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Research Paper

Preandean geological configuration of the eastern North Patagonian Massif, Argentina

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ABSTRACT

The Preandean geological configuration of the eastern North Patagonian Massif is established through the use of geological and geophysical analysis. The positive gravity anomalies located near the Atlantic coast are due to 535 and 540 Ma old rocks belonging to the Pampean Orogeny (Precambrian–middle Cambrian), which are widely recognized in central and northern Argentina. The Famatinian Cycle (Ordovician–Devonian) is represented by a Silurian–Devonian marine basin equivalent to those of eastern-central Argentina and South Africa, and which was deformed at the end of the Devonian by an ~E–W to WNW–ESE compressional event, part of the Famatinian Orogeny. Containing strong gravity gradients, the NW–SE belt is coincident with fault zones which were originated during the Gondwanide Orogeny. This event also produced NW–SE overthrusting of the Silurian–Devonian sequences and strike-slip faults that displaced blocks in the same direction. This deformation event belongs to the Gondwanide Orogeny that includes movements related to a counterclockwise rotation of blocks in northern Patagonia. The strong negative anomalies located in the western part of the area stem from the presence of rocks of the Jurassic Cañadón Asfalto basin interbedded in the Marifil Complex. These volcaniclastic sequences show mild deformation of accommodation zones in a pre-Jurassic paleorelief.

1. Introduction

The southern regions of the Buenos Aires, La Pampa and Mendoza provinces, part of the so-called central Argentina, show minor physiographic, geological and structural differences with respect to the Patagonian Rio Negro and Neuquén provinces. In between lies, according to Llambías (2008), a 'hinge zone' that shows mixed geological features of both regions. In this particular area, N–S Paleozoic geological structures, typical of central parts of Argentina, turn to an NW–SE direction and seem to be truncated at the latitude of the Rio Colorado–Río Negro against a nearly E–W-oriented structure (Fig. 1).

Due to poor outcrops of Paleozoic rocks, and abundant Mesozoic and Cenozoic cover, absence of detailed geological mapping and the truncation of the structures, several authors have visualized Patagonia as a terrane exotic to South America.

Earlier, Keidel (1925), Windhausen (1931) and later Dalmayrac et al. (1980) outlined the differing geological characteristics of Patagonia with respect to the rest of Argentina. Ramos (1984, 1986) explained these differences by proposing that Patagonia represents an allochthonous terrane, separated from Gondwana–South America by an oceanic basin before the Carboniferous. Later, Patagonia approached Gondwana–South America, initiating N–S directed subduction with a final stage of collision between both continental blocks occurring during the Permian. Paleomagnetic studies carried out by Rapalini (1998, 2005), on the Silurian–Devonian rocks of the

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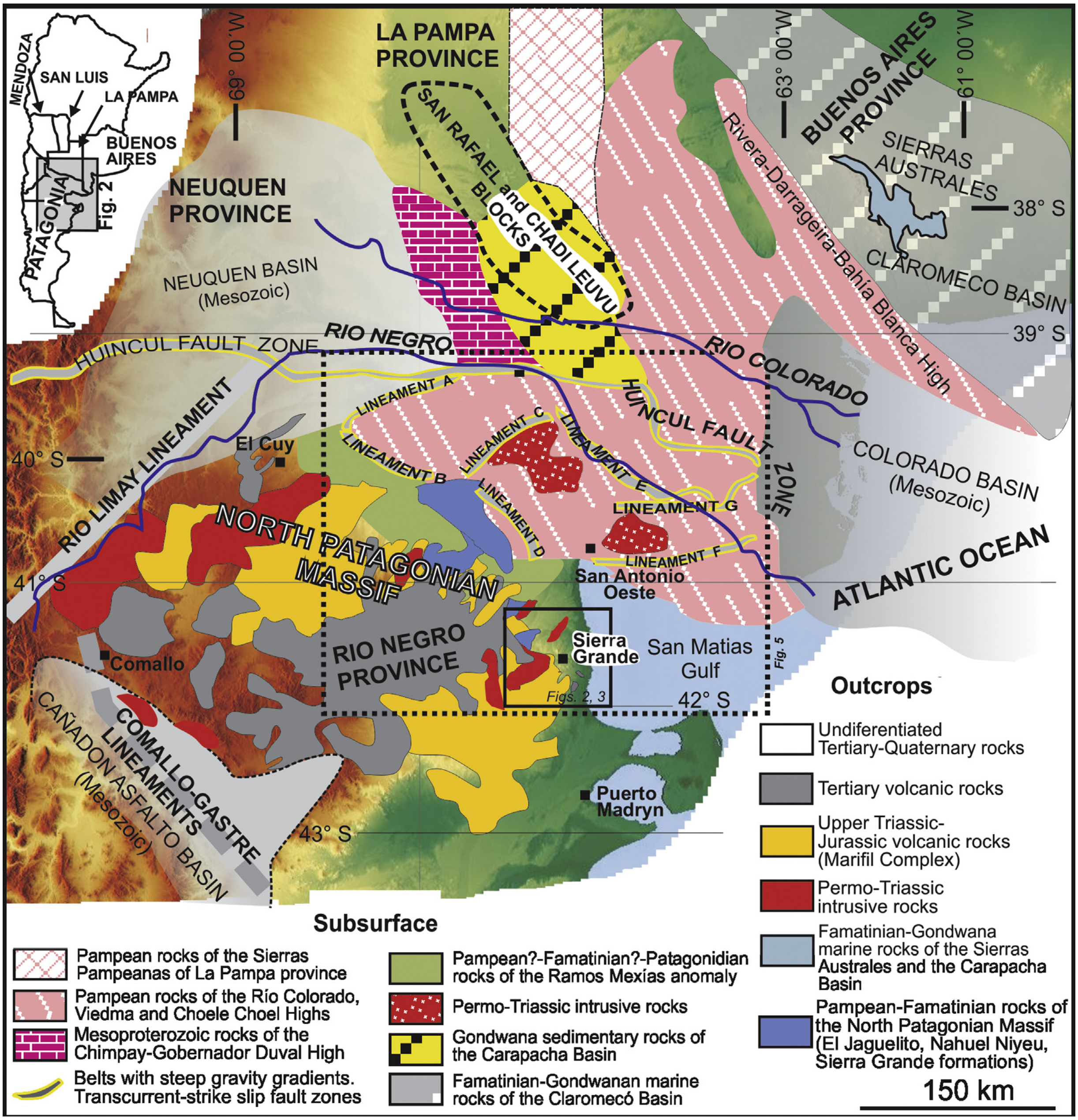

Figure 1. Map showing the southern parts of the Buenos Aires, La Pampa and Mendoza provinces, located in central Argentina. The region with N–S-oriented geological structures is mostly located in the north and central parts of La Pampa province. These structures turn NW–SE when approaching the Río Colorado, where they are truncated by a nearly E–W-oriented structure at the latitude of the Río Colorado–Río Negro. The change to an NW–SE orientation can be observed also in the middle part of the Buenos Aires province and in the southern part of La Pampa province. The Pampean basement appears both in northern Patagonia and in central Argentina.

North Patagonian Massif indicate that Patagonia has not undergone major latitudinal displacement relative to South America since the Devonian. Ramos (2008), López de Luchi et al. (2008) and Rapalini et al. (2010) have all proposed models that combine the autochthony of Patagonia, the limited separation of Patagonia with respect to Gondwana by a Silurian–Devonian marine basin, and finally a Carboniferous–Permian approach and deformation that originated the closure of this basin.

However, several doubts remain that preclude considering this hypothesis as accepted. As yet no evidence has been found of rocks exhibiting oceanic crustal affinities, or of Carboniferous basins located either in the suture zone or in the northern part of Patagonia. The pattern of gravity and magnetic anomalies (Kostadinoff and Labudía, 1991; Kostadinoff et al., 2005; Gregori et al., 2008) north, south and directly over the proposed boundary are incompatible with the existence of a belt of high-density-oceanic crustal rocks below the Quaternary cover. There is however proof of the continuity of the Pampean (Neoproterozoic–middle Cambrian) and Famatinian (Upper Cambrian–Devonian) orogens southward of the supposed boundary (González et al., 2002; Rapela and Pankhurst, 2002; Kostadinoff et al., 2005; Gregori et al., 2008; Martínez Dopico et al., 2011).

Geological and geophysical studies of northern Patagonia by Gregori et al. (2008) have shown the existence of several areas characterized by positive and negative gravity anomalies. The former occur north and south of the supposed boundary and are interpreted as continental crust of Pampean affinity (late Neoproterozoic–middle Cambrian: see Fig. 1). The negative ones are assigned to rocks belonging to the Famatinian or Gondwana Orogenies.

One interesting result of the Gregori et al. (2008) study is the presence of belts characterized by steep gravity gradients, which are nearly coincident with shear zones and mylonitic belts active during the Gondwana era (Fig. 1).

The most prominent of these is the E–W-trending Huincul Fault zone that shows dextral movement along strike as a result of the E–W translation and counterclockwise rotation of a large crustal block with a continental crust similar to other blocks of the North Patagonia Massif. The indentation of such a block resulted in the tectonic escape of surrounding blocks, each with a different trajectory, and this may explain the diversity of stress directions occurring during the Gondwanide Orogeny (Gregori et al., 2008).

As indicated above, the Famatinian Orogen (middle Cambrian–Devonian) appears north and south of the escape tectonic zone, and is represented by magmatic rocks and sedimentary basins. The Claromecó Basin (Fig. 1) is located north of the escape tectonic zone, while the Sierra Grande basin is located in the eastern and northeastern parts of the North Patagonia Massif. If Patagonia was indeed an allochthonous terrane, then the Claromecó and Sierra Grande basins were formed separately on different continental crusts.

However, according to Gregori et al. (2008), the Claromecó and Sierra Grande basins were formed on the same continental crust, and are possibly of Pampean or older origin. Based on this hypothesis, their actual distribution and disconnection in two separated depocenters north and south of the Huincul Fault zone, may be due in part to the block tectonic escape which occurred during the Gondwana Orogeny.

This paper focuses on the analysis of the three-dimensional architecture and development of the Silurian–Devonian Sierra Grande basin, in order to correlate it with the basin of the same age located north of the hinge zone. We also aim to better recognize the nature and tectonic configuration of the Pampean and Gondwana blocks, as well as the design of contemporaneous lineaments and faults and their significance in the overall geological configuration of northern Patagonia.

