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Evidences of a tectonic uplift and seismic hazard in south of the Pie de Palo Range, San Juan-Argentina

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ABSTRACT
In the Central Andean region of Argentina, we found gravimetric and geomorphological evidence of an uplifting of the crystalline basement of Pie de Palo range. Within this zone, we observed a positive gravimetric anomaly in the extreme South of Pie de Palo, extending towards the South of Pampean ranges. By means of the geophysical technics, it was possible to determine the magnitude and geometrical form of the anomalous body. The evidence of a tectonic uplifting is also clearly manifested in the LandSat images, by observing the displacement of the course of the San Juan River towards the South. The study region is one of the major cortical and lithospheric regions with seismic activity in the country, where three of the most devastating earthquakes occurred over the last 73 years. The results would indicate that this region will continue to be one of the major seismically generating potential, significantly implying seismic dangers. The seismic risk studies indicate that the greatest hazard zone is found between the Pre-Cordillera and the Pie de Palo Range. The highest maximum acceleration values (PGA) are 242, 393, and 543 gal for return periods of 72, 475, and 2475 years, respectively.

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1. Introduction

The city of San Juan, Argentina lies in the region where the Andean Precordillera transitions eastward into the Pampean Ranges. The accreted terranes in the vicinity of 32°S and 68°W overlie a section of the descending Nazca slab, as outlined by the Wadati–Benioff seismicity. This slab flattens at a depth of 100–125 km before resuming a more normal angle of subduction to the East (Cahill and Isacks 1992). The Juan Fernandez Ridge, a zone of overly-thickened oceanic crust that has been cited as a possible cause of this flat subduction, has been traced eastwards under the South American continent in the San Juan region based on magnetic anomalies (Yáñez et al. 2001). Many workers (e.g. Anderson 2005; Wagner et al. 2005; Cahill and Isacks 1992) have observed a relatively dense cluster of small, intermediate depth (80–120 km) earthquakes in the vicinity of the flat slab that follows the inferred path of the Juan Fernandez ridge beneath San Juan.

The area under study lies in the dune-covered plain situated southeast of the Pie de Palo range between two geologic provinces: the Western Pampean Ranges to the East and the Precordillera to the West (Figure 1). The Precordillera is a Paleozoic orogen, constituted at the latitude of the area under study by Paleozoic marine sedimentary rocks, and Triassic and Tertiary continental deposits (Baldis et al. 1982; Astini et al. 2000; Astini et al. 2005). The Western Pampean Ranges are

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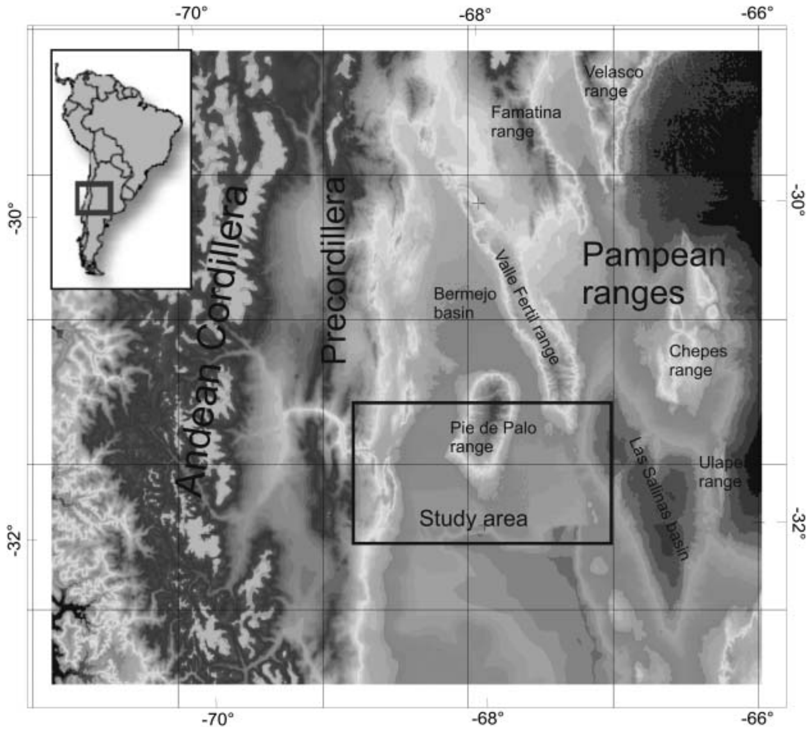

Figure 1. Location of the Pie de Palo range in the Pampean Ranges and the main mountain chains.

characterized by the presence of metamorphic and igneous rocks of Precambrian and Paleozoic age (Caminos 1979; Gordillo and Lencinas 1972; Schmidt et al. 1995).

North of 32° south latitude, the main Quaternary structures are related to westward vergent overthrusts, as in the Cerro Salinas fault (Comínguez and Ramos 1990), as well as in the Los Berros and La Rinconada areas (Bastías et al. 1984, 1990). The first locality lies in the Western Pampean Ranges, whereas the second and third are in the Eastern Precordillera.

