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3D gravity modeling of the Corrientes province (NE Argentina) and its importance to the Guarani Aquifer System

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ABSTRACT

This paper presents a geological model of Corrientes province (Argentina) based on Bouguer gravity anomaly data, obtained in 2073 measurement points. To build the model, the IGMAS+ interactive program was used. Two areas of approximately 135,000 km^2 were modeled in this study. The selection of these areas was based on the sectors where the largest number of gravity anomaly measurements was made and other type of data was available to perform the parameterization (i.e, lithology profiles in boreholes, seismic profiles and audio-magnetotelluric AMT soundings). The initial geological configuration proposed was composed by four layers: basement, sediments (Paleozoic–Lower Cretaceous), basalts (Serra Geral Group, Lower Cretaceous) and post-basaltic sediments. The result shows a basement compartmentalized in structural blocks separated by large faults. The connection of Asunción and Río Grande Arches is confirmed along a structural high that crosses Corrientes province from SE to NW. The basaltic layer shows lateral changes in its thickness, due to faulting, almost disappearing on the NW of Corrientes. This structural configuration has a special hydrogeological importance because it produces the rise of the Guaraní Aquifer System sedimentary series near the surface and the intense fracture network makes this area prone to local recharge and regional discharge.

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1. Introduction

Corrientes province, on the Northeast of Argentina (Fig. 1), is one of the most unknown areas from the geological point of view, among other causes, due to its geomorphologic characteristics. A large plain predominates with minimum and maximum elevations of 27 and 161 m above sea level in an area larger than 88,000 km^2 (Santa Cruz, 1981). Thus the oldest identified materials on the surface correspond to basalts of the Serra Geral Formation and Solari Member sandstones interlayered among them (Herbst and Santa Cruz, 1995; Herbst et al., 1985), both dating from the Lower Cretaceous. The study area lies inside the Chaco–Paraná Basin where Lower Paleozoic sediments are identified (Fernández Garrasino et al., 2005).

The Guaraní Aquifer System (GAS) covers the Chaco-Parana basin in Corrientes province. This system is one of the most important groundwater reservoirs; it is shared by four neighboring countries covering an area larger than one million square kilometers. The geological and hydrogeological structure of the GAS is well known in Brazil, Paraguay and Uruguay (Araújo et al., 1999; Campos, 2000; Gastmans et al., 2012; LEBAC, 2008) but the lack of direct deep information in Argentina, especially in Corrientes, made this area prone to baseless interpretations.

The objective of this study is to determine the deep geological structure of Corrientes province as regards both the geometry of the basement and the distribution and thickness of the sediments that fill in the basin in order to understand how the aquifer operates. It will be a useful tool to assess the impact of exploitation used to supply 8 million inhabitants in the area of study.

2. Geological setting

Corrientes province is situated in the Chaco–Paraná Basin, one of the largest in South America that covers the northeast of Argentina. It has an elongated form due to the precambric lineation by the union of the continents in the early Gondwana during the Brasilian–Pan Afrikan orogeny (Fernández Garrasino et al., 2005; Tankard et al., 1995).

The basin is underlain by cratonic Precambrian to early Paleozoic metamorphic and plutonic basement similar to crystalline rock exposed in the Caacupú High (Preciozzi et al., 1985). It has been dated between 441 and 787 millions of years (Ma) in deep borehole samples (Fernández Garrasino, 2008). The Chaco–Parana basin contains a thick Mesozoic to Tertiary clastic and volcanic section, in addition to Paleozoic

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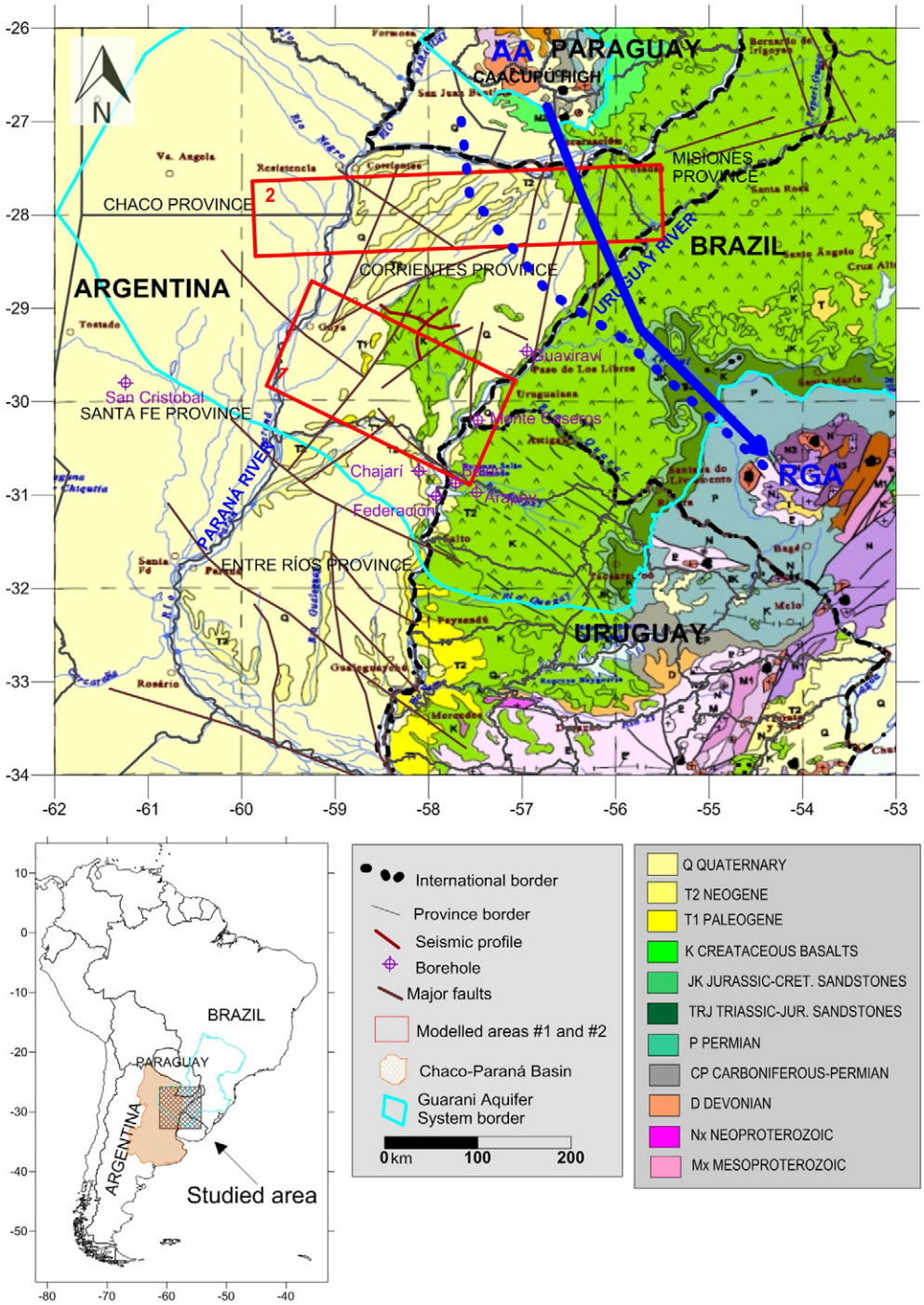