2. Geological background

Several papers examined the geology and structure of the eastern North Patagonia Massif and the Sierra Grande Formation (Valvano, 1954; de Alba, 1960, 1964; Navarro, 1960; Müller, 1965; Núñez et al., 1975; Gelós, 1977; Cortés, 1981; Zanettini, 1981, 1993; Cortés et al., 1984; Busteros et al., 1998; von Gosen, 2002, 2003). Gregori et al. (2008) contained a more detailed discussion of this topic.

The oldest rocks in the area (Fig. 1) are low-grade metamorphic rocks of the El Jagüelito and Nahuel Niyeu formations and Mina Gonzalito Complex. The first unit has a youngest detrital zircon age peak at ~535 Ma, whereas the second is slightly younger at ~515 Ma (Ramos, 1975; Giacosa and Paredes, 2001; Pankhurst et al., 2006). Fossil remains analogous to those of the Pampean rocks of central Argentina and common to other areas of Gondwana supercontinent occur in the El Jagüelito Formation (González et al., 2002, 2011). The Mina Gonzalito Complex itself has its main provenance at 535–540 Ma.

These ages indicate that they are part of the Pampean Orogeny (late Proterozoic–middle Cambrian) widely distributed across north-central Argentina (Sierras Pampeanas de San Luis and Córdoba) (Aceñolaza and Toselli, 2009; Aceñolaza et al., 2010). All ages refer to the 2009 International Stratigraphy chart of the International Commission on Stratigraphy.

The El Jagüelito Formation is intruded by bodies of the Punta Sierra Complex (Núñez et al., 1975; Varela et al., 1997, 1998; Pankhurst et al., 2006; González et al., 2008), including the Arroyo Salado Granodiorite (476 ± 4 Ma, 475 ± 6 Ma, U/Pb zircon and 467 ± 16 Ma, Rb/Sr), Hiparsa Granite (357 ± 57 Ma, Rb/Sr and 476 ± 6 Ma, zircon) and Punta Sierra Granite (483 ± 22 Ma, Rb/Sr).

These units are unconformably covered by the marine Silurian–Devonian Sierra Grande Formation (Fig. 1). This unit is composed mainly of quartzites with interbedded levels of up to 46% of magnetite, reaching 1500 m thick. These values were recorded in boreholes near the southern and eastern ore deposits, south of Sierra Grande locality. Fossil remains indicate a Silurian to Devonian age, and are equivalent to those found in the sedimentary sequences of Sierras Australes in the Claromecó Basin (Fig. 1). The Sierra Grande and Claromecó basins can also be correlated with the Table Mountain, Bokkeveld and Witteberg groups of the Cape Basin in South Africa (Tankard et al., 2009), as well as with the Paleozoic sequences of the Malvinas (Falkland) Islands and Antarctica (Keidel, 1916, 1925; Buggisch, 1987).

Field observations in the studied area indicate that the Sierra Grande Formation underwent east-directed overthrusting due to oblique strike-slip faulting.

A second Silurian–Devonian basin is located 300 km west of the studied area, and named the Calcatapul Basin. The configuration and characteristics of the Calcatapul Basin are outside the scope of this study, although it should be noted that the similarities with the Sierra Grande Basin are remarkable Proserpio (1978).

The units described above in the Sierra Grande area were intruded by late Paleozoic granites (Stipanicic et al., 1968) including the Peñas Blancas, La Laguna, La Verde Granites. These rocks are compositionally S-type granites with lower density than the Pampean rocks.

The Triassic and Jurassic periods are represented by a thick sequence of volcanic breccias, tuff, ignimbrites and subvolcanic acidic bodies of the Marifil Complex (Fig. 1). The lower section of the Marifil Complex, the Puesto Piris Formation (Núñez et al., 1975), includes conglomerate, sandstone, limestone, and tuff of continental rift origin. These units represent most of the outcrops of the area, making correlation between the Paleozoic units difficult.

The outcrops of the Marifil Complex are mostly composed of epiclastic facies, with a few areas (Cerro Cancha) represented by domes, dikes and low-degree ignimbrites.

The Jurassic age of the Marifil Complex was determined by means of fossil flora remains (*Otozamites* sp., *Dictyozamites* sp. and *Ptilophyllum* sp.) and K/Ar dating, which provided ages of between 153 ± 10 and 192 Ma (Núñez et al., 1975; Lizuaín, 1983) i.e. spanning the Sinemurian and Kimmeridgian. South of Sierra Grande, Cortés (1981) obtained a K/Ar age of 189 ± 5 Ma, while Ar-Ar dating carried out by Féraud et al. (1999) indicated an age from 187.4 to 175.1 Ma (Pliensbachian to Toarcian).

In the Arroyo Perdido area, 150 km southwestwards, volcanic and sedimentary units have been correlated with the Marifil Complex.

The Tramaleo Formation, composed of fluidal rhyolites and minor andesites, has a K/Ar age of 158 ± 5 Ma (Pesce, 1979), whereas the andesites and minor rhyolite lava flows of the Los Mártires Formation (Nakayama, 1975) have been assigned K/Ar ages of 176 ± 10 and 172 ± 10 Ma (Pesce, 1979). The Mancucci Formation is composed of gray basalt with a K/Ar age of 156 ± 10 Ma (Pesce, 1979). The ages of all these units fall within the Oxfordian–Toarcian and can therefore be correlated with the Marifil Complex. A westwards diminution in age of the volcanic cycle was also recognized by Féraud et al. (1999) in central and southern Patagonia. There, the Santa Anita Formation is constituted by conglomerate, sandstone and limestone of fluvial and lacustrine environments, and has been correlated with the Cañadón Asfalto Formation that outcrops in the central part of the Chubut province.

This unit also contains lacustrine, fluvio-deltaic and marginal lacustrine carbonate sediments, with volcanoclastic and volcanic intercalations.

A Bathonian–Kimmeridgian origin (∼167.7 to 150.8 ± 4.0 Ma) was reported by Cortiñas (1996), which is partly coeval with the volcanic cycle of the eastern North Patagonian Massif.

Finally, thin Oligocene marine sequences cover a flat paleorelief on the top of the Jurassic–Cretaceous rocks, while the Pleistocene and Holocene are represented by the Tehuelche Formation.

3. Geophysics

Few geophysical surveys have been carried out in the North Patagonian Massif. Kostadinoff and Gelós (1994), Kostadinoff et al. (2005), and Gregori et al. (2008) have described several gravity and magnetic anomalies, including the Huincul Fault zone and the Choele Choel High, north of the present study area. During this study, magnetic data were collected using a G-856 proton precession magnetometer. The daily geomagnetic variation and the International Geomagnetic Reference Field-the tenth generation (Macmillan and Maus, 2005) values were used to calculate the magnetic anomalies.

The regional values of the terrestrial gravimetric field were obtained using a Worden gravimeter. Both gravity and magnetic measurements were carried out on benchmarks provided by the Instituto Geográfico Militar and Servicio Geológico Argentino, whose elevation precision varies between 1 and 30 cm.

A total of 272 gravity and magnetic stations were established, with the geographic positions of the stations determined using GPS.

Locations and distribution of the new gravity and magnetic measurements are shown in Fig. 2. Bouguer gravity anomalies were calculated following Blakely (1997), whereas a vertical gradient of 0.3086 mGal/m and a density of 2.67 g/cm^3 for the flat slab were used (Hinze, 2003). Topographic corrections were not applied because the area is characterized by a nearly horizontal plateau.

Residual anomalies were obtained after subtracting the regional gravity response (which is mostly attributed to the isostatic effects associated with the slow postglacial uplift of Patagonia) from the

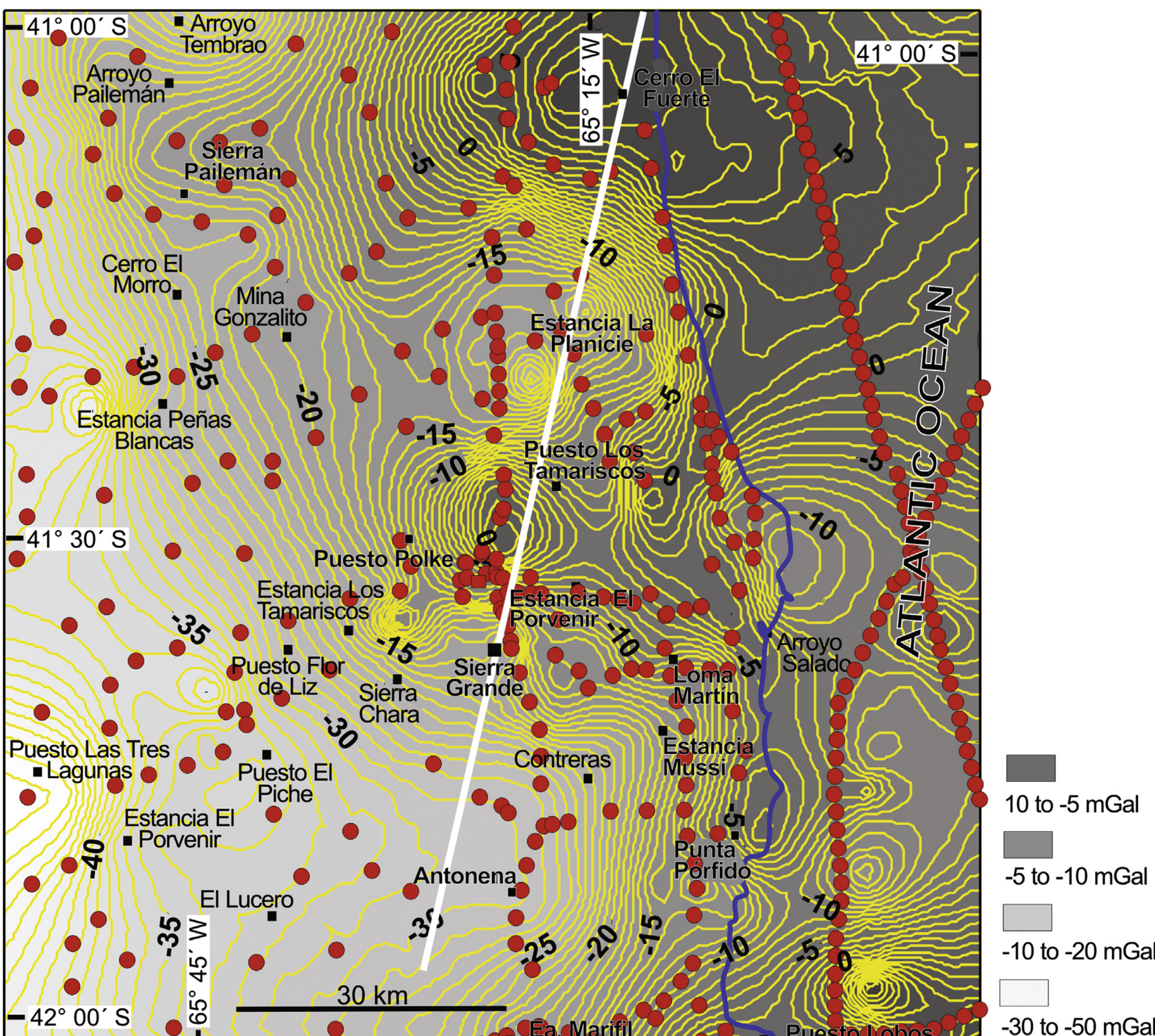

Figure 2. Residual anomaly map showing the distribution of positive and negative anomalies, using 1 mGal isoline spacing. The former are mostly located near the Atlantic coast, with the latter in the western part of the study area. Location and distribution of the gravity and magnetic stations are displayed. Trace of profiles in Fig. 4 is indicated.