South of 32° latitude, the principal Quaternary tectonic deformations are characterized by overthrusts vergent to the East and fault propagation folds (Bettini 1980; Figueroa and Ferraris 1989; Cortés and Costa 1996; Costa et al. 2000a,2000b and 2005).

In 1990, a gravimetric profile was surveyed across the middle part of the Pie de Palo range. This survey corroborated the existence of a positive anomaly on this range.

Subsequent hydrostatic sensor isostatic work (Martínez et al. 1994) indicated that, as in other Pampean Ranges, there is no probable anti-root capable of reproducing the short wavelength of the Bouguer anomaly (Introcaso et al. 1990).

In recent gravity measurements on the Pie de Palo region, researchers reproducing the positive gravimetric anomaly previously identified by Introcaso and Huerta (1972), Introcaso et al. (1990), and Martinez et al. (1994) determined that it is prolonged south of this range, with notable geomorphological evidence. For this reason, the present study intends to identify the structure that causes this anomaly by applying the analytic signal and Euler deconvolution techniques.

2. Database and procedure

New gravimetric measurements carried out in the region of the Pie de Palo range and surroundings were added to the database of the Geophysics-Seismologic Institute of the National University of

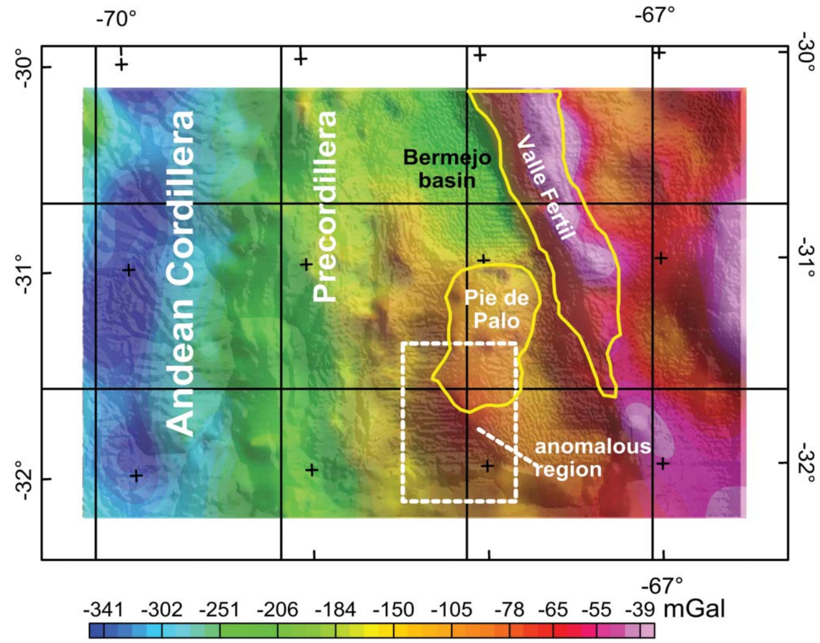

Figure 2. Bouguer anomaly chart plotted on the terrain digital elevation model, for linking the Bouguer anomalies to the main geologic structures.

San Juan. A total of 2400 gravimetric values for the studied area were added to both databases, all of them linked to the reference value in Miguelete, province of Buenos Aires, in the System IGSN1971.

For the calculation of the anomalies, the classic techniques were used (Hinze et al. 2005). 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 flat slab correction (Hinze 2003). 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 (1962) and Nagy (1966).

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 (Briggs 1974). Figure 2 shows the Bouguer anomaly chart plotted on the digital elevation model of the area under study, as a geo-reference for the gravity anomalies. From this chart, one can observe that in the southern extreme of the Pie de Palo range, the Bouguer anomaly is only relatively positive, because the chart is influenced by the negative gradient imposed by the Andean root.

By separating the gravimetric effects and obtaining those linked to the geological structures in the intermediate and upper crust to reach the objective, the gravimetric effects of regional tendency that could be caused by the crust-upper mantle discontinuity were deduced.

The authors consider that the results that best reflect the regional effects were obtained with the filtering by upward continuation at 40 km height. As a result, a Bouguer residual anomaly chart was obtained (Figure 3) where the extension of the positive gravity anomaly south of the Pie de Palo range can clearly be observed.

3. Neotectonics

The San Juan and Mendoza Rivers are tributaries of the Desaguadero River which makes up the eastern boundary of Mendoza province. Both the San Juan and Mendoza Rivers have experienced