Fig. 1. Location map of the Chaco–Paraná Basin and Corrientes province including the geological map (modified from Schobbenhaus and Bellizzia, 2001). It also includes the major faults, the modeled areas and a diagram showing the union of Asunción (AA) and Río Grande Arches (RGA). In solid line, the path according to Rossello et al. (2006) and in dotted line, the path proposed in this paper.

strata, and has a covering of Quaternary sediment (Winn and Steinmetz, 1998). The sedimentary deposits have more than 5000 m thick recognized in the San Cristobal Well in Santa Fe (Argentina). Those sediments are associated to tectonics cycles and events of the western Gondwana. They show sedimentary successions that define transgressive and regressive sequences due to the variation of the sea level in the Paleozoic.

2.1. Stratigraphy

There are four sedimentary sets in the Lower Paleozoic separated by discontinuity surfaces (Fernández Garrasino, 2008). They have been described only on the Northwest of the basin and its existence is not probably in Corrientes province. The description, from bottom to top, is:

a) Platform facies sandstones (Árbol Blanco Fm., Mingramm, 1965). At the top there are fine sandstones with lithic fragments of volcanic origin (Pinaré Fm., Mingramm, 1965) and micaceous shale of the lower Las Breñas formation (Mingramm and Russo, 1972).
b) Mid and coarse quartz sandstones with silica cementation and poor sorted (Las Breñas Fm) from platform facies.
c) The third level has a different sedimentary pattern. In fact, diamictites of glacial origin have been described as Zapla Fm.

(Mingramm and Russo, 1972) and black shales as Copo Fm (Padula and Minggramm, 1967). Both are Silurian.

d) Fine quartz sandstones with silica cementation (Caburé Fm., Padula and Mingramm, 1967) at the bottom and light black shales (Rincón Fm., Padula and Mingramm, 1967) at the top. Both are Devonic and have a marine origin.

Some detrital and shallow marine facies deposits were sedimented during the Upper Paleozoic (Silva Busso, 1999; Winn and Steinmetz, 1998), and produced great changes and lateral variability in sediments. Also, the lack of outcrops restricts the description of sedimentary units being made from a few borehole samples, and the correlation between them is thus very difficult.

Carboniferous white sandstones and black shales of fluvio-lacustrine facies (Sachayof Fm., Mingramm, 1965) and the quartzite diamictite of upper Charata Fm. (Padula and Mingramm (1969)) have found on the Western basin accordingly overlaying formations, we can find the Chacabuco Fm. (Padula and Mingramm, 1969), grey mudstones, bituminous, and with sandy and limey levels.

Those three formations are equivalent, to ones on the East, with the fluvio-glacial conglomerates and sandstones of Ordoñez Fm. (Russo et al., 1987). Overlaying it in a concordantly way the Victoriano Rodríguez Fm. (Russo et al., 1987) are sandstones with red and grey mudstones.

At the end of the Permian period, the Gonwana orogeny conditioned the sedimentation because the subsidence was by continental flexion and by crustal extension previous to the Pangea break up (Barredo and Stinco, 2010). The reactivation of ancient faults of the basin basement produced its compartmentalization in blocks and a non-connection of the craton with the paleo-ocean Panthalassa (Gastmans et al., 2012; Zalán et al., 1990). As a result, a regional unconformity in the upper Permian shows the beginning of a large continental sedimentation during the Jurassic and the Cretaceous.

During this period a complex paleogeographic framework was established. Most of them were fluvial and aeolian sediments. In Argentina those clastic sediments were grouped as Misiones Fm. (Putzer, 1962), composed of commonly reddish, very fine to medium-grained sandstones arranged in sets of cross stratification of medium- and large-scale (5 m thick and hundreds of meters long in average), attributed to giant crescent eolian dunes (Hirata et al., 2011). According to Gastmans et al. (2012), this unit comprises in Argentina the Guaraní Aquifer System (GAS).

The concordant upper limit is represented by the lava flow that covered that sedimentary basin. The basic magmatism is associated with the continental break up that originated the Atlantic Ocean in the Middle Jurassic. The magmatic rocks are joined into the Serra Geral Group (Wildner et al., 2007), and include the sills interlayered between the Permian sediments and dikes that cut it off with a NW orientation (Comin-Chiaramonti et al., 1997; Santa Ana and Veroslavsky, 2003).

The intercalation of ergs and the first volcanic flows allowed the preservation of aeolian sandstones. They have an important thickness in Argentina with almost 100 m (Herbst et al., 1985; Scherer, 2002; Wildner et al., 2007). These sedimentary deposits are evidence of non-volcanic hiatus, registering breaks in volcanism and allowing sufficient time for erosion and sedimentation between lava outpourings.

The total thickness is over 1500 m in the Paraná basin and near 1000 km in the Chaco–Paraná basin, and decreases towards the margin (Fariña et al., 2007). The basalt flood is composed of different lithologies: basaltic breccia, vesicular basalt and porphyritic basalt. Some of them appear as peperite breccias, confirming the interaction between lavas and non-consolidated wet sediments (Lagorio and Leal, 2005). The basalts have been dated in a maximum of 137 Ma and a minimum of 127 Ma Milani et al. (2007).

Those Mesozoic sediments disappear towards the Western side of the basin, in Santa Fe and Chaco provinces and from the same age we can find the Buena Vista Fm. (below) and San Cristobal Fm. (up) (Fernández Garrasino, 2008). They are composed of fluvial/aeolian sands and sandstones.