Bouguer gravity anomaly map. The resulting residual anomaly map (Fig. 2) allowed us to compare known geology with specific gravity signatures.

Density and magnetic susceptibility determinations (see Gregori et al., 2008) were carried out at the Universidad Nacional del Sur on representative samples from the surveyed area (Table 1). Magnetic susceptibility was measured also in situ, while gravity gradients were calculated using Surfer 8™. The magnetometric measurements are represented in the map shown in Fig. 3. For corrections and procedures see also Gregori et al. (2008).

In order to enhance the boundaries or faults between geological bodies filtering procedures based on the Werner deconvolution method as well as, analytical signal and Euler deconvolution filters were used.

4. Results

Three positive residual gravity anomalies, several negatives, two belts with steep gravity gradients and an NW–SE elongated region with a strongly negative anomaly were identified in the area between 41°00′S–42°00′S and 65°53′W – the Atlantic coast (Fig. 2).

Magnetic maps of total intensity anomalies show an area characterized by positive values (0–350 nT) east of Mina Gonzalito, extending to the sea. The west and northwest of the study area present anomaly values of between −50 and 50 nT, following an N–S orientation (Fig. 3). A negative anomaly dominates the southwest area, reaching −300 nT near Puesto El Lucero.

4.1. Positive gravity anomalies

4.1.1. Cerro El Fuerte High

A positive residual gravity anomaly (6–8 mGal) is located in the Cerro El Fuerte area (Fig. 2). The anomaly extends N–S for more than 40 km, and 50 km in an E–W direction, reaching Arroyo Pailemán and Mina Gonzalito, an area characterized by anomalies of up to −20 mGal.

The Cerro El Fuerte anomaly extends more than 50 km into the marine platform in an easterly direction. Measurements on the marine platform were done by the Instituto Argentino de Oceanografía using the Robert Conrad Oceanography Ship of the Lamont Doherty Geological Observatory. Magnetic anomalies in this area range from 0 to 50 nT, displaying a poorly defined N–S orientation (Fig. 3).

4.1.2. Arroyo Salado High

Several positive residual gravity anomalies (between 3 and −8 mGal, Figs. 2 and 4) appear between Puesto Los Tamariscos, Estancia El Porvenir, Puesto Polke and the Atlantic coast, extending for more than 40 km in an NW–SE direction. The anomaly bends to the SE, following the path of Arroyo Salado, and then to the south along the coast. To the north, this high connects with that of the Cerro El Fuerte. The S and SW borders of the Arroyo Salado anomaly are sinuous, phasing to small negative anomalies (−22 mGal), with the eastern border defined by a −10 mGal anomaly line.

In this area magnetic anomalies vary between 0 and 250 nT, and follow an NE–SW orientation. A maximum is reached between Loma Martín and Arroyo Salado (Fig. 3).

4.1.3. Punta Pórfido High

This small gravity anomaly represents the southern tip of the Arroyo Salado High, from which it is separated by a narrow negative area (−9, −10 mGal). Characterized by values ranging from −8 to +3 mGal (Fig. 2), the Punta Pórfido High disappears southward as it passes into a region of negative gravity anomalies.

Magnetic anomalies range between 0 and −100 nT and form part of the major anomaly that surrounds the positive anomalies located near Sierra Grande and Loma Martín (Fig. 3).

4.2. Negative anomalies

Three negative gravity anomalies, ranging from −31 to −10 mGal, are located to the west of the positive ones discussed in the previous section.

4.2.1. Estancia La Planicie anomaly

Situated to the SW of the Cerro El Fuerte High and north of the Arroyo Salado High, this residual gravity anomaly extends in a WSW–ENE direction for 30 km, with values ranging between −10 and −24 mGal (Fig. 2). Gravity gradients on the NE border of the Estancia La Planicie anomaly are high, between 1.47 and 2.2 mGal/km. These values decrease to 0.63 mGal/km on its eastern border. A strong 5 km long magnetic anomaly (100 nT) is located 10 km southwest of the gravity minimum (Fig. 3).

4.2.2. Sierra Grande anomaly

The Sierra Grande anomaly extends for 12 km in an SW–NE direction and 20 km in an NW–SE direction (Fig. 2). Values of around −22 mGal gradually decrease southwestwards, phasing into the belt of strong negative anomalies. The northern border follows a sinuous W–E orientation and presents a steep gravity gradient (2.21–2.49 mGal/km). This anomaly is coincident with the maximum magnetic anomaly (350 nT), its 10 km diameter centered on the town of Sierra Grande (Fig. 3).

4.2.3. Antonena anomaly

Located 20 km south of the town of Sierra Grande, the Antonena anomaly is almost equal in length and width, with dimensions of 20 and 21 km respectively. Gravity values range from −16 to −30 mGal (Fig. 4). Unlike the Sierra Grande and Estancia La Planicie anomalies, its borders are characterized by very low gradients (0.85–1.6 mGal/km). In this area magnetic anomalies show values of around 0 on the northern and eastern borders, decreasing to −100 nT in the west (Fig. 3).

4.3. Belts with strong gravity gradients

A 100 km long, NNW–SSE-oriented belt of strong gravity gradients appears between Arroyo Tembrao (Río Negro province) and Punta Pórfido, near the border of the Chubut province (Fig. 2).

This anomaly is located between the −15 and −28 mGal anomaly lines. The northern segment, NNW–SSE in strike, extends between Arroyo Tembrao and Sierra Chara. Gravity

Table 1
Densities and magnetic susceptibilities.

Age	Unit (Formation)	Lithology	Magnetic susceptibility (SI)	Density (g/cm^3)
Tertiary	Somuncurá	Basalt	0.001240	2.53
Tertiary	Somuncurá	Basalt	0.007000	2.62
Tertiary	Somuncurá	Basalt	0.006500	2.48
Jurassic	Marifil	Ignimbrite	0.000120	2.33
Permian	Laguna Medina	Granite	0.000350	2.55
Silurian–Devonian	Sa Grande	Quartzite	0	2.57
Silurian–Devonian	Sa Grande	Quartzite	0	2.55
Ordovician	Hiparsa	Granite	0.000090	2.53
Cambrian	Nahuel Niyeu	Phyllite	0.000130	2.65
Cambrian	Nahuel Niyeu	Phyllite	0.000280	2.70
Cambrian	Jagüelito	Phyllite	0.000190	2.56

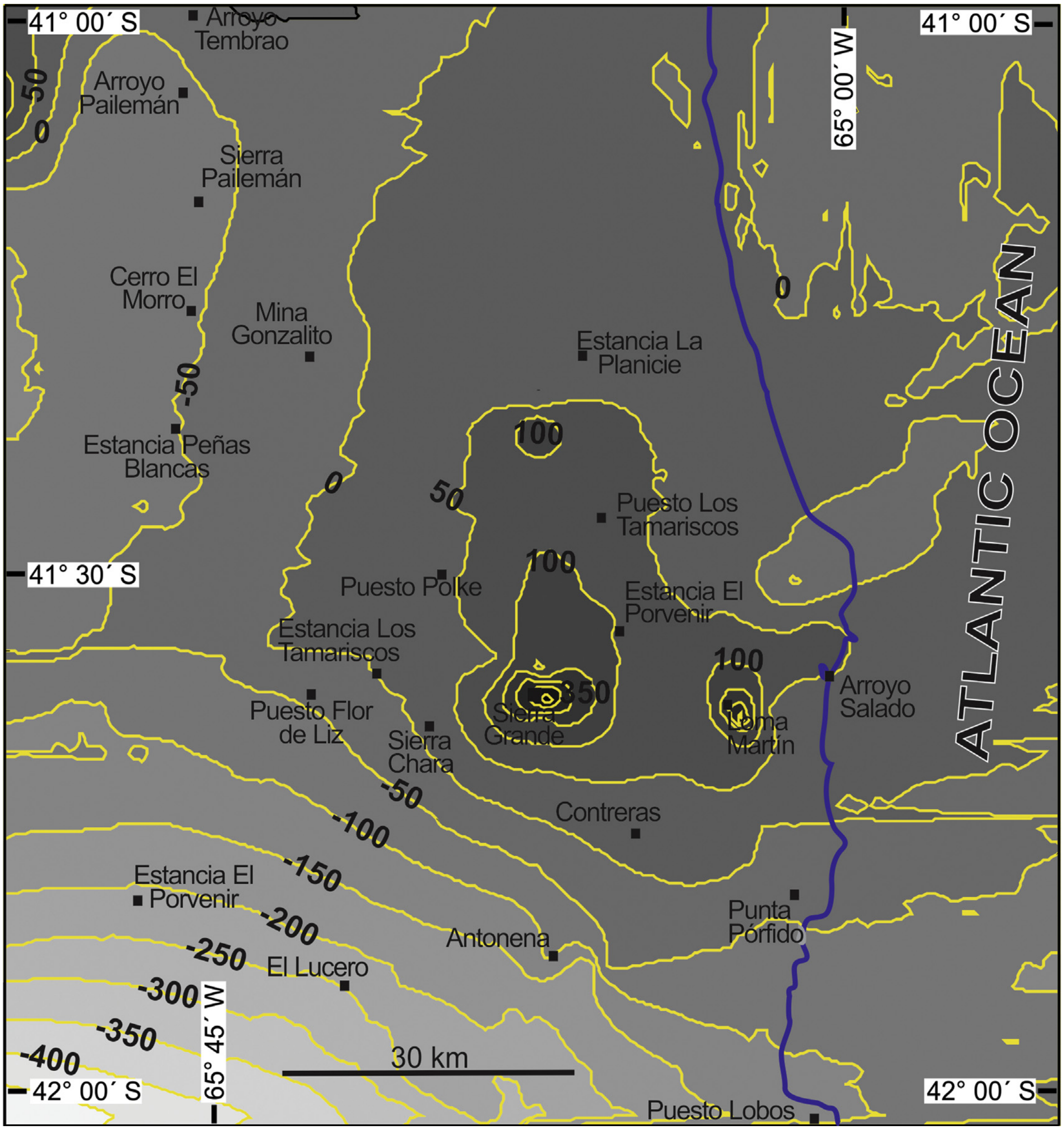

Figure 3. Magnetic anomaly distribution map, using 10 nT isoline spacing. No obvious correlation with Bouguer anomalies was observed.