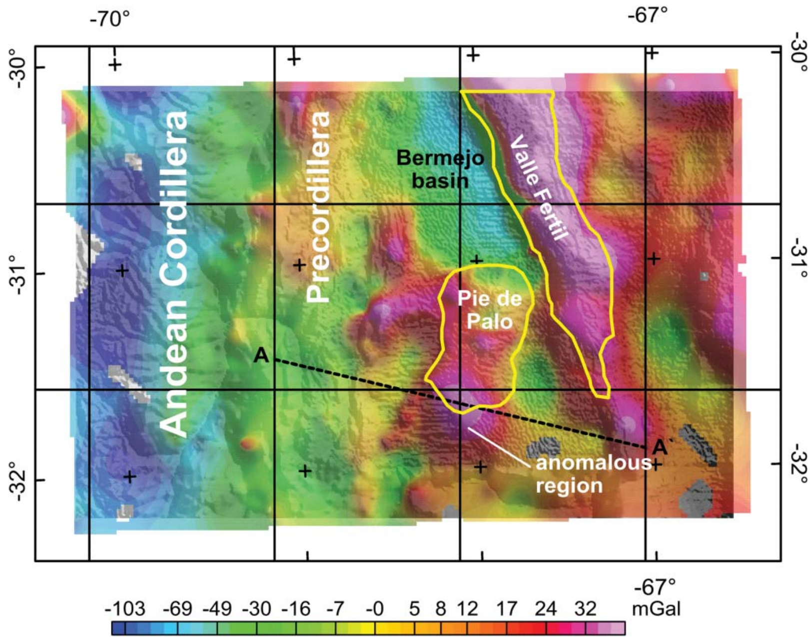

Figure 3. Bouguer residual anomaly chart obtained by the ascending prolongation filter at 40 km elevation above the average sea level.

many changes in their courses during the Quaternary, showing centrifugal behaviour in their displacements from the periphery of a non-outcropping ascending block towards their present positions (Vitali 1941; Rodríguez 1966).

This analysis supports the hypothesis of an uplifting basement block lying at certain depths, which would have caused the migration of the river courses away from the block Figure 4.

This phenomenon could be compared with the one that took place in the eastern flank of the Pie de Palo range during the 1977 earthquake (M = 7.4) when a vertical displacement was produced (Volponi et al. 1982; Introcaso et al. 1995, 1998). By means of geodetic levelling, researchers discovered that this tremor produced a permanent ground deformation of 1.30 m, whereas the displacement measured in the scarps did not exceed 0.30 m (Bastías 1986). This difference in height agrees with the corresponding gravimetric variation demonstrated by measurements of '*g*' carried out before and after the 1977 earthquake (Robles and Introcaso 1988; Introcaso et al. 1995, 1998).

Otherwise, the focus mechanisms (Alvarado et al. 2005) for events produced at depths shallower than 50 km, and, on the whole, situated in coincidence with the region presently studied, indicate a clear compressive state.

4. Geophysic evidences

4.1 Seismology and seismic hazard

In the last century, three more strong earthquakes of magnitudes Ms = 7.4, 7.0, and 7.4 with depths less than 30 km occurred in 1944, 1952, and 1977, respectively. For the last century, the 1944 earthquake was the most destructive in the Argentinean history, causing 10,000 deaths in a population of merely 90,000 and devastating 80% of the city, in the epicentral area and around greater San Juan (INPRES 2005).

It is well known that the Andean foreland in the Precordillera and Pie de Palo range of San Juan (Argentina) is an area of significant crustal seismic activity (Volponi et al. 1984; Smalley and Isacks 1990; Regnier et al. 1992; Smalley et al. 1993). This seismic activity is directly associated with the

Figure 4. Satellite image obtained, where the migration of the San Juan river course is observed over a period of time.

thin-skinned Precordillera and the thick-skinned western Pampean ranges (Figure 5). There, shallow seismicity indicates upper crust thickness and brittle deformation style. The area under study is located on a flat-slab hypocentre distribution zone (anomalous Wadati–Benioff zone) 100 km deep (Smalley and Isacks 1987; Reta 1992).

This hypocentre distribution defines the subducted plate geometry and allows authors to infer the approximate thermal limits of the South American Plate overthrust (Smalley and Introcaso 2003).

Seismic activity is located at a depth of 35 km in the Precordillera (Smalley and Isacks 1990; Smalley et al. 1993; Smalley and Introcaso 2003), while it is concentrated at a medium depth of 25 km (with a maximum of 30 km) below western Pampean ranges (Pie de Palo and Valle Fertil ranges). This seismic activity could represent the flattening of listric faults (Regnier et al. 1992; Smalley and Introcaso 2003).

Shallow hypocentre maximum depth at Pampean ranges is approximately 30 km. The maximum crustal seismic activity depth defines the base of the upper crust brittle layer. This brittle–ductile transition depth is unusually profound and suggests that the crust in San Juan is relatively cold. This could be the result of thermal isolation in the upper part of the continental lithosphere caused by the colder subducted plate (Dumitru et al. 1991).

The findings of Ruiz et al. (2002) reveal the results of monitoring the changes of gravity of seismic-tectonic origin in the period between 2000 and 2007, in a network of 47 fixed points covering active structures in an area of 2500 km^2. The results observed an important elevation in the variations of gravity linked to the alignment which coincides with the crystalline outcrops of Pie de Palo, Valdivia, and Barboza ranges, reaching the same region of seismic activity in data provided by the National Institute of Seismic Prevention (INPRES). Curiously enough, INPRES provided data for

