data, [Marengo, 2006] as well as from data from seismographic sections studied by Webster et al. 2004, and Chebli et al. 2005, the aforementioned were compared to the General La Valle data.

The Cretaceous-Cenozoic subsidence history of the General Levalle basin can be divided into three distinct stages clearly separated by episodes of erosion, non-deposition, and/or diminished or reduced sedimentation rate. The oldest subsidence episode corresponds to the history of graben filling dominated by extensional forces. This filling is separated by a potent reflector [located at a depth of ~1 s] which marked the beginning of a subsidence stage, slightly greater in wavelength, which crosses the graben borders, interpreted as an episode of thermal subsidence. The other strong reflector [~0.4s] depending on the location in the seism, [Webster, et al 2004] marks the initiation of an accommodation of the Cenozoic basic. In the basement, this is characterized by a monotonous succession of great lateral continuity of high frequency and scarce amplitude [Webster et al 2004] This accommodation is approximately hundreds of km and appears to accompany the geometry of the depocenter of the Quaternary Basin of the Pampean Plain [Marengo 2008]. This pattern of accommodation characterized by the great wavelength in the Tertiary successions was also observed by Marengo [2006] based on the reconstruction of the well data. In his work, Marengo divides the Cenozoic into 5 depositional states, separated by sedimentary packets both marine and coastal in origin,[FMS Laguna Paiva & Parana].

A structural map on the floor of the Oligocene-Miocene packets Fm Laguna Paiva shows the tabular arrangement and regular EW and NS direction, as is shown by the seismic sections. Also, considering that the deposition of marine transgressions should level the post-Cretaceous and paleo-relief lower Tertiary, filling in areas with high subsidence, from the observation of regional stratigraphic sections, it definitely rules out the possiblilty of increased subsidence for the Oligocene-Miocene and Middle Miocene (the age of Fms Laguna Paiva and Parana, respectively) on the former General Levalle Cretaceous basin. Furthermore, seismic lines on the Mesozoic basin of General Levalle also show that it did not accumulate the greatest tertiary-quaternary total thickness. Under the Cenozoic isopach, structural map on top of these stages of sedimentation and seismic sections indicate that the General Levalle basin was not the post-Cretacian region of greatest subsidence in the region of the pampas during episodes of Cenozoic-Quaternary subsidence.

The packet is marked by tabular and long Cenozoic reflector wavelength which crosses the Cretaceous depocenter. This clearly shows that it is unlikely that there is any imbalance or inherited trait or that any was generated after the compressive forces in General Levalle Mesizoic basin.

Davila et al., (2005) and Davila (2008), interpreted the largest component of the collapse of the Plains during the Cenozoic have been generated by dynamic subsidence (or negative dynamic topography (eg Mitrovica et al., 1989) by countervailing isostatic effects (Hager, 1984) generated in the asthenospheric wedge during the subduction of the Nazca sub-horizontal slab beneath South America. The constant flooding in this region, one of the most important from the agricultural and livestock perspective in Argentina, are possibly the result of the dynamic topography, combined with the influence of flexural subsidence and load generated by the mountains located west of the region (see Davila and Lithgow-Bertelloni, 2008, Davila et al., 2010 and Gimenez et al., 2009).

Assuming that the convective forces induced by the subduction of the Nazca plate beneath the Sierras of Cordoba have influence in the post-Cretaceous subsidence (cf. Dávila and Lithgow-Bertelloni, 2008), it should be ruled out that the corrected Bouguer anomaly for the effect of sediment recorded in this work is due to an effect of "uprising" isostatic post-Mesozoic. By contrast, the dynamics of mantle sinking favor dynamic phenomena a hundred meters in this region of the peri-cratonic foreland (Dávila and Lithgow-Bertelloni, 2008), as suggested by the thickness of the Cenozoic sedimentary plain (Dávila, 2008) . Along with the subsurface stratigraphy and geodynamic models recently developed for this region, positive anomalies could be the result of: (1) the presence of dense bodies emplaced at deep crustal levels, (2) an overly-densified lower crust or even (3) an anomaly in the geometry of the crust, either by the effect of a 'stretched out or thinned out' crust, a legacy of Cretaceous rifting episode.

Since the cortical thickness of this region is not important enough, (see Figure 7) metamorphic facies changes that can densify crust <40 km are discarded. The position of this basin in the main tectonic loading of the Sierras de Córdoba would also rule out an effect of flexion (see Davila, 2008). Given the undoubted origin of Mesozoic rifting basin, the location of these anomalies are located on Cretaceous extensional depocenters and considering that the geometry of the crust-mantle interface obtained by gravity inversion does not show anti-root evidences, it is possible that this anomaly may be a consequence of the total effects generated by dense bodies emplaced during the breakup of crust and upper crustal thinning by stretching and normal faulting, preserved to this day.

Conclusions

From a gravity survey in the region of the General Levalle basin in the Province of Cordoba, we performed a 3-D gravity model with variable density to the top of the basement, which provided an analysis of the whole area. The geometry of the basin Cenozoic reflectors, which extends longitudinally N-S, forms two separate depocenters marked at its center by a transfer zone between them. The northern depocenter, is more shallow, reaching 6,000 meters. The southern depocenter, is deeper than the former, and it continues south (basin Macachín) and through it to the Colorado basin connected to the Atlantic Ocean.

Through inversion by regional gravimetric Bouguer anomaly, this study discovered that the basin does not have an anti-root to compensate the sequences. Based on the supposition that the convective forces induced by sub-duction of the Nazca Plate under the Cordoba Sierras have influence on the post-Cretacic subsidence [Davila – Lithgow-Bertelloni 2008] one would have to discard that the Bouguer Anomaly corrected by the effect of sediments recorded in this research is due to the effect of post Mesozoic uplifting. Quite to the contrary, the 'mantle dynamics' would favor the 'sinking dynamic' of hundreds of meters in this peri-cratonic foreland area [Davila – Lithgow] as suggested by the Cenozoic sedimentary thickness of the plains. The effect obtained by subtracting the sedimentary Bouguer anomaly effect, could correspond to: (1) dense bodies emplaced at lower crustal levels, (2) a lower overly-dense crust, (3) an anomaly in the geometry of the crust, either by the effect of a thinned crust inherited from the Cretaceous or bending post-Mesozoic episode, generating levels denser than those a mantle may occupy, where one would expect lighter crust. However, interpretations 1 and 3 are better suited to the geometry of the mantle and crust discontinuity estimates of the composition of the lower crust.

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