Overlaying the basalts (and its clastic intertrap) in a nonconformity way, there are calcareous sandstones (Puerto Yeruá Fm., Herbst et al., 1985) during the Upper Cretaceous. All the sediments defined in Uruguay like Guichón and Mercedes formations, and the Paleocene limestones and calcretes of the Pay Ubre Fm. have been included under this denomination (Tófalo et al., 2008).

The Fray Bentos Fm (Herbst, 1971) is situated in the limit Oligocene–Miocene. It consists of sandy or clay mudstones with calcareous and silica cementation. Its thickness is 55 m in Entre Ríos province, decreasing Northward.

In the Upper Miocene a large seawater ingression occurs. Its sediments are called Paraná Fm. (Fernández Garrasino and Vrba, 1999), with typical shallow marine and littoral sedimentary sequences. This formation is widely represented in the west side of Corrientes province. In the Miocene–Pliocene the Paranaense paleosea experimented a regression, allowing the erosion of part of those sediments. Some of them were overburden by Plio-pleistocene fluvial sediments of Ituizangó Fm. They are yellow and brownish-red fine sandstones (occasionally sandy conglomerates) of quartz clast. It is usual to find clay lenses and oxides of iron (Herbst et al., 1985).

On the north of Corrientes province, Ituizangó Fm. lays, in discordance, over the Serra Geral basalts and inland overlays Fray Bentos Fm. Near to the Paraná River it covers the Paraná Fm. and generates a large alluvial fan (Orfeo et al., 2011).

It is overlaid by the Toropí-Yupoí Fm and the Yupoí Fm. during the Pleistocene. Both are sandstones and mudstones with calcium and magnesium carbonates. In some places they are interbedded with the Ituizangó Fm (Iriondo et al., 1998).

The Holocene sediments show the effect of the climatic changes. Then in the Lower and Mid Holocene the climate was wet, allowing the existence of a fluvial network (Iriondo, 1991). In the Upper Holocene, in a dry climate, an aeolian silt (San Guillermo Fm.) covered the region. Furthermore, the extension of the basin and the large number of climatic events avoid the condensation of the sedimentary record.

The different geological formations present in the Chaco–Paraná basin in Argentina are shown in Table 1.

2.2. Tectonic

The tectonic setting of the Chaco–Paraná basin shows a basement with a structure of aborted continental rift (retroarc basin). It was formed during the Cambrian–Ordovician while the subduction started in the continental margin (Ramos, 2000). This rift, as a result of a transtensional tectonic and associated to a compressive stress field, produced the reactivation on ancient cortical faults (Milani, 2004).

The Gondwanic orogeny, from the Lower Carboniferous until the Upper Triassic, determined the sedimentation because the subsidence was by continental flexure and cortical extension previously to the Pangea breakup. The nearby Pangean plate margin was affected by intermittent convergence, commonly transpressive, during this period (Winn and Steinmetz, 1998). Rifting within southwest Gondwana during the late Paleozoic resulted in northeast-oriented grabens and horsts in the Chaco–Paraná.

From the Triassic, the basin had a continental rift mark. In the Jurassic an elevation occurred before the Atlantic open, causing the tectonic inversion of the existing faults. The subsequent subsidence produced the melting of large volumes of the lithospheric mantle and the extrusion of the flood basalts included in the Serra Geral Group (Peate, 1997; Wildner et al., 2007).

During the Cenozoic, the area was affected by subsidence and it allowed the ingression of the Paranaense sea (Jordan et al., 1983). The Pliocene and Quaternary deposits are post-orogenic and are related to the tectonic evolution of the area due to the Andean orogeny that produced a generalized uplift of all the area.

Table 1
Chronostratigraphy of the Chaco–Paraná Basin in Argentina. Geological formations of each layer used in the gravimetric model are included. In zigzag lines are showed the main discontinuities.

Ma	Era	Period	Epoch	Formation E	Formation W	Maximum Thickness	Model layer
	Cenozoic	Quaternary	Holocene	San Guillermo	Salto chico		Layer 1
			Pleistocene	Yupoi	Ensenada		
2.58				Toropi-Yupoi			
		Neogene	Pliocene	Ituizango			
			Miocene	Paraña			
23.03				Fray bentos			
		Paleogene	Oligocene	Puerto Yerua		1196	
			Eocene				
			Paleocene	Pay Ubre	Mariano Bocco		
65.5							
	Mesozoic	Cretaceous	Upper				
			Lower	Serra Geral Gr.		961	Layer 2
145.5				Misiones	San Cristobal		Layer 3
		Jurassic	Upper			518	
			Middle				
199.6			Lower				
		Triassic	Upper		Buena Vista		
			Middle				
251.0			Lower				
	Paleozoic	Permian	Lopingian				
			Guadalupian				
			Cisuralian	Victoriano Rodriguez		1400	
299.0				Ordoñez	Chacabuco		
					Charata	1590	
		Carboniferous	Pennsylvanian		Sachayoj		
359.2			Missisippian				
		Devonian	Upper				
			Middle		Rincon	600	
416.0			Lower				
		Silurian	Pridoli		Cabure	484	
			Ludlow				
			Wenlock		Copo	348	
			Liandovery		Zapla	71	
443.7							
		Ordovian	Upper				
			Middle		Las Breñas	319	
488.3			Lower				
		Cambrian	Furongian		Pinare	500	
			Series 3		Arbol Blanco	234	
			Series 2				
542.0			Terreneuvian				
	Proterozoic	Neoproterozoic	Ediacaran	Basement			Layer 4

The most important structure is the Dorsal of Asunción–Rio Grande (DARG). It is a large anticline that connects the Asunción and Rio Grande Arches (Lebac, 2008; Rossello et al., 2006). Its core has the basements outcrops on the South of Paraguay and in the Brazilian province of Rio Grande do Sul. But in the intermediate part, along the Corrientes province, there are no basement outcrops by sinking regarding its margins.

Their limits are two major faults parallel to the Uruguay River. The DARG was a regional high that produced a post-Triassic different sedimentation pattern between the Paraná and Chaco–Paraná basins (Milani, 2004; Rossello et al., 2006).