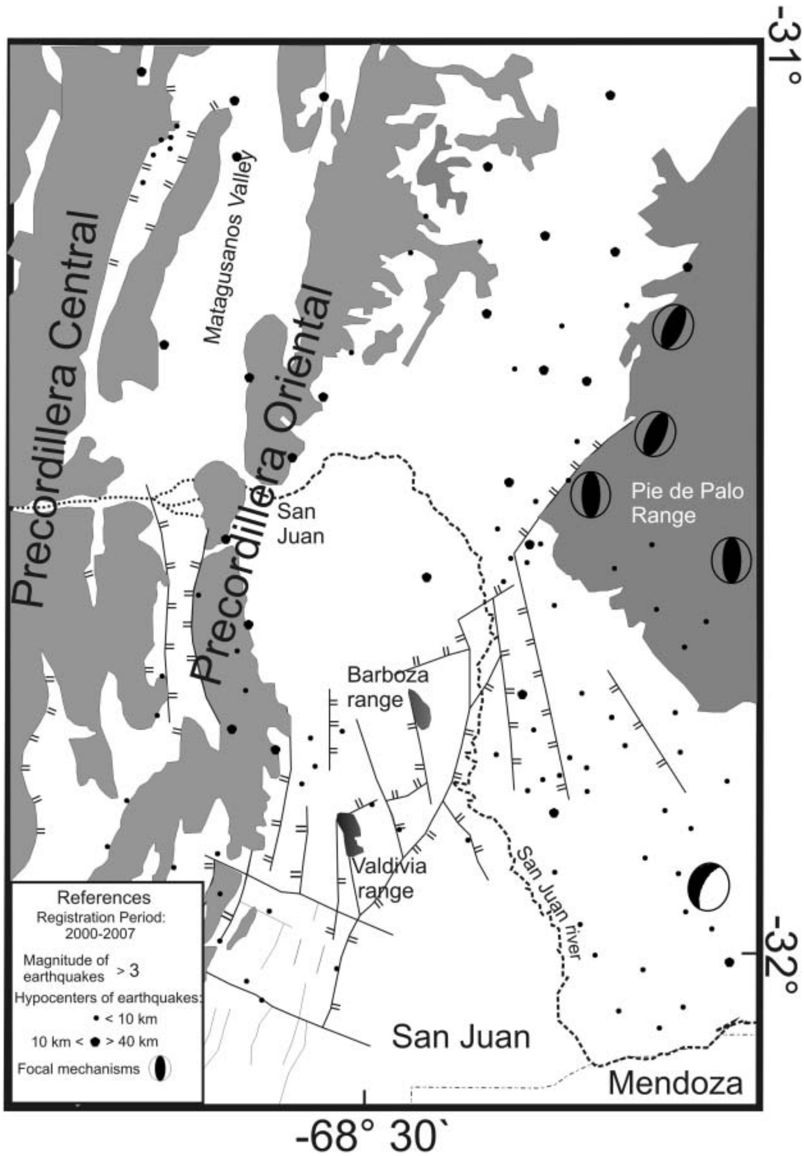

Figure 5. The geomorphological map of the study area plotted the hypocentres of tremors with magnitudes of > 3, during the period 2000–2007, obtained from the I.N.P.R.E.S. database, which indicate the principal mechanisms of the focus, results obtained by Alvarado et al. (2005).

the same area revealing a 'nest' of superficial earthquakes, in which some events reached magnitude 4. These results coincide completely with the results which are shown in the present study.

With respect to regional seismic hazard probability analysis (PSHA), this study zone was revised in the work of Gregori (2011/2015). These studies evaluated the regional seismic hazard in the West of Argentina between 30°S–32°S of latitudes and 67°W–69.5°W of longitude by means of a classic probability method (Cornell 1968). This method is based on the definition of a function of probability distribution for a selected parameter of a seismic movement (maximum acceleration) on a point of interest, due to the expected seismicity in the area surrounding the site, during a period of stipulated exposition.

This method requires the elaboration of a reasonably complete catalogue as its first step. This catalogue must carefully unify the different types of reported seismic magnitudes. In this case, all of the seismic magnitudes were converted to the magnitude moment Mw. In order to evaluate the integrity of the catalogue, the distribution of the events in time for different magnitude ranges were analysed.

Given that the seismic phenomena can be assumed as a random process, having a Poisson distribution required the elimination of all activity dependent on or repetitive in nature (aftershocks) in the catalogue used.

Afterwards, spatial analysis of seismic activity was provided by the catalogue and based on the additional geological, geo-physical, neo-tectonic, paleo-seismological, and satellite information. This analysis was followed by identification of seismic sources dividing the study zone into a system of three geologically and seismologically homogeneous regions (seismically tectonic regionalization) which determined a model of seismic occurrences by means of their corresponding frequency–magnitude distribution.

Moreover, it required knowledge of the ground movement attenuation law and the movements. Finally, probability analysis with selected data was carried out, which allowed for the estimation of ground movement values for different periods of time.

Figures 6(a, b, and c) represent the seismic hazard Central-West Argentina is exposed to, with maximum acceleration values (PGA) 50%, 10%, and 2% probability values of being exceeded in 50 years, which correspond to a return period of 72, 475, and 2475 years respectively.