gradients are nearly constant in this part of the belt, with an average of 1.2 mGal/km. All gravity gradient vectors point W or WSW, with a few exceptions. Near Cerro El Morro the belt is cut and displaced by an NE–SW lineation (Fig. 2), possibly due to the Mina Gonzalito block.

The southern segment, between Sierra Chara and Punta Pórfido, strikes NW–SE. A change in direction occurs near the western extension of the Arroyo Salado High, with gravity gradient vectors pointing in the WSW direction from a maximum of 1.64 mGal/km west of Estancia Los Tamariscos to a minimum of 0.62 mGal/km east of Contreras.

Finally, a 30 km long NE–SW-oriented belt of strong gravity gradients occurs from Estancia Mussi to Estancia Marifil. Here gravity gradient vectors point WNW or NW, with values of between 1.39 and 0.99 mGal/km.

4.4. Strong negative gravity anomalies

Strong negative gravity anomalies occur in the western part of the study area, ranging from −22 to −48 mGal (Fig. 2). Eastwards they pass transitionally to the belt of strong gravity gradients, while westwards they extend more than 80 km.

Here the gravity gradients are constant and relatively low, varying between 0.12 and 0.63 mGal/km. Most gravity gradient vectors point W, although a few are oriented north or east. These are related to the strongest subcircular negative gravity anomalies, located west of Estancia Peñas Blancas (−41 mGal), Puesto Flor de Lis (−40 mGal), near Puesto El Piche (−35 mGal) and in Puesto Las Tres Lagunas (−48 mGal).

Magnetic anomalies range between 0 on the eastern border and −400 nT in the southwest of the area. Two distinct regions can be differentiated (Fig. 3): a northern one located between Arroyo Tembrao and Arroyo Ventana and a southern one between this locality and the border with the Chubut province. The first shows N–S isolines with maximum values (0 nT) in the east and west of the area, while minimum values (−50 nT) are restricted to the center.

The area between Arroyo Ventana and the Chubut province border displays WNW–ESE anomalies, which vary between −50 and −450 nT (Fig. 3).

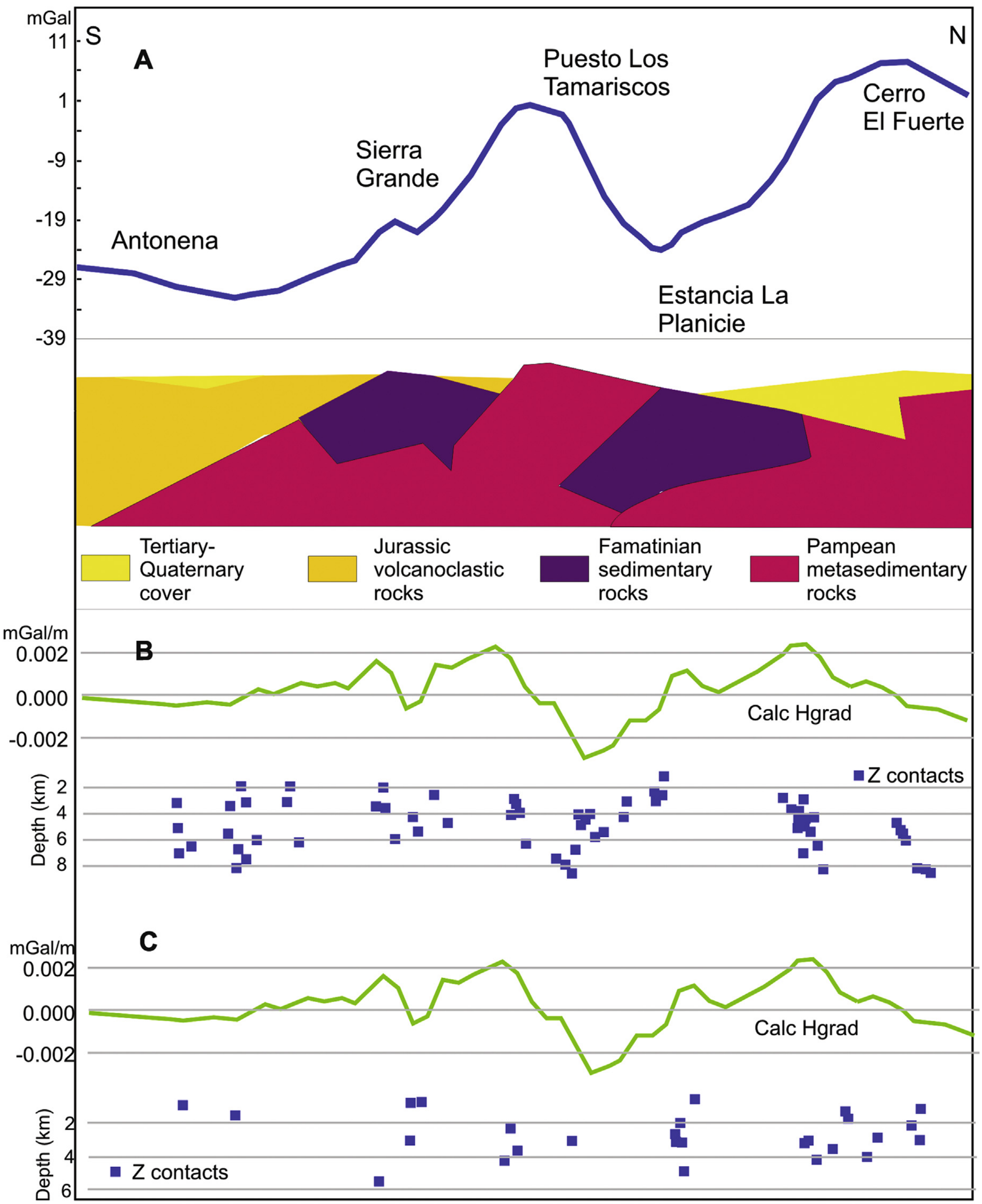

Figure 4. (A) N–S profile showing the residual Bouguer anomaly between Cerro El Fuerte and Antonena. Also a gravity modeled profile is displayed. The geological configuration at surface was obtained from data of outcrops, whereas the measured densities and the size of the rock bodies were used to compute a prismatic model (Heiland, 1951). (B) Analytical signal: the horizontal gradient of the residual Bouguer anomaly along the same profile as that of (A). Squares symbolize the solutions (contacts or faults). (C) Displays the estimated depths using the Euler deconvolution of the analytic signal.

5. Discussion

Unfortunately, no seismic surveys, but only a few boreholes drilled for iron surveying into the Sierra Grande Formation were available to provide information regarding the subsurface architecture of the region. As a result, information from outcrops and correlation with previously analyzed areas were employed. In addition to the residual Bouguer gravity anomaly and magnetic anomaly maps, Fig. 4 shows an N–S profile between Cerro El Fuerte and Antonena where several filtering processes were applied.

Fig. 4A displays the residual Bouguer anomaly values along the profile. Also a gravity modeled profile is displayed. The geological configuration at surface was obtained from the data of outcrops, whereas the measured densities and the size of the rock bodies were used to compute a prismatic model (Heiland, 1951). The results of the analytical signal (Nabighian, 1972) are shown in Fig. 4B. The horizontal gradient of the residual Bouguer anomaly along the same profile appears in the upper part. In the lower part the squares symbolize the solutions (contacts or faults) found. As shown, the solutions can be grouped into three defined clusters. The other three are less clear. The one located near Cerro El Fuerte possibly represents an E–W fault related to the horst structure represented by the El Fuerte High (see below). The cluster located north of Estancia La Planicie can be assigned to the border of the Estancia La Planicie negative anomaly.

South of Estancia La Planicie appears the most defined cluster, which possibly corresponds to the southern border of this negative anomaly. This border is also represented by a small cluster located immediately north of Loma Alfaro.

The last two clusters show a scattered population. That located north of Sierra Grande is nearly coincident with the southern border of the Arroyo Salado High as proposed in Fig. 5. The last cluster, which is the most scattered, is coincident with the proposed trace of the belt with strong gravity gradients as derived from the analysis of the residual Bouguer anomaly map (Fig. 5).

Fig. 4C displays the estimated depths using the Euler deconvolution of the analytic signals. As in Fig. 4B only in the northern part of the profile are defined clusters recognized. Those located near Cerro El Fuerte and Estancia La Planicie seem to be concordant with those of Fig. 4B.

5.1. Positive gravity anomalies and the Pampean basement in the eastern North Patagonian Massif

The Cerro El Fuerte and Arroyo Salado highs represent the southern extension of the Viedma and Choele Choel highs (1–15 mGal), as well as the Bajo de Valcheta anomaly (Gregori et al., 2008), located 40 km to the north (Figs. 5 and 6) where there are outcrops of Pampean rocks. The Arroyo Salado and Cerro El Fuerte highs are part of a larger positive gravity anomaly that extends offshore (Fig. 5).