The main directions of the tectonic lineations are NE and NW (Zalán et al., 1990). The NE direction is the same that originated the basin and it is characterized by straight faults with variable length and absence of basalt dikes. The NW one responds to the Atlantic Ocean opening and the faults are filled with diabase dikes.

3. Gravity modeling

Two 3D gravimetric models have been carried out based on the Bouguer gravity anomalies. The land gravity data set was collected and processed primarily by the Geodatos company during 2006 and 2007, and consists of 1468 gravity points measured for the Project of Environmental Protection and Sustainable Development of the Guaraní Aquifer, PSAG (LEBAC, 2008). The gravity measurements are distributed along 6 transects in the Argentine provinces of Entre Rios, Corrientes, Misiones, Santa Fe and Formosa. The database is completed with 605 gravity observations measured by the National Geographic Institute (IGN) from 1968 to 1998. The data set covers a flat area and the approximate average spatial density of these data is one observation per 150 km-squared. The gravity values were referred to the International Gravity Standardization Network 1971 (IGSN71) global gravity datum and were measured by a Lacoste and Romberg model G gravimeter. Simple planar Bouguer anomalies were computed using an infinite lateral plate of thickness equal to the observation height to model the gravitational attraction of the topography with a constant topographic mass–density of 2.67 Mg/m^3; adding the second-order free-air correction and an atmospheric correction for the observation elevation and referred to the Geodetic Reference System 1980 (GRS80) normal ellipsoid (Moritz, 1980).

The 3D density models constructed are located in Corrientes province including a small segment of the North of Entre Rios, the West of Misiones and the South of Paraguay. In both cases, the models were based on geological profiles, with NW–SE orientation for MODEL 1 and W–E for MODEL 2, and lengths of 200 and 400 km, respectively. Those geological profiles were made according to the geological information available: surface geological maps (Herbst and Santa Cruz, 1995; Schobbenhaus and Bellizzia, 2001), cross sections included in academic thesis (Mársico, 2013; Mira, 2012; Oleaga, 2002; Silva Busso,

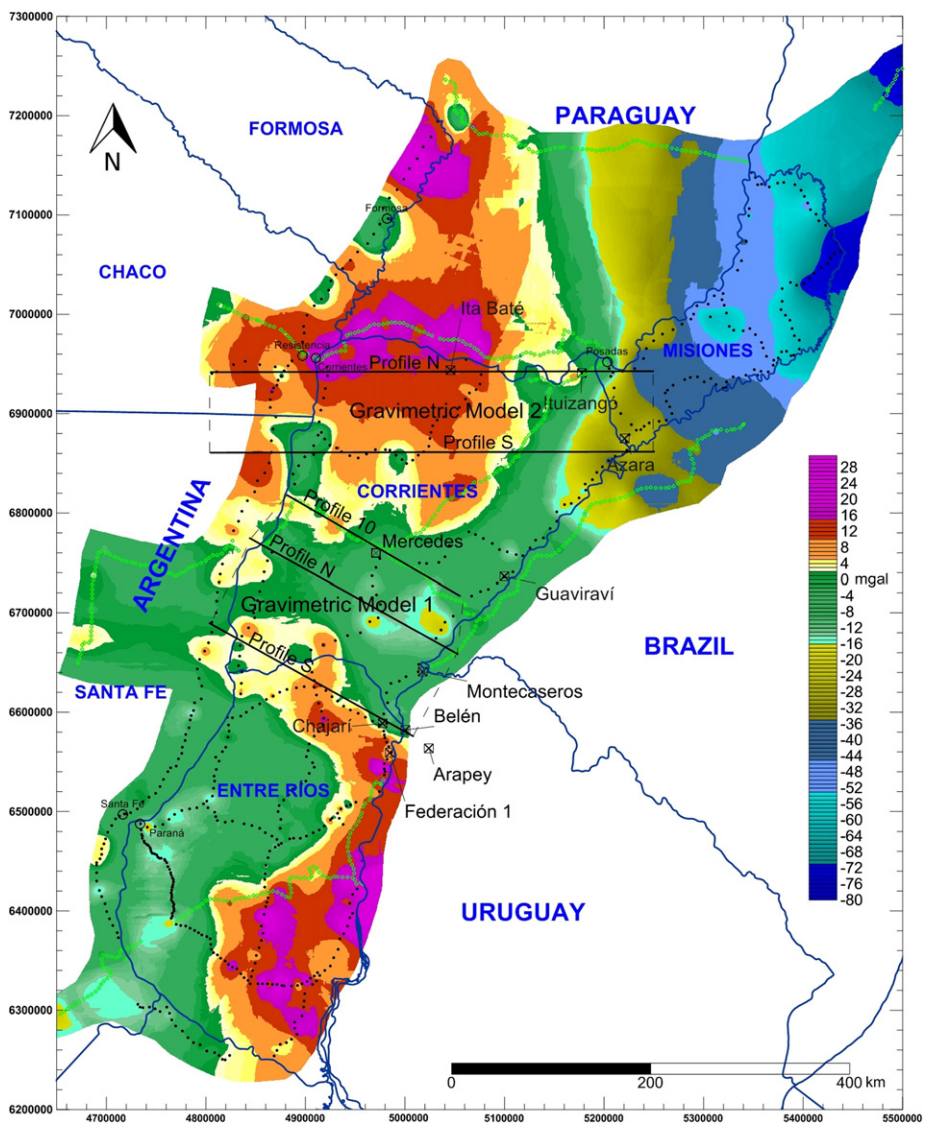

Fig. 2. Simple Bouguer gravity anomaly map (modified from GEODATOS, 2008; Lebac, 2008) referred to the Geodetic Reference System 1980 (GRS80) in mGal without topographic correction. Atmospheric reduction has been applied. It has been made from 1468 stations (green dots) of SAG project, measured by Geodatos between the years (2006–2007) and 605 stations (black dots) of the National Geographic Institute (1968–1998). The location of the gravimetric models is shown.

Table 2
Layers and density adopted for gravimetic models.

Layers	Lithology	Density (Mg/m^3)
1	Sediments (Upper Cretaceous–Holocene)	2.10
2	Serra Geral Group basalts (Lower Cretaceous)	3.00
3	Sediments (Paleozoic–Lower Cretaceous)	2.10
4	Basement (Precambrian)	2.67

1999) and papers or reports (Corbo et al., 2012; LEBAC, 2008). Most of them were based on geophysical information like AMT soundings or resistivity depth-sounding that provided resistivity profiles and the situation of major discontinuities. Also, borehole profiles give us detailed stratigraphic profiles.