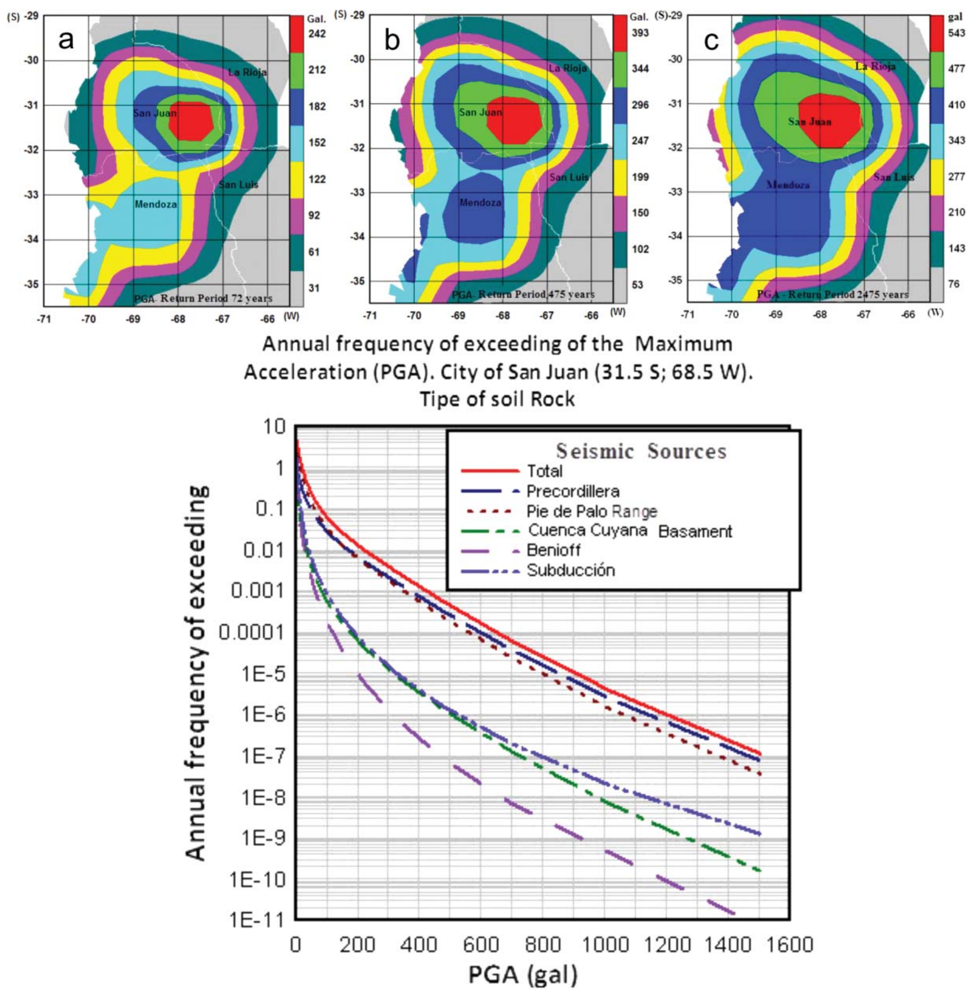

Figure 6. Maps of seismic risk represented by maximum peaks of acceleration (PGA) with (a) 50%, (b) 10%, and (c) 2% of probability of being exceeded within period of 50 years (72, 475, and 2475 years) return period, respectively, and (d) annual frequency of exceeding maximum acceleration for San Juan Province. Contribution to the seismic risk of each one of the sources and the total.

These maps show the iso-acceleration curves and the colour red depicts the greatest maximum acceleration localized in a circular zone that covers the city of San Juan, San Juan province and its neighbouring departments, reaching maximum acceleration values of 242 gal for earthquakes with a return period of 72 years and 393 and 543 gal for return periods of 475 to 2475 years respectively.

Undoubtedly, this zone (Central-West Argentina) is considered that of the greatest seismic risk in maximum acceleration values (PGA) with probability of 50%, 10%, and 2% of being exceeded within 50 years. These percentages coincide with the localization of the Pre-Cordillera and the Pie de Palo Range, seismotectonic subregions (seismic origins) which have generated major earthquakes in the last century. Figure 6(d) presents the annual frequency of curve values exceeding the maximum acceleration (PGA) calculated for San Juan, city in San Juan and province (31.5°S, 68.5°W).

4.2 Euler deconvolution

The Euler deconvolution was applied to the vertical gradient of the Bouguer anomaly, which was regularized by means of the Fourier rapid transform, keeping a 2000 m equidistance. This technic is based on the Euler homogeneity equation and adds a 'structural index' to produce depth estimations (Thompson 1982; Reid et al. 1990; Mushayandebvu et al. 2004). With this methodology, a variety of geological structures, such as faults, contacts, intrusive dykes, etc., can be identified and their depths estimated. However, the conventional approach to solving the Euler equation requires tentative values of the structural index, with results that are not fully automatic (Dewangan et al. 2007).

Two factors were considered for the use of this technique: (1) the adequate mobile window size, which, in turn, considers the adopted data grill spacing (trying with windows sized from 20 and 35 km); (2) the structural index was evaluated for 0.5, associated with faults (Roy et al. 2000), in a depth range from 5000 to 40,000 meters. The technique developed by Cordell (1985) was applied to the Bouguer anomaly chart, in order to minimize the effect of the topography, assuming a reference surface prolonged to 3300 meters above the maximum topographic elevation. The result obtained (Figure 7) shows a cluster of solutions situated at different depths that justify the Bouguer anomaly and its gradients.