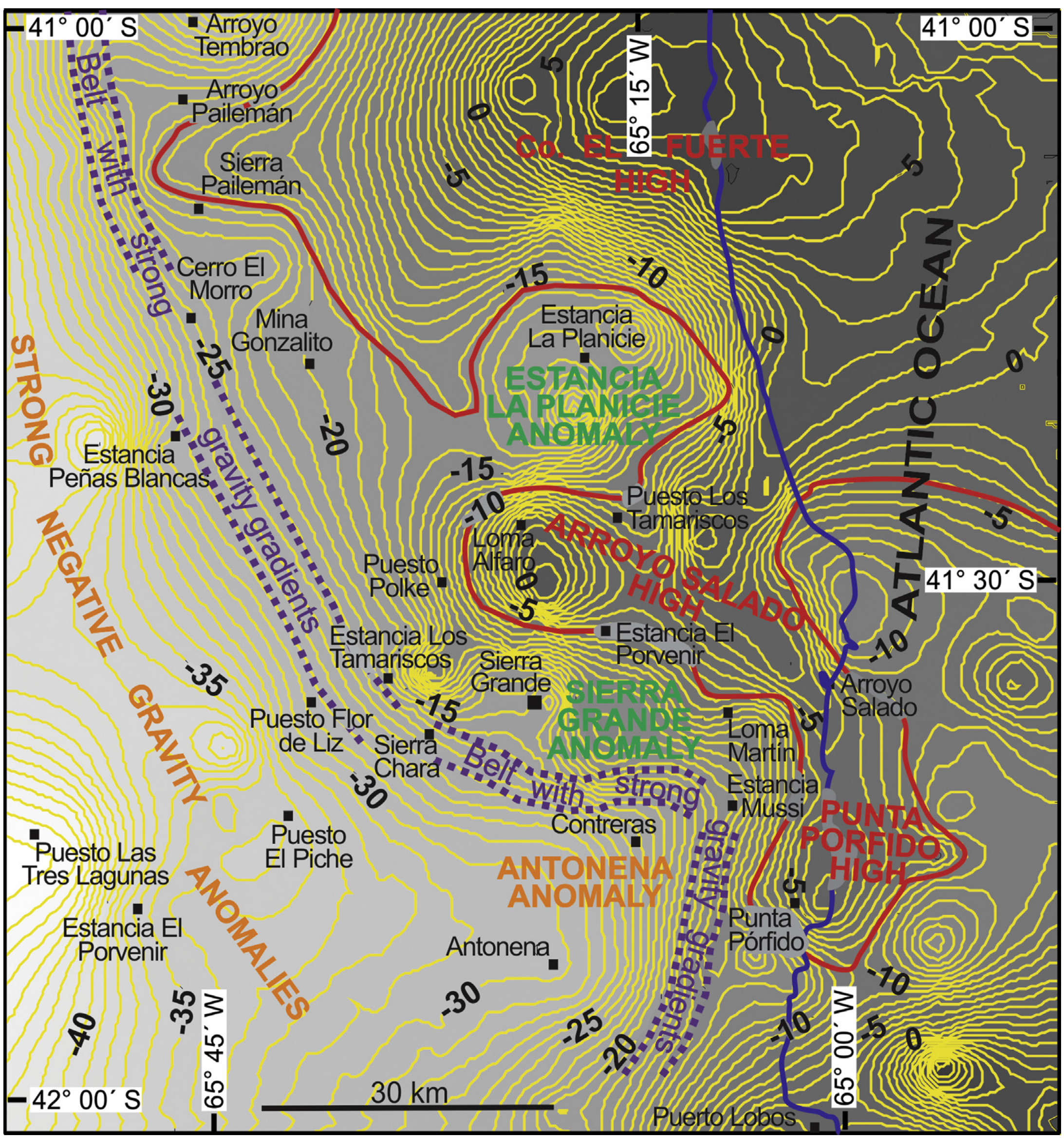

Figure 5. Residual anomaly map (1 mGal isoline spacing) showing the distribution of structural highs, negative anomalies, belts of strong gravity gradients and strong negative anomalies.

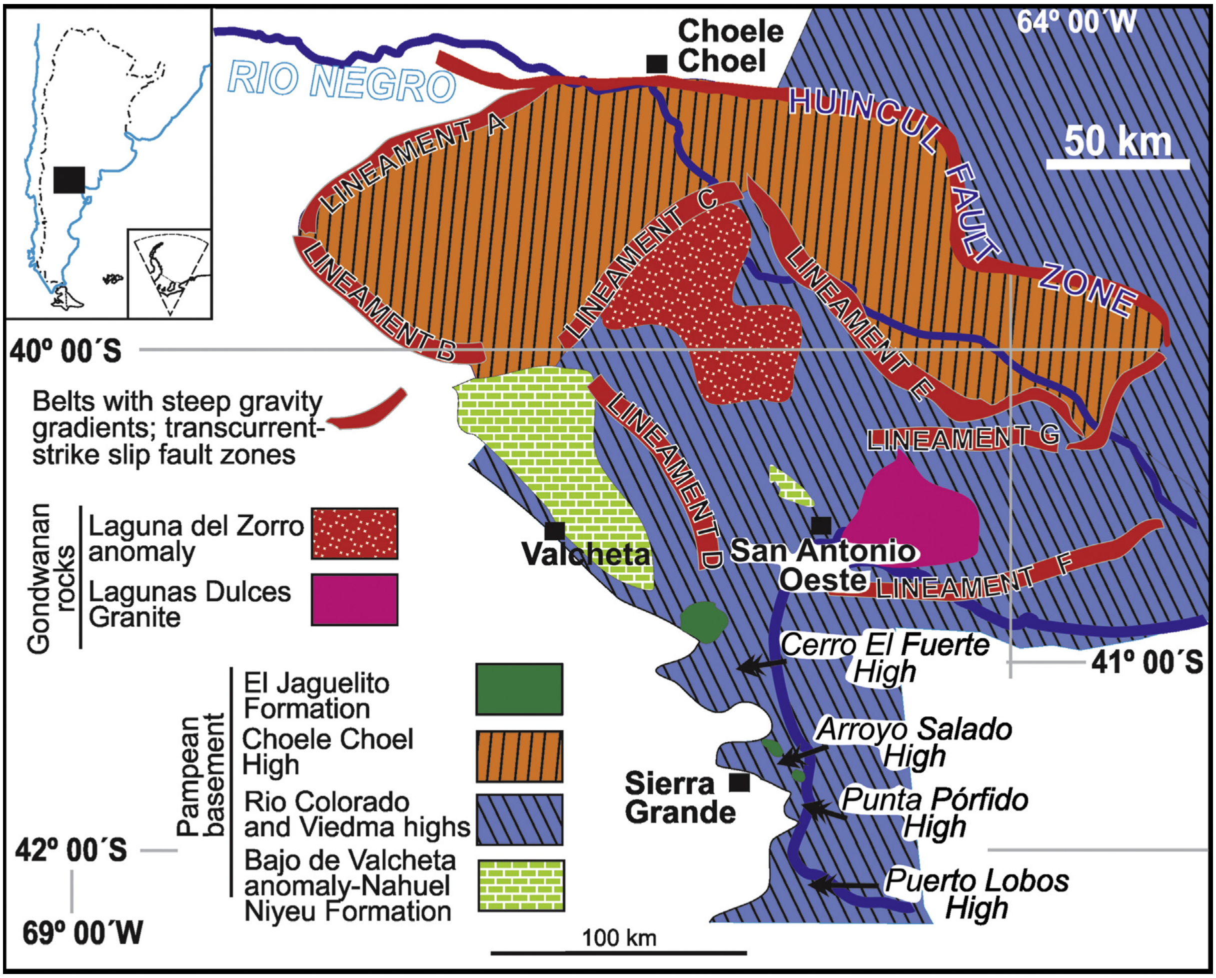

Figure 6. Regional map of northern Patagonia showing the distribution of basement highs assigned to units of the Pampean Orogeny. Belts of strong gravity gradients recognized by Gregori et al. (2008) are also displayed.

In contrast to the Cerro El Fuerte High, the Arroyo Salado High contains outcrops of the Pampean Mina Gonzalito Complex and the El Jagüelito Formation. In the same area there are also outcrops of the sedimentary rocks of the Famatinian (middle Cambrian–Upper Devonian) Sierra Grande Formation, which occur as folded and thrusted beds with a W–E orientation. In the area of Loma Alfaro the thickness of the Sierra Grande Formation measured in outcrops reaches 2100 m.

Near the Atlantic coast appear granitic rocks of the Famatinian Punta Sierra Complex. The rock density of this unit is very low and its contribution to the gravity anomalies is irrelevant. Since the magnitudes of these gravity anomalies are comparable with those of the Río Colorado and Viedma highs (Kostadinoff et al., 2005; Gregori et al., 2008), the Cerro El Fuerte and Arroyo Salado anomalies were therefore assigned to basement highs (Fig. 5), mainly composed of Pampean age rocks but with minor contributions from the marine Famatinian rocks.

In the Punta Pórfido High there are small outcrops of the El Jagüelito Formation and Punta Sierra Granite. Both are covered by rhyolites and ignimbrites of the Jurassic Marifil Complex. However, given a thickness of only 50 m and the low density of the rocks, its contribution to the gravity anomaly is null (Fig. 5).

As recognized by Gregori et al. (2008), the northeastern part of the North Patagonian Massif is characterized by positive anomalies that were assigned to the highs of the Pampean basement (Figs. 5 and 6).

Therefore the Cerro El Fuerte, Arroyo Salado and Punta Pórfido highs (Fig. 5) represent the southern prolongation of the Pampean Viedma and Choele Choel highs located to the north. As a result, the characteristic central Argentinean Pampean Orogeny can now be traced further south, up to the border with the Chubut province (42°S).

5.2. Negative anomalies and the Famatinian basins of the North Patagonian Massif

The Sierra Grande anomaly (Fig. 5) is coincident with major outcrops of the Sierra Grande Formation and small occurrences of the El Jagüelito Formation. The gravity anomaly (−22 mGal) is coincident with the 10 km diameter maximum magnetic anomaly (350 nT) that appears centered on the town of Sierra Grande. No outcrops of Paleozoic rocks are observed in the area of the Estancia La Planicie, although both the magnitude of the gravity anomaly and its design are comparable with that of the Sierra Grande anomaly. The strong magnetic anomaly (>100 nT) of Fig. 3 is similar to the Sierra Grande area. The high gravity gradients (2.2 mGal/km) on its NE border are assigned to a fault system with the same orientation. The thrusting of the Sierra Grande Formation, in which the thickness was augmented by deformation, may explain the observed gravity anomalies.