The location of each model was chosen coinciding with the maximum distribution of gravity stations (Fig. 2).

In this study, 3D gravity modeling was performed using the software Interactive Gravity and Magnetic Application System IGMAS+ (Götze et al., 2010). This program uses polyhedrons and/or triangulated grids to perform the three-dimensional modeling. A constant density (susceptibility and/or remanent magnetization if appropriate) is assigned to each polyhedron. The numerical algorithms are based on the method developed by Götze (1978, 1984), Götze and Lahmeyer (1988) and Schmidt and Götze (1998). IGMAS+ supports the construction of models with the possibility of varying the model geometry and density to compare then the measured and calculated potential fields, allowing a fully three-dimensional gravity modeling (Schmidt et al., 2010). The models are defined through a number of vertical cross sections but the program made the triangulation between them to automatically generate the 3D model structure, i.e. it connects the profiles generating a three-dimensional model (Alasonati Tašárová et al., 2009). There is an interaction between the different profiles: any change in the geometry of one of them has a repercussion in others.

The first step of 3D modeling is to define the initial model geometry using parallel profiles. The model surfaces that limit the layers (i.e., the surfaces among the parallel vertical sections) are generated by triangles,

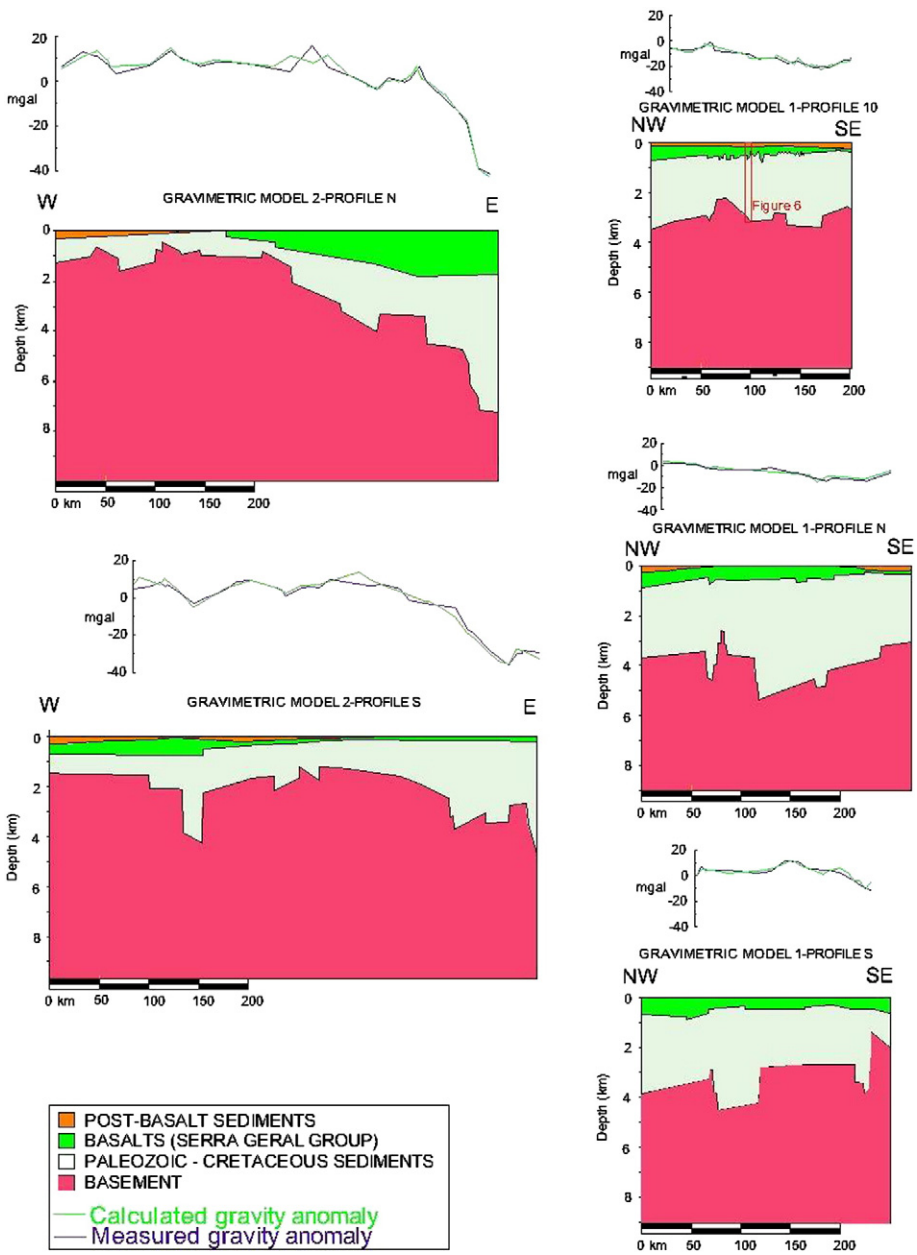

Fig. 3. Vertical cross-section from the 3D density model along profiles in the study area. Note the good fit between measured (dark) and calculated (light) Bouguer anomaly.

this triangulation is performed automatically by the program. Later, the additional information is included in the models such us, seismic profiles, boreholes and AMT soundings. Finally, the adjustment of the models is iteratively carried out manually in order to achieve an optimal fit between observed and modeled gravity anomaly (Gómez Dacal, 2012).

In terms of the general geological features of the area where the profiles are located, and in accordance with the data and results of the geophysical studies of SAG (GEODATOS, 2008), the models comprise four bodies that represent the following geological units: sediments from the Upper Cretaceous to the present; basalts of Serra Geral Group; Paleozoic and Mesozoic sediments situated below the basalts and finally, the basement. It is the same differentiation made in other studies in the area (Corbo et al., 2012; Mariani et al., 2013) because they are the main known layers covering the basement in the Chaco–Paraná Basin. The density values used for the models are shown in Table 2. They are usual values for those lithologies based on literature (Nettleton, 1971; Parasnis, 1997). Moreover, they have been estimated as the mean of 343 samples analyzed (LEBAC, 2008), also used by GEODATOS (2008) in AMT soundings.