The solutions, on the whole, are easily observable and aligned according to: (1) the Bermejo–Desaguadero fault; (2) a cluster of solutions along the western edge of the Pie de Palo range (Ramos 1999; Ramos et al. 2002); (3) an important accumulation of trapezoidal shaped solutions south of the Pie de Palo range. These sources respond mainly to depths between 10 and 20 km. This would coincide with a structural high proposed by Ortiz and Zambrano (1981) and is in agreement with the accumulation of earthquakes detected south of this range (Kadinsky-Cade 1985; Smalley and Isacks 1987).

4.3 Analytic signal

The analytic signal technique was used for analysing the extension of the anomalies situated south of the Pie de Palo range, and was applied to the values of the Bouguer anomaly. This technique is based on the methodology developed by Nabighian (1972) by applying the concept of analytic signal to data from the potential field in two dimensions, and was improved subsequently for studies in three dimensions (3D) by Roest et al. (1992) and Salem and Smith (2005).

This technique permits enhancement of the gravity anomalies produced by geologic discontinuances and clearly indicates the edges of anomalous bodies (Nabighian 1972). In Figure 8, the analytic signal chart has been plotted, which observes that in the region south of the Pie de Palo range a positive anomaly stands out in coincidence with the results of Euler deconvolution.

The analytic signal was applied in two sections for the localization and estimation of the generating sources: AS1, oriented from W to E (Figure 9) and AS2, oriented from N to S (Figure 10). The results obtained respond to the Bouguer anomaly gradients. The parameters selected for this case

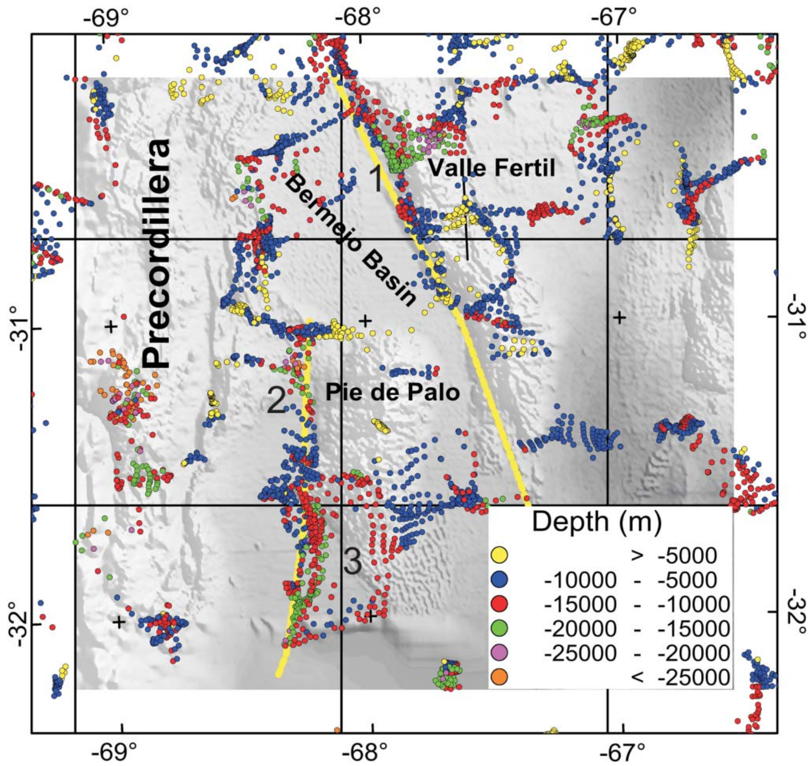

Figure 7. Euler deconvolution for a 0.5 structural index plotted on the topographic elevation model. Solutions were determined over a 5 to 40 km depth range, with intervals of 5 km. Three principal alignments were interpreted, identified in the figure as 1, 2, and 3 and described in the text.