In northern Patagonia two Silurian–Devonian (Famatinian Orogeny) basins can be identified. The first (Sierra Grande Basin) includes the aforementioned marine sequences that extend for 600 km (Fig. 7) along the eastern and northern parts of the Rio Negro and Chubut provinces. Including several outcrops, the northern section of this basin is represented by the small negative gravity anomalies of the Sierra Grande and Estancia La Planicie (Figs. 5 and 7), these being nearly coincident with strong magnetic anomalies. The southern part of this basin includes the anomalies detected by Kostadinoff (1992), Kostadinoff and Gelós (1994) and Kostadinoff and Schillizzi (1996). Two are located north and south of the city of Puerto Madryn, with gravity anomaly levels of around −10 mGal and magnetic anomalies not comparable with those of the Sierra Grande area.

In the area between the Río Chubut and Camarones, three negative gravity anomalies (Estancia Pozo Hondo, Estancia Santa Magdalena and Estancia La Nueva) were described by Kostadinoff and Schillizzi (1996). These are coincident with strong magnetic anomalies and have therefore also been assigned to the Sierra Grande Formation.

The eastern border of the Sierra Grande Basin was thought to be located on the actual marine platform, in a line extending south from Salinas del Gualicho to Península Valdez. Silurian–Devonian sequences were drilled here by the PV-X1 borehole (Marinelli and Franzin, 1996). However, the Tayra x-1 borehole, located 350 km offshore, cut a Paleozoic sequence typical of the Sierra Grande Formation (Marinelli and Franzin, 1996), putting in doubt the location of the eastern border. Ewing et al. (1963) suggested that rocks exhibiting a similar seismic response to the Silurian–Devonian sequences appear in the Colorado Basin (Figs. 1 and 7) on an angular unconformity over the metamorphic basement.

The western border of the Sierra Grande Basin is also unclear since it is covered by a Tertiary basaltic plateau, although there are small outcrops near Nahuel Niyeu and Arroyo Salado (Caminos et al., 2001), located 150 km northwest of the Sierra Grande area. This border is nearly coincident with the belt of strong gravity gradients that strike NW–SE from Sierra Grande to Valcheta. A possible explanation for the presence of strong negative gravity anomalies in this belt is that the sedimentary rocks of the Sierra Grande Formation continue in an SE–NW direction along the western border of the Pampean highs (Fig. 7).

By modeling the −22 mGal anomaly found in this area, using a density contrast of −0.1 g/cm^3 between the Sierra Grande Formation and the Pampean basement, it is possible to suppose the existence of a 1.6 km thick sedimentary pile formed by quartzites of the Sierra Grande Formation.

As indicated in the geological backgrounds, the Sierra Grande Formation shares lithological, faunal and deformational styles with the Silurian–Devonian rocks of the Claromecó Basin in the Buenos Aires province, located 350 km to the northeast (Figs. 1 and 7). The Puelche x-1, Cruz del Sur x-1 and other boreholes, drilled offshore into the Jurassic–Cretaceous Colorado Basin, also cut Upper Paleozoic rocks, indicating that the Claromecó Basin extends to a latitude of 40°42′S (Fig. 7).

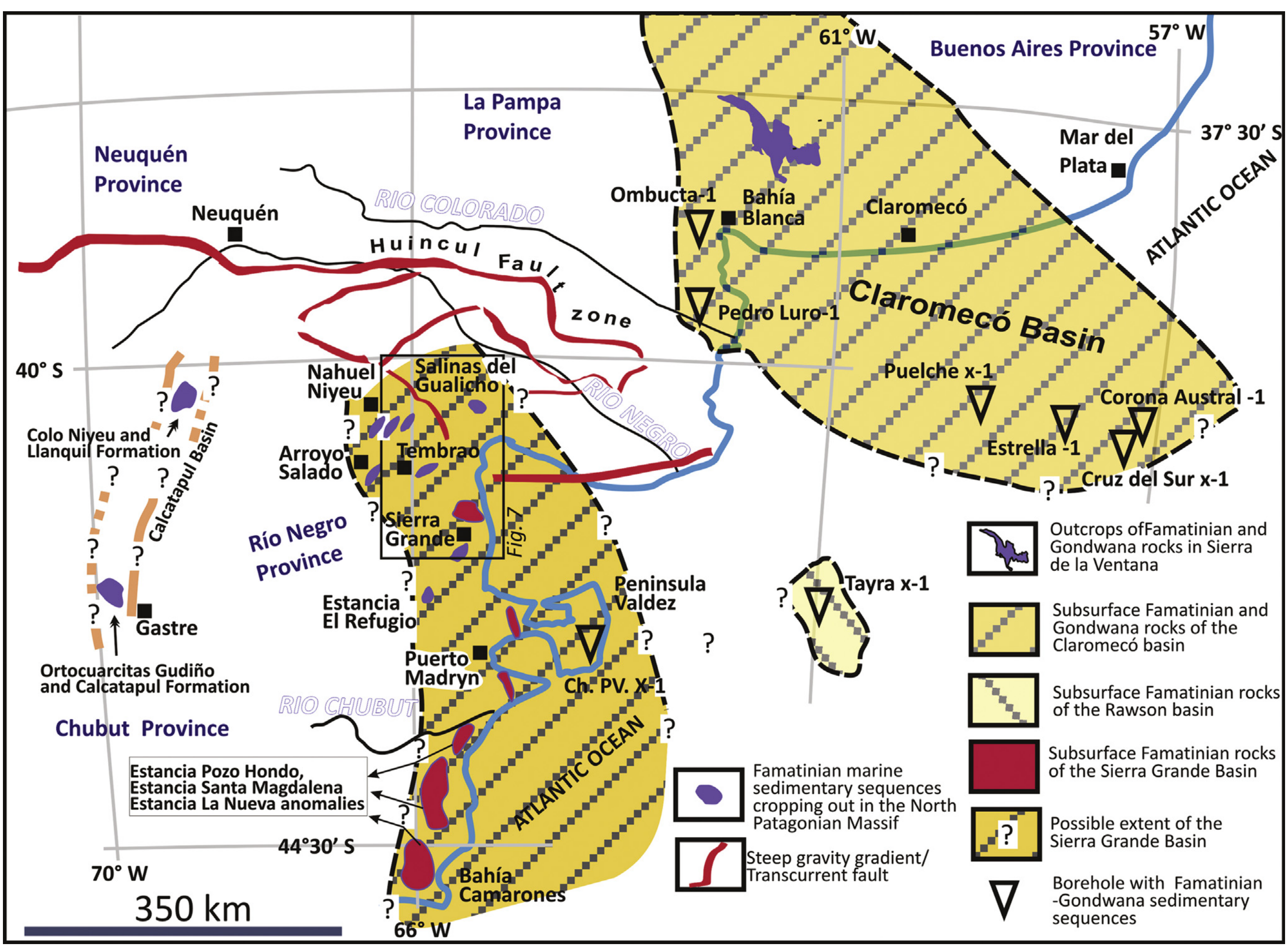

Figure 7. Regional map of northern Patagonia and southern Buenos Aires province showing the distribution of the Silurian–Devonian marine sequences of the Claromecó and Sierra Grande depocenters. The Calcatapul Basin is depicted, while the Huincul Fault zone and other lineaments are also displayed.

Because the Sierra Grande and Claromecó depocenters share numerous geological characteristics and a similar design – elongated NW–SE-oriented troughs – we propose that both were not only part of the same basin, but were also connected with the South African basins. Uriz et al. (2008) also postulated that both depocenters were part of the same basin based on analysis of detrital zircon.

Movement along the dextral Huincul Fault zone during the Gondwanide Orogeny (Gregori et al., 2008) would have dismembered the basin, separating the northern (Claromecó) and southern (Sierra Grande) depocenters.

5.3. Ellipsoidal negative gravity anomalies and the Gondwana granitoids

In the area west of the Gonzalito Mine and El Jagüelito Fault zone there are extensive outcrops of Gondwana granites (Peñas Blancas, La Laguna, La Verde), while outcrops of Peñas Blancas granite also occur north of Puesto Flor de Liz. Gravity anomalies are ellipsoidal in design, similar to the −41 mGal and −38 mGal examples west of Las Peñas Blancas (Figs. 2 and 5). Those located south of Flor de Liz reach a value of −39 mGal. Based on the disposition and the low density of these rocks, the anomalies can be attributed to these rocks.

5.4. Belt of strong gravity gradients and NW–SE-oriented fault systems in the eastern North Patagonian Massif

As indicated, this belt is a relatively well-defined zone between the −22 and −25 mGal lines, extending between 41°S (Arroyo Tembrao) and 41°30′S (Punta Pórfido) for more than 124 km (Figs. 2 and 5). The belt is partly coincident with the El Jaguelito Fault Zone (Ramos, 1975; see Fig. 8).

The section between Arroyo Tembrao and Cerro El Morro is aligned NNW–SSE and can be traced on the surface due to the presence of disrupted blocks of the El Jagüelito Formation and mylonites of the Peñas Blancas Stock. The fault zone also separates outcrops of the Peñas Blancas Stock and the Mina Gonzalito Complex. Geological mapping shows the fault zone to be about 3 km wide, accompanied immediately to the east by rhyolitic dikes following the same orientation. The latter are up to 1 km long and sometimes display a sigmoidal design, possibly due to later emplacement in a fault zone or a coeval deformational event. In both cases the El Jagüelito Fault zone could be more than 10 km wide.

To the west and north the fault zone is covered by Tertiary basalts of the Somuncurá Formation, and to the east by Quaternary deposits.

As indicated in Fig. 4, the orientation of the belt of strong gravity gradients is redirected slightly southeastward near Cerro El Morro. This variation is possibly related to the presence of outcrops of the Mina Gonzalito Complex. Also south of Cerro El Morro, the belt is displaced westward along the El Morro Fault zone (Figs. 5 and 8).