IGMAS + enables to create a geologic model of the subsurface and integrates seismic, well, and geology data with observed gravity and magnetic measurements. For the modeling process we used geophysical and borehole information as geometric constraints in order to avoid ambiguity. These data include the Guaviraví boreholes profile (Corrientes), Chajarí, Montecaseros and Federación 1 (Entre Ríos), Belén and Arapey (Uruguay) and some of the AMT performed, like those of Itá Baté, Ituizangó and Azara (GEODATOS, 2008). Those essays provided information about lithological profiles and thickness of the layers used during the modeling. No further information, like borehole logs, were available.

4. Results

Profiles have been extracted from each model where the geometry of the different layers is shown. Besides, the Bouguer gravity anomaly values measured and calculated have been included showing the outstanding adjustment (Fig. 3). In fact, the adjustment between measured and calculated values is lower than 4.8 mGal and with a mean value of 0.4 ± 1.5 mGal.

The profiles of the gravimetric models show a basement with high and low structures, reflecting its tectonic history, where tectonic events have been taking place along the geological periods and compressive and distensive successive stages have occurred. The thickness of infrabasaltic sediments is slightly higher than 2000 m in MODEL 1, in MODEL 2 it varies laterally and decreasing Westward. The basalt level presents sudden thickness changes evidencing its fracturation. In general, the basalt thickness increases Westward with the exception of the North profile of MODEL 2. 2D maps of basement depth and basalt layer thickness derived from the gravity models are shown in Figs. 4 and 5, respectively.

5. Discussion

The information provided by the gravimetric models must be analyzed based on two premises: a) the models have been solved by the inverse problem, i.e., setting certain features of the model, so there is not a unique solution, in fact there is an infinite number of valid solutions and any of them could be equally valid but, adding further stratigraphic and geometric information obtained from boreholes, seismic profiles and AMT soundings, only a few of them are possible; b) that gravimetric data are indirect measurements of a physical feature that we describe through a model; they are not a direct measurement of the problem parameters.

Even bearing in mind the model simplification with only four layers, these gravimetric models shed new light, on the subsurface disposition at depth in the Argentine provinces of Corrientes, West of Misiones and North of Entre Ríos.

The adjustment of the Bouguer anomaly values measured in the stations with respect to those calculated by the gravimetric models is very good, with differences lower than 4.8 mGal. In MODEL 2 there is an area with a high value. The explanation is that it may be due to an excessive simplification of the geological model in that area where, for example, the presence of diabase dikes interbedded among pre basalt sediments was detected (Fernández Garrasino et al., 2005; LEBAC, 2008; Oleaga, 2002). This fact has already been noted at the Belen borehole (Uruguay) where diabases predominate as from 1373 m deep. Those dikes, of a density clearly higher than the sediments, are relatively usual and frequent in lava effusion areas. An alternative explanation could be that the intense weathering in the basalts could affect a great thickness of them in more fractured areas or with more fluids circulation. For instance, sections with tens of meters of very weathered basalt

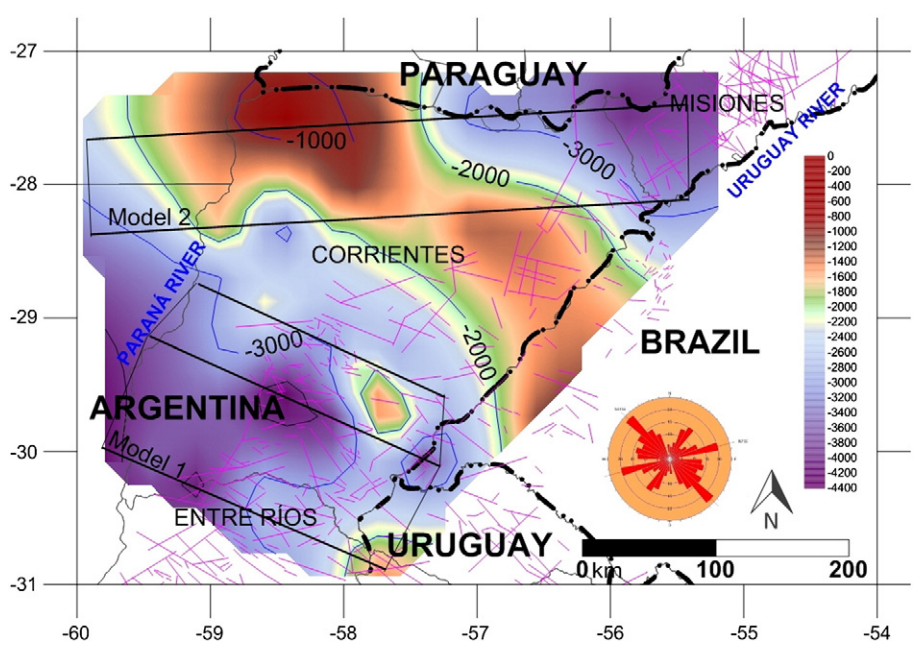

Fig. 4. Basement depth map as from the gravimetric models carried out. The photo-lineation traces and the rose diagram have been included (from Mira, 2012).

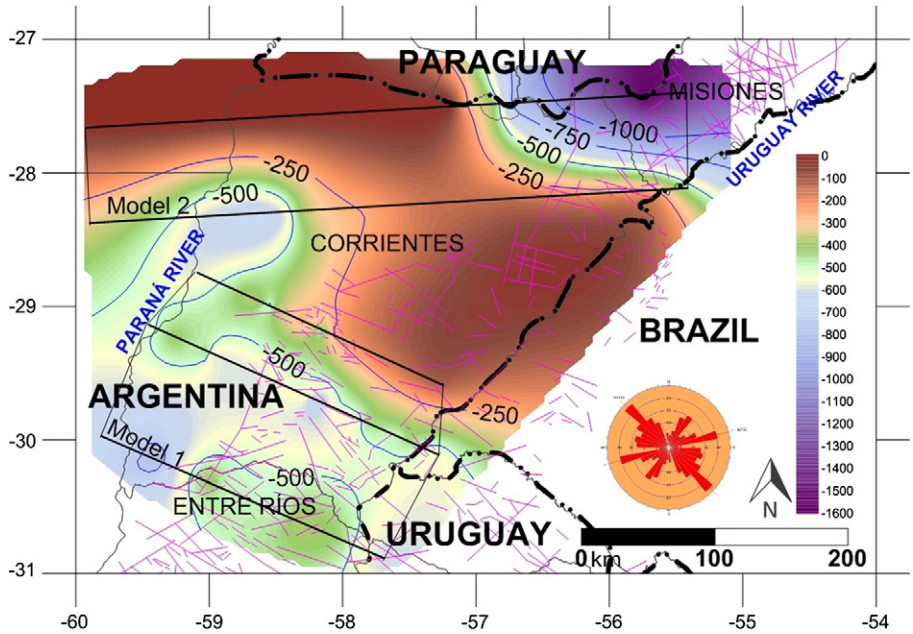

Fig. 5. Basalt thickness map calculated from the gravimetric models.