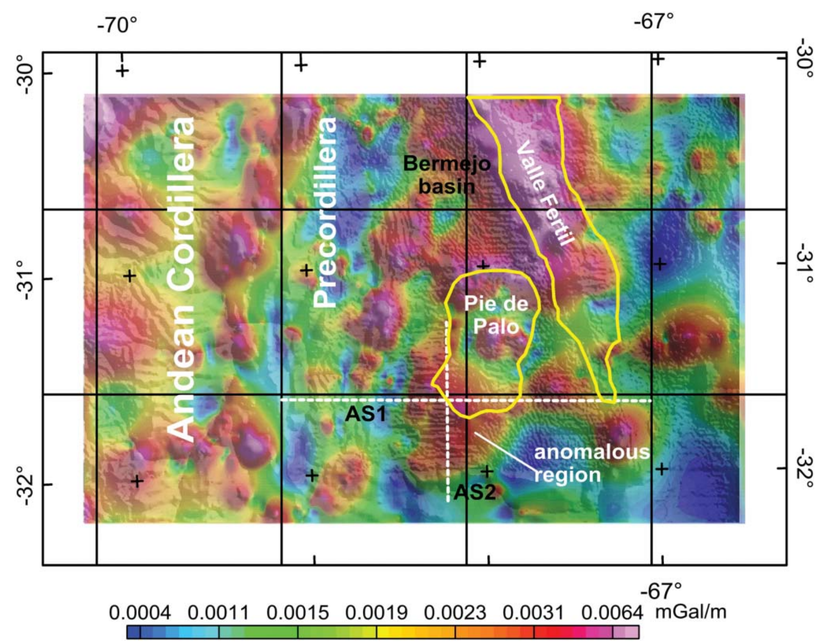

Figure 8. Analytic signal amplitude chart applied to the Bouguer anomaly. The edges of the Pie de Palo and Valle Fértil ranges have been drawn for better reference. In addition, the two sections in which the 2D analytic signal was applied are indicated.

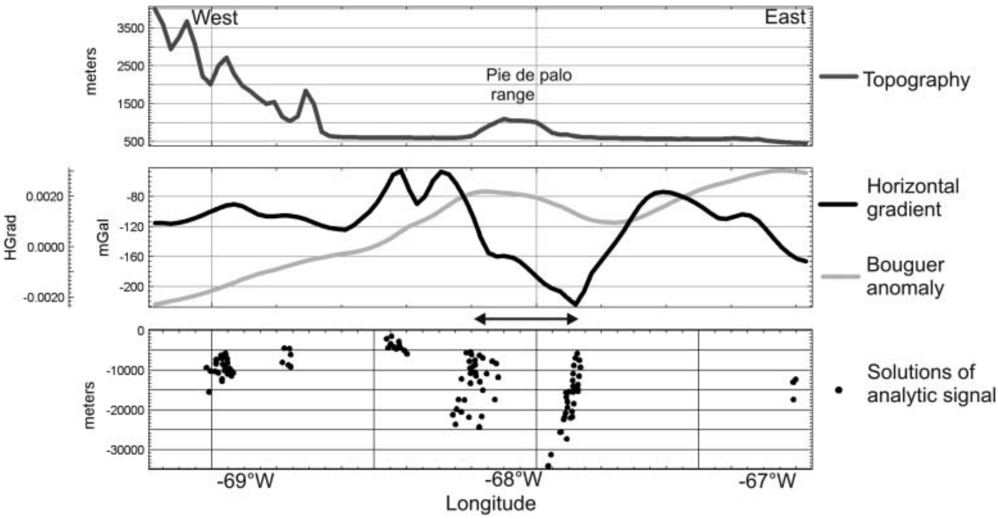

Figure 9. The 2D analytic signal corresponding to E-W trending section AS1. The topographic elevation is plotted above in a dotted line; the gravimetric profile in a grey line, and the horizontal gradient of the Bouguer anomaly in a black line. Below the solutions that justify the Bouguer anomaly (grey) and the horizontal gradient (black) are shown.

were: window width, 30 km, with the wavelength of the most important anomalies in the area, and investigation depth, 35 km.

From the analysis of Figures 9 and 10, the following can be observed: in the E-W trending section AS1, the solutions corresponding to contacts clearly indicate the edges of the anomalous structure, measured by an approximate extension equivalent to the width of the Pie de Palo range in the surface, about 55 km. In section AS2, which is oriented N-S, the contact solutions indicate that this structure extends about 62 km to the south.

In both sections, the solutions are situated mainly between 5 and 20 km in depth, whose values coincide with the depths found by the Euler deconvolution.

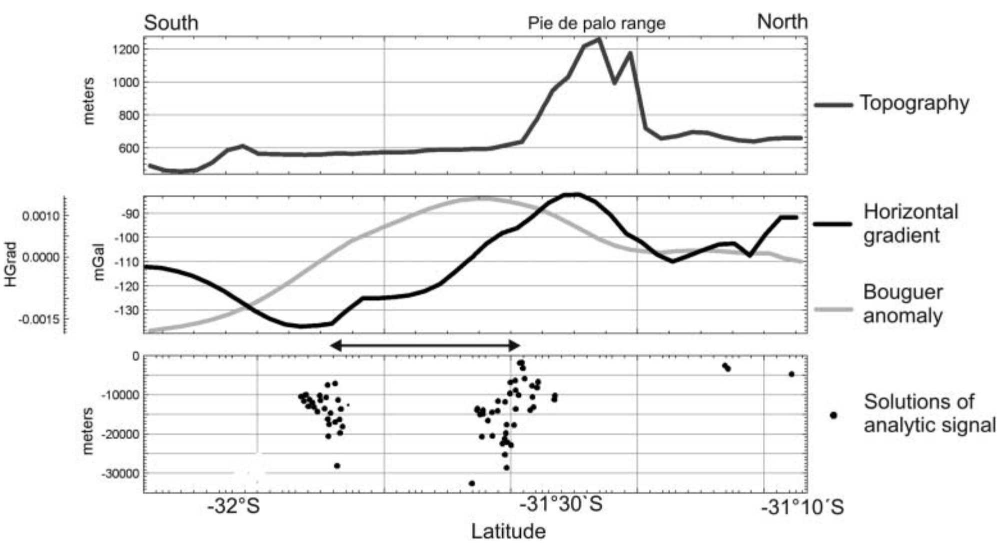

Figure 10. The 2D analytic signal corresponding to N-S trending section AS2. The topographic elevation is plotted above in a dotted line; the gravimetric profile in a grey line, and the horizontal gradient of the Bouguer anomaly in a black line. Below the solutions that justify the Bouguer anomaly (grey) and the horizontal gradient (black) are shown.