This fault zone continues in an SE direction south of the Estancia Los Tamariscos until Sierra Chara. Although no evidence was found at the surface our interpretation based on the trend of the gravity gradient is that the fault continues in the subsurface.

The ignimbrites of the Marifil Complex outcrop in the area of Sierra Chara, but show no evidence of deformation. Their emplacement therefore appears not to be constrained by the presence of the fault zone. The change in orientation of the fault zone from SSE to SE south of Sierra Chara is likely to be related to the presence of the western border of the Arroyo Salado High.

South of Sierra Grande, there is evidence of the fault zone at the surface. The Törnquist and Mina Delta faults can be traced along several kilometers (Fig. 7). The former is known to be an NW–SE-oriented dextral strike-slip fault, while unfortunately no kinematic information regarding the latter was available.

No surface trace of the fault system is visible between Sierra Chara and Estancia Mussi, although gravity lines and gradient vectors suggest a gradual change in fault direction to ESE.

As previously indicated, south of Estancia Mussi the belt is reoriented to an NNE–SSW direction, with gravity gradient vectors of around 1.39 mGal/km pointing WNW/NW.

The El Jagüelito Fault zone possibly is not related to this part of the belt, with the latter instead nearly coincident with a fault system recognized by Cortés (1981) west of Estancia El Refugio, in the northeastern part of the Chubut province (not shown) and known as the Guanacote Fault system.

This system was initially described as a horst and graben structure, but has been reinterpreted as a northeast dextral strike-slip fault zone (Haller et al., 2005).

In addition to the El Jagüelito Fault zone, Giacosa (2001) also described the northern and southern Peñas Blancas Fault zones (Fig. 8), located 6 km to the west. All three fault systems appear to be related and were originated during the same period of deformation. The northern and southern Peñas Blancas Fault zones are composed of mylonites and foliated granites displaying mylonitic lineation. Both have been interpreted as compressional strike-slip fault systems.

The El Jagüelito Fault zone consists of protoclastic and protomylonitic rocks, with mylonitic lineation dipping 14°–22° in a north and northeasterly direction. Giacosa (2001) assigned the El Jagüelito Fault zone to an N–N15° dextral transpressive shear zone, with extensional sectors arising during movement between 270–253 and 188 Ma.

In their study of the area east of the El Jagüelito Fault zone near Mina Gonzalito, González et al. (2008) identified two sectors in the Pampean basement, separated by the NNW–SSE Mina Gonzalito shear zone. This strike-slip structure dips 54°–80° to the east and exhibits mylonitic lineation, indicating SSE to NNW transport. Eastwards, González et al. (2008) described the 40°–60° west-dipping Laguna Grande shear zone, which also displayed sinistral movement.

The El Jagüelito, Mina Gonzalito and Laguna Grande Fault zones are all parallel to Lineament 'D' of Gregori et al. (2008), although their displacement several kilometers westwards (Fig. 8) may be a consequence of movement along Lineament 'F'. von Gosen (2002) studied the Peñas Blancas Granite, finding NE–SW compression. In La Laguna Granite a few kilometers to the west, a dextral strike-slip sense of movement has been described, with its western border intruded by the non-foliated La Verde Granite. Since the La Verde and other granitic bodies in the eastern area of the North Patagonian Massif are not deformed, the Gondwana deformation in this area must be earlier than the intrusion of these bodies (La Verde Granite 253 ± 9 Ma, K/Ar biotite, Busteros et al., 1998; Arroyo Pailemán Stock, 268 Ma, Rb/Sr, Grecco et al., 1994; Mina San Martin Granite, 267 Ma, U/Pb zircon, Pankhurst et al., 2006).

The sedimentary rocks of the Silurian–Devonian Sierra Grande Formation are intensely deformed. Braitsch (1965) identified several N–S anticlines and synclines, associated with N–S, east-dipping overthrusts assigned to ∼E–W compression.

DEMAG (1963) and Zanettini (1981) both mapped several fault zones and folded structures occurring in the ore deposits located south of Sierra Grande (Fig. 8). An NW–SE-oriented syncline with an axis plunging 56° NW appears in the eastern part of this area (eastern ore deposit), associated with a curved ∼W–E overthrust dipping to the north. The interpretation of the folded structure suggests ∼NE–SW compression (the significance of the W–E overthrust will be discussed later). Two and a half kilometers to

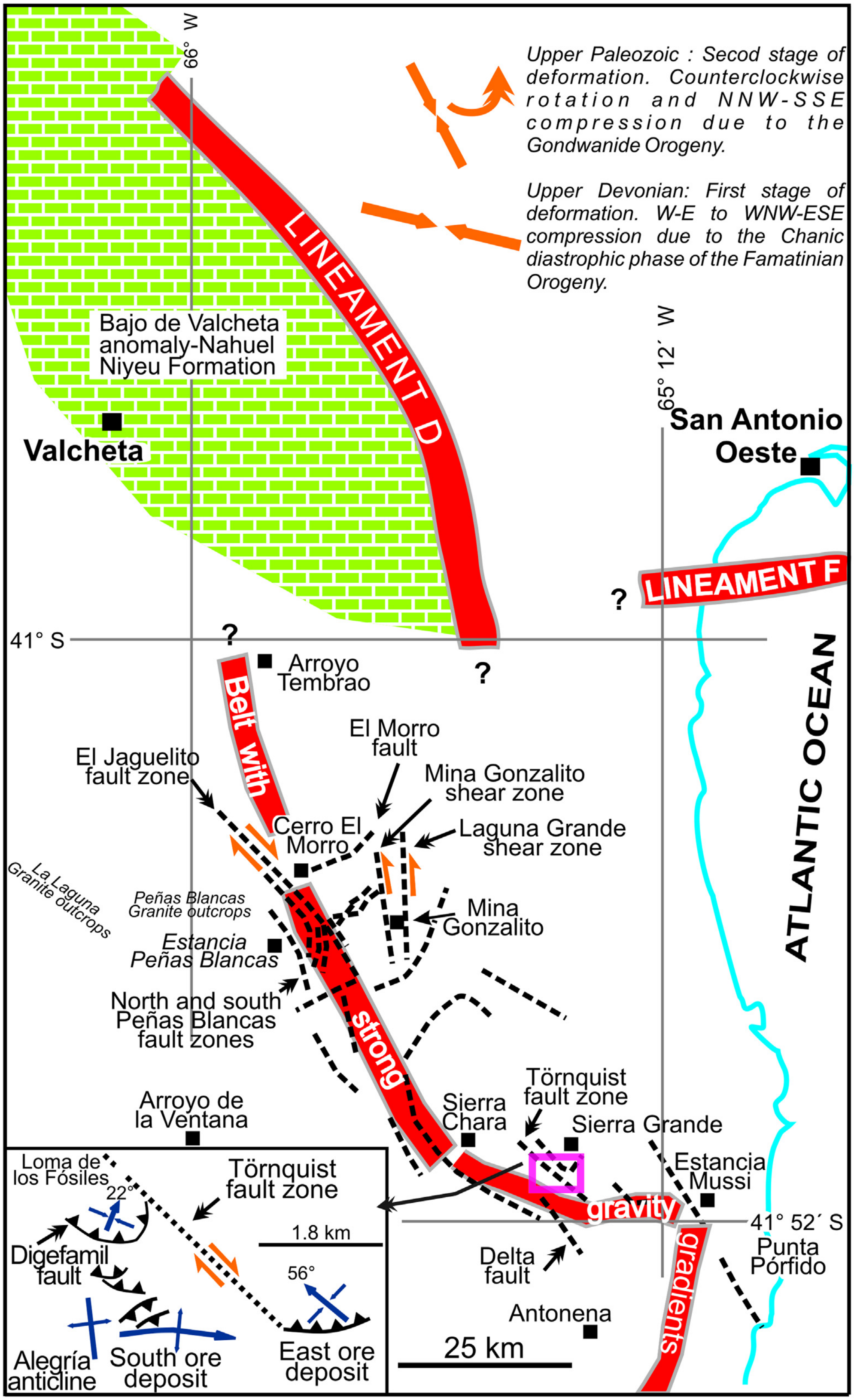

Figure 8. Geological sketch displaying the trace of the El Jaguelito and Peñas Blancas Fault zones, lineament “D” (Gregori et al., 2008), as well as the belt characterized by strong gravity gradients detected in this study.

the west appears the N–S Alegría anticline. This structure is associated with small NW–SE strike-slip faults and ENE–WSW-directed faults (Fig. 8). The interpretation of the Alegría anticline points to ~W–E compression.

In the northern part of this area, near Loma de los Fósiles, the structure is an SSW–NNE anticline plunging 22° to the NE and a curved ~WSW–ENE overthrust dipping NE known as the Digefamil fault.

The overall interpretation of the ~N–S anticlines and synclines is that a first stage of deformation resulted from W–E to WNW–ESE compression. It is possible that this deformation produced the retraction of the Silurian–Devonian marine basin, in a similar way that the Curamalal and Ventana Groups (Cambrian to early Devonian) of Sierras Australes were deformed during the late Devonian–early Carboniferous time (Massabie and Rossello, 1984).

In eastern Precordillera, an early Paleozoic deformation phase was also recognized by von Gosen (1995). The age of the deformation was estimated to be in the late Devonian to pre-late Carboniferous interval (von Gosen et al., 1995).

This event, known as the Chanic diastrophic phase, is part of the Famatinian Orogeny which is widely recorded across central-western Argentina (Azcuy and Caminos, 1987).

A similar situation was established in the Cape basin (South Africa). There, episodes of shortening and uplift spanning 30 Ma closed the basin. This deformation was recorded between the top of the early Carboniferous and the base of the late Carboniferous (Tankard et al., 2009).

The curved ~W–E-oriented overthrusts occurring near Loma de los Fósiles and in the eastern ore deposit, as well as the W–E-striking, ESE-dipping anticline east of the Alegría anticline and the Törnquist Fault mapped by DEMAG (1963), seem to reflect a different style of deformation.

Located near Loma de los Fósiles, the Digefamil fault is another gentle NNW-dipping curved, SE-vergent overthrust (Fig. 8) that carries a syncline, possibly parallel to the Alegría anticline.

East of the Alegría anticline appears a ~W–E-oriented anticline, while within the eastern ore deposit a ~ SSE-vergent overthrust is observed (the NW–SE syncline mentioned above). The syncline located near Loma de los Fósiles and that in the eastern ore deposit seems to be the same, albeit disrupted, displaced and rotated for more than 3 km along the dextral strike-slip Törnquist Fault zone.