(almost clays) have been recognized in the recent thermal borehole of Curuzú Cuatiá, Corrientes province (Angeleri, *personal communication*).

Another feasible explanation of the difference between the measured gravity anomalies and those calculated could be the heterogeneities in the basement composition and its consequent lateral change in density values. According to Fulfaro (1996), the Río de la Plata Craton in the South area of Paraguay is composed by: migmatites, amphibolites, schist and rhyolite dikes near Paraná (Tebicuary Complex), metaconglomerates, sandstones, siltstones (Paso Pindo Group), granites, rhyolites and pyroclastic rocks in the area near Asunción. The existence of granite pebbles as component of Cretaceous sandstones, in samples from the Botucatu formation, (Bondpland, Misiones province), indicate a basement of that nature (Mira, 2012).

The basement geometry is characterized by the presence of large high and low structural blocks delimited by large sub-vertical discontinuities. In fact, the faults that delimit the different basement blocks reveal on the surface and control the drainage pattern of rivers and streams (Mira, 2012). The basement depth map (Fig. 4) highlights the existence of a strip approximately 2000 m deep that diagonally crosses Corrientes province from SE to NW and it would form a structural high coinciding with the DARG, corroborating its existence, proposed by Fernández Garrasino and Vrba (1999) and Rossello et al. (2006), but with its axis situated approximately 200 km westward (Fig. 1).

The photo-lineation traces (Figs. 4 and 5) confirmed that its main directions (N75E and N315E) are the same with the large regional faults (Mira, 2012). Also, the DARG ax has an orientation equivalent to the second one, N315E. Therefore, it is confirmed that the structure of the basement has a surface expression. It has a special hydrogeological importance determined by two factors: the rise of the GAS sedimentary series near the surface and the fracture network. This made this area prone to local recharge and regional discharge through the basalts as it has been confirmed in the other areas of the SAG (Fernandes et al., 2012).

According to Fig. 4, it is confirmed that the basement in Corrientes has a structural configuration in blocks aligned with a practically N–S orientation. It is the same structural configuration proposed by GEODATOS (2008) and Corbo et al. (2012) for Western Uruguay and Eastern Entre Ríos.

On the Northeast of Corrientes province the basement is situated less than 500 m deep, and even the basalt layer disappears confirming its lack

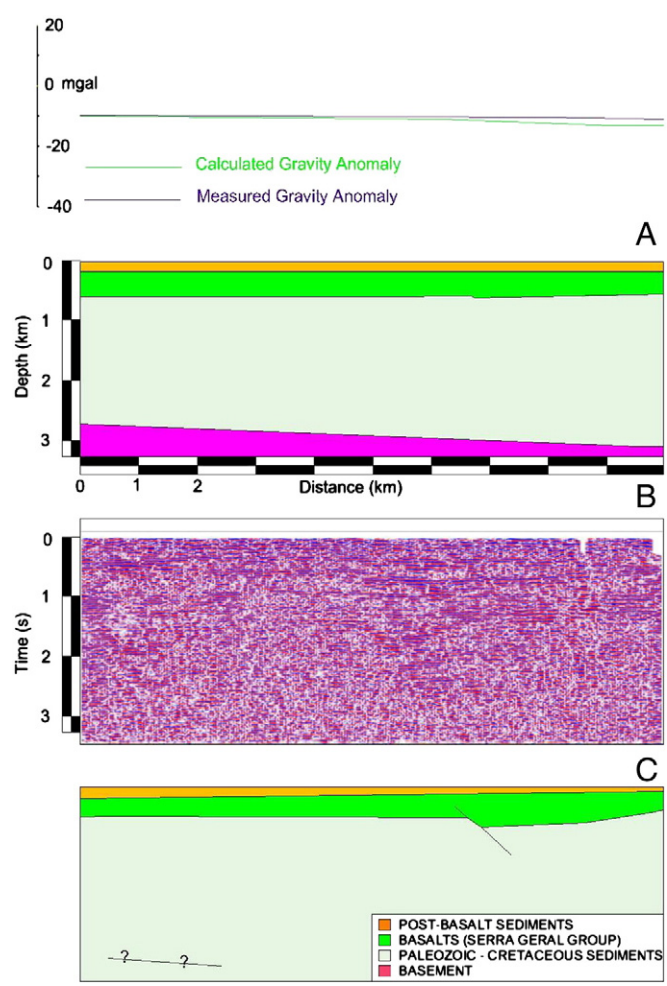

Fig. 6. Comparative cross sections of: A) an area of profile 10 of the gravimetric MODEL 1 (see location on Fig. 3, B) seismic section and C) interpreted seismic section.

of record in boreholes. These data are in accordance with the AMT survey profile carried out by GEODATOS (2008) in Ita Baté (Corrientes).

The gravimetric MODEL 1 agrees with the seismic profiles made by YPF in the center of Corrientes province (Fig. 6). The gravimetric MODEL 2 shows a thickness of the basalt layer higher than 1500 m on the East half and, though in the Paraná Basin more than 1700 m of basalt thickness have been reported in its center (LEBAC, 2008), in the Misiones province there are estimated values in Alem between 1013 and 1453 m (Curcio, 2008; SEGEMAR-DIGEOMIN, 2002).

6. Conclusions

A geological model has been developed. It is characterized by:

a) A faulted basement divided in raised and sunken blocks. There is a dorsal with basement depths between 500 and 1500 m that crosses Corrientes province from SE to NW. The shallowest basement would be near Alto de Caacupú (Paraguay)
b) The basement on both sides of the dorsal deepens rapidly reaching depths above 3000 m.
c) The basalts thickness varies. In MODEL 1 the average would be around 500 m of thickness, decreasing to the Northeast, where it would not be greater than 100 m. In MODEL 2 the thickness is low (lower than 200 m) where the basement is shallower, disappearing on the Northwest corner of Corrientes. Towards Misiones province it would increase considerably though with a thickness larger than the specified.
d) The existence and position of the DARG has a special hydrogeological importance because it produces the rise of the GAS sedimentary series near the surface and the intense fracture network made this area prone to local recharge and regional discharge of groundwater.