5. Cortical model

Using existing geological and geophysical information, a crust model inspired by Ramos et al. (2002) was prepared. The authors propose the Pie de Palo region was formed by a crystalline basement block, whereby the gravimetric effect adjusts to the Bouguer residual anomaly curve obtained from section A-A' in Figure 3. The densities used in the model were obtained from the conversion of the interval velocities determined by Snyder (1988) by means of Brocher (2005). In Figure 11 (upper part), the Bouguer residual anomaly curves are shown, as well as the curve calculated from the gravimetric effects of the cortical model shown in the lower part of the figure.

6. Results and discussion

In the South-Southwest extreme of the Pie de Palo range, researchers observed that the positive gravimetric anomaly determined in this range continues to the South. Based on the migration of the San Juan River course, it is possible to infer the presence of a rising, shallow structure, probably related to the basement of the Pampean Ranges. This inferred structure coincides with the basement height indicated by the Euler deconvolution and analytic signal methods. The Pie de Palo range is the most seismically active mountain block of the Pampean ranges; it was the site of the last powerful earthquake that occurred in the area (1977). The results obtained indicate that this region continues to be one of the major potentially seismogenic areas, concluding that the geological danger is highly significant.

The results of the Euler deconvolution and 3D analytic signal amplitude indicate the presence of an anomalous body in the southern extreme of the Pie de Palo range with dimensions similar to those of this range. The two-dimensional (2D) analytic signal was analysed in two sections, each trending perpendicular to the other. In the W-E oriented section, the solutions are between 5 and 25 km deep, and limit the horizontal extension of the anomalous body to 55 km. In the N-S trending section, the solutions are from 5 to 20 km deep, so that the extension of this body to the South is 62 km.

The probability of seismic hazard analysis results indicate that the area between the Precordillera and the Pie de Palo range is the region of the highest seismic hazard. This includes the city of San Juan and its neighbouring zones. The PGA values are of 242, 393, and 543 gal for a return period of 72, 475, and 2475 years, respectively. This zone agrees with a southwest–northeast region, where its

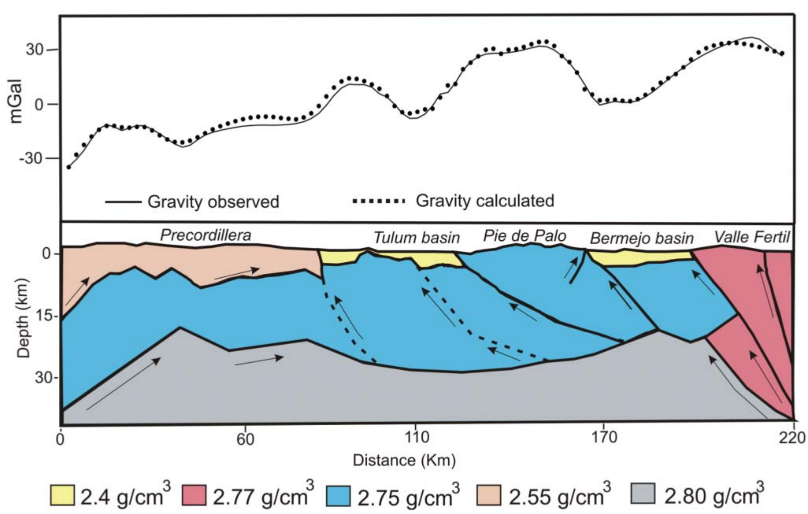

Figure 11. Crustal model following Ramos et al. (2002), the gravimetric effect of which adjusts the Bouguer residual anomaly curve across the Pie de Palo range.

seismo-tectonic features favour a higher release of seismic energy probably related to the subducted oceanic Juan Fernández ridge directly beneath San Juan.

Finally, by considering the geological and geophysical evidence, a section of the upper crust was modelled through the anomalous region, which justifies the Bouguer residual anomaly. The result thereof indicated that the Pie de Palo ranges seem to respond to a model which suggests this range would be uplifting due to a regional basement fold, probably related to the subducted oceanic Juan Fernández ridge in the direction of the Pie de Palo range.

7. Conclusions

The Pie de Palo range, located in west of the Pampean Ranges in Argentina, present one of the major cortical and lithospheric regions with seismic activity in the Argentina. The results indicate that this region is currently rising possibly due to the subduction effect of Juan Fernández ridge, making it an area of extremely dangerous seismogenic potential and major geological risk. The seismic risk studies indicate that the highest maximum acceleration values (PGA) are 242, 393, and 543 gal for return periods of 72, 475, and 2475 years, respectively, for this region of study.

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