The ~W–E anticline and SSE-vergent overthrust located in the Loma de los Fósiles and eastern ore deposit are possibly the result of ~N–S compression associated with the counterclockwise rotation of blocks along the Törnquist Fault zone. Such movement and related deformation can also be observed in the El Jagüelito, Mina Gonzalito and Laguna Grande fault zones, as well as in Lineament 'D' of Gregori et al. (2008).

A second stage of deformation can therefore be recognized in the Sierra Grande area, characterized by NNW–SSE compression (Fig. 8). This deformational event is known to belong to the Gondwanide Orogeny of northern Patagonia (Gregori et al., 2008).

5.5. Strong negative gravity anomalies and the Marifil Complex or equivalent Jurassic units of the eastern North Patagonian Massif

Characterized by strong negative gravity anomalies (−46 to −35 mGal), the western part of the study area is in fact part of a larger anomaly that extends for more than 80 km in a westerly direction (Figs. 2 and 5). Known as the Ramos Mexías anomaly (Gregori et al., 2008), it contains small outcrops of Pampean metamorphic rocks (Nahuel Niyeu Formation) and Gondwanan intrusive and volcanic rocks (Navarrete Plutonic Complex). More abundant outcrops belong to the Jurassic Marifil complex (Caminos et al., 2001) and include rift-type sedimentary rocks, acidic ignimbrites and lava flows, as well as subvolcanic acidic rocks.

The Cretaceous and Tertiary sedimentary rocks (Neuquén and Malargüe Groups, Collón Cura Formation) reach thicknesses of no more than 250 m, and as a result their contribution to the gravity anomalies can be ignored.

A positive correlation exists between the relative location of the strong negative anomalies and that of the outcrops of the Marifil Complex.

In the southeast corner of the area (Figs. 5 and 9), between Amuchástegui, Laguna Walter and the Atlantic coast, anomalies vary in amplitude between −22 and −30 mGal. In this area outcrops of epiclastic facies of the Marifil Complex can be observed, with a few sectors (Cerro Cancha) represented by domes, dikes and ignimbrites.

Values of the negative anomalies decrease westwards (Figs. 2 and 4), reaching a minimum of −48 mGal near Puesto Las Tres Lagunas.

Between Cerro Condor, La Verde, La Auriciana and Arroyo Tembrao there are not only outcrops of the Marifil Complex, but also of Gondwana granites and Pampean basement, with gravity anomalies measured at between −25 and −41 mGal. The pattern of these gravity anomalies appears not to be controlled by the distribution of the Marifil Complex.

Applying a prismatic model (Heiland, 1951) for the calculation of the residual gravity anomalies located near Estancia El Porvenir, in which a density of 2.65 g/cm^3 for the basement rocks and 2.45 g/cm^3 for the pyroclastic rocks of the Marifil Complex are utilized, a thickness in excess of 7 km may be expected for this unit.

Clearly such a figure is beyond serious consideration, since a maximum thickness of the Marifil Complex of 900 m was detected in the Atlantic area of the Chubut province (Camacho, 1979). Also, such a huge thickness has never been recorded anywhere in the eastern part of the North Patagonian Massif. One plausible explanation for this result is that the negative anomalies originate from the effects of the Silurian–Devonian sedimentary rocks, as well as the pyroclastic rocks of the Marifil Complex and other sedimentary rocks. The latter do not outcrop in this area, but have been recorded in the central and western part of the North Patagonian Massif known as the Cañadón Asfalto Formation.

If the subsurface existence of the Silurian–Devonian sequences is taken into account, and considering an average thickness of 1 km (as observed in the Sierra Grande area), a residual negative gravity anomaly of only −14 mGal remains.

Using a density contrast of −0.2 g/cm^3 between the pyroclastic rocks of the Marifil Complex and the quartzites of the Sierra Grande Formation, we can expect a thickness of up to 1.8 km for the first unit. This figure is still too high when compared with known thicknesses, although if levels of Jurassic sedimentary rocks are interbedded in the Marifil Complex it should not be completely ruled out.

Consequently it follows that the strong negative gravity anomalies found in the Puesto Las Tres Lagunas area are not a result of the Marifil Complex alone.

As indicated in the geological background several Jurassic sedimentary units can be correlated with the Marifil Complex. Some of these units can be interbedded with the Marifil Complex at subsurface levels.

Therefore we propose that the Cañadón Asfalto Basin as defined by Cortiñas (1996) extends to latitude of 66°00′W, contributing, together with the Sierra Grande Formation and Marifil Complex, to the generation of the strong negative anomalies observed in the western part of the study area.

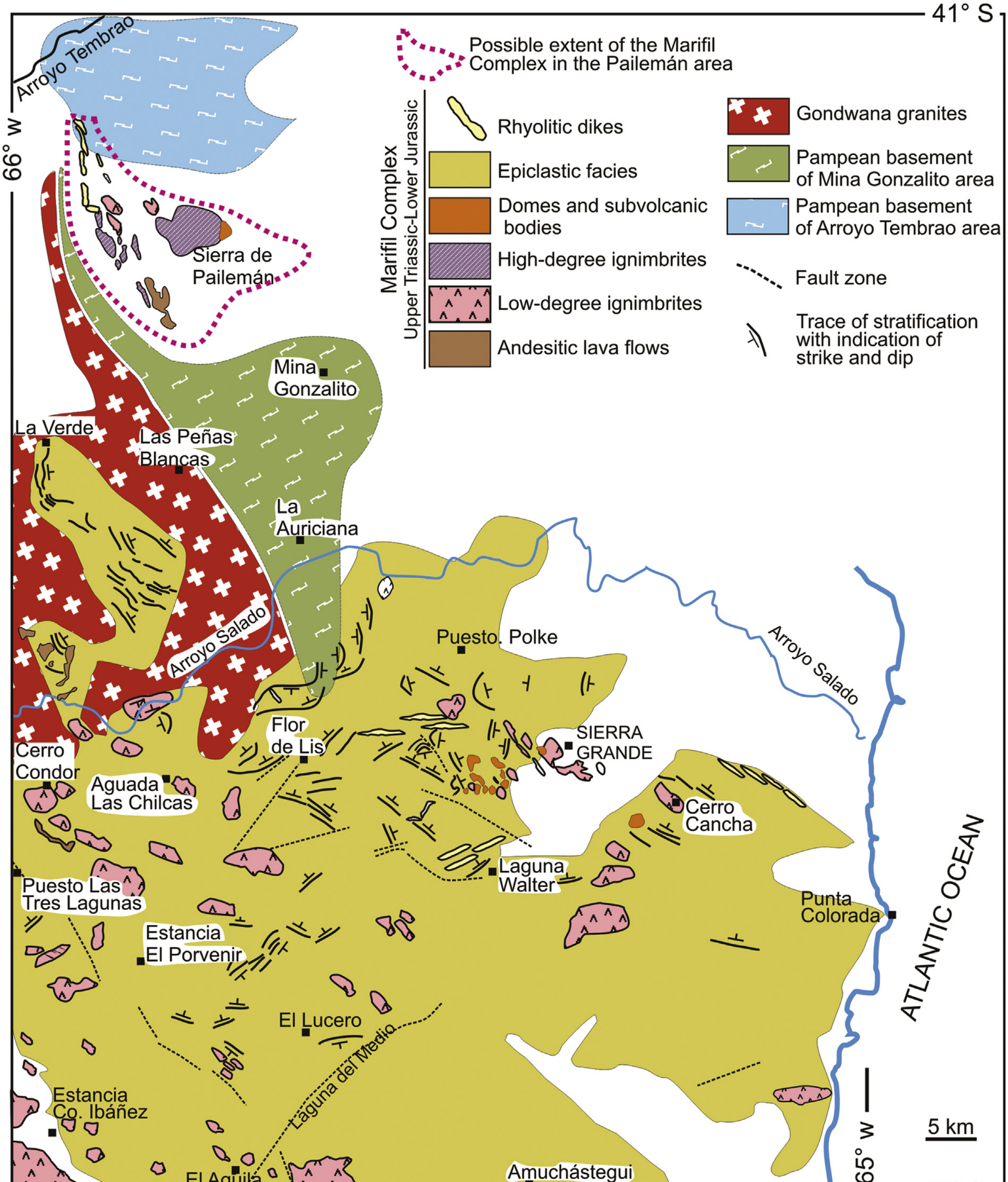

Figure 9. Geological sketch displaying the outcrops of the Marifil Complex lithofacies, which are believed to contribute to the strong residual Bouguer anomalies of the western part of the study area.

6. Conclusions

The positive gravity anomalies located near the Atlantic coast of the North Patagonian Massif are interpreted to be generated by rocks belonging to the Pampean Orogeny, with ages of ~535 and 540 Ma. These rocks are equivalent to those of the San Rafael Block, Precordillera, Sierras Pampeanas de San Luis and Córdoba of north-central Argentina. In Patagonia this orogeny can be traced as far as 42°S.

The Famatinian Sierra Grande depocenter displays a configuration similar to that of the Claromecó depocenter, indicating that both were part of the same basin, disrupted and displaced along the dextral Huincul Fault zone during the Gondwanide Orogeny (Gregori et al., 2008).

The NW–SE-oriented belt of strong gravity gradients running between Arroyo Tembrao and Punta Pórfido is coincident with several fault zones (El Jagüelito, Peñas Blancas, NNW–SSE Mina Gonzalito, Laguna Grande, etc.), all of which were originated during the same period of deformation that ended in the Upper Permian, known as the Gondwanide Orogeny.

In the Sierra Grande area, the N–S-striking structures are interpreted as the result of an ∼E–W to WNW–ESE compression event known as the Chanic diastrophic phase, part of the Famatinian Orogeny.

In contrast, the W–E-striking anticlines, dextral strike-slip Törnquist Fault zone and the Silurian–Devonian sequences overthrusted in an SSE direction are due to a second, NNW–SSE-oriented stage of compressional deformation possibly associated with the Gondwanide Orogeny.

The belt of strong negative anomalies located in the western part of the area is derived from the presence of rocks of the Jurassic Cañadón Asfalto and Santa Anita formations interbedded in the Marifil Complex.

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