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References

Alasonati Tašárová, Afonso, J.C., Bielik, M., Götze, H.-J., Hók, J., 2009. The Lithospheric Structure of the Western Carpathian–Pannonian Basin Region Based on the CELEBRATION 2000 Seismic Experiment and Gravity Modelling. Elsevier B.V. http://dx.doi.org/10.1016/j.tecto.2009.06.003.

Araújo, L.M., França, A.B., Potter, P.E., 1999. Hydrogeology of the Mercosul aquifer system in the Paraná and Chaco–Paraná Basins, South America, and comparison with the Navajo–Nugget aquifer system, USA. Hydrogeol. J. 7 (3), 317–336.

Barredo, S., Stinco, P., 2010. Geodinámica de las cuencas sedimentarias. In: Petrotecnia, April 2010.

Campos, H., 2000. Mapa Hidrogeológico do Aqüifero Guaraní, escala 1:2.500.000. Editado por ISOMAPA — Consultoria e Projetos Ltda (São Paulo). Acta Geológica Leopoldensia, (São Leopoldo, Rio Grande do Sul), 23 (4).

Comin-Chiaramonti, P., Cundari, A., Piccirillo, E.M., Gomes, C.B., Castorina, F., Censi, P., De Min, A., Marzoli, A., Speziale, S., Velázquez, V.F., 1997. Potassic and sodic igneous rocks from eastern Paraguay: their origin from the lithospheric mantle and genetic relationships with the associated Paraná flood tholeiites. J. Petrol. 38, 495–528.

Corbo, F., Arzate, J., Oleaga, A., 2012. Structure of the Guarani Aquifer in the surroundings of the Uruguay River from magnetotelluric soundings. Geofis. Int. 51 (1), 17–37 (March).

Curcio, R., 2008. Estudio geofísico mediante sondeos magntetotelúricos en la Provincia de Misiones. Informe técnico del Consejo Federal de Inversiones de Misiones.

Fariña, S., Schmidt, G., Vassolo, S., 2007. Volumen 2 – Geología e Hidrogeología. – Informe no publicado (Proyecto SAG-PY: Uso Sostenible del Sistema Acuífero Guaraní en la Región Oriental del Paraguay SEAM/BGR). File BGR 0127039, Asunción, Hannover.

Fernandes, A.J., De Assis Negri, F., Azevedo Sobrinho, J.M., Varnier, C., 2012. Análise de fraturas dos basaltos do Aquífero Serra Geral e o potencial de recarga regional do Sistema Aquífero Guarani. Bol. Geol. Min. (ISSN: 0366-0176) 123 (3), 325–339.

Fernández Garrasino, C., 2008. Borde chacoparanense occidental de Argentina (Provincias de Salta, Tucumán, Santiago del Estero, Catamarca, Córdoba, Santa Fe, Entre Ríos y Corrientes). Informe del Consorcio Guaraní. Proyecto SAG-OEA/BM/GEF, Montevideo. (52 pp.).

Fernández Garrasino, C., Vrba, A., 1999. Estructura del tope de la Formación Serra Geral (Neojurásico-Eocretácico) en la Mesopotamia argentina y adyacencias. 14° Congreso Geológico Argentino, Actas 1: 185–188, Salta.

Fernández Garrasino, C., Laffitte, G., Villar, H., 2005. Cuenca Chacoparanaense. VI Congreso de Exploración y Desarrollo de Hidrocarburos. Simposio Frontera Exploratoria de la Argentina (97–114 pp.).

Fulfaro, V.J., 1996. Geology of Eastern Paraguay. In: Comin-Chiaramonti, P., Gomes, C.B. (Eds.), Alkaline Magmatism in Central–Eastern Paraguay. Relationships with Coeval Magmatism in Brazil. Edusp-Fapesp, SaÃoPaulo, Brazil, pp. 17–30.

Gastmans, D., Veroslavsky, G., Kiang Chang, H., Caetano-Chang, M.R., Nogueira Pressinotti, M.M., 2012. Modelo hidrogeológico conceptual del Sistema Acuífero Guaraní (SAG): una herramienta para la gestión. Bol. Geol. Min. 123 (3), 249–265 (ISSN: 0336-0176).

GEODATOS, S.R.L., 2008. Informe Final sobre Geofísica del SAG. SNC-LAVALIN. Proyecto SAG, OEA, BM, GEF. Montevideo. 266 pp.

Gómez Dacal, M.L., 2012. Modelado gravimétrico tridimensional del Macizo Norpatagónico Tesis de Grado. Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata.

Götze, H.J., 1978. Ein numerisches Verfahren zur Berechnung der gravimetrischen Feldgrößen drei-dimensionaler Modellkörper. Arch. Meteorol. Geophys. Bioklimatol. A 25, 195–215.

Götze, H.J., 1984. Über den Einsatz interaktiver Computergraphik im Rahmen 3-dimensionaler Interpretationstechniken in Gravimetrie und Magnetik. Habilitations-Schrift.Technische Universität Clausthal (121 Seiten).

Götze, H.J., Lahmeyer, B., 1988. Application of three-dimensional interactive modeling in gravity and magnetics. Geophysics 53 (8), 1096–1108.

Götze, H.J., Schmidt, S., Fichler, C., Planka, C., 2010. IGMAS+ a new 3D gravity, FTG and magnetic modeling software. Geophys. Res. Abstr. 12 (EGU2010-1306).

Herbst, R., 1971. Esquema estratigráfico de la provincia de Corrientes, República Argentina. Asoc. Geol. Argent. Rev. 26 (2), 221–243 (Buenos Aires).

Herbst, R., Santa Cruz, J., 1995. Mapa geológico de la Provincia de Corrientes E: 1:500.000. Secretaría de Minería. Dirección Nacional del Servicio Geológico de Argentina.

Herbst, R., Santa Cruz, J., Popolizio, E., Capurro, R., Escobar, E., 1985. Mapa Litoestratigráfico de la Provincia de Corrientes Universidad Nacional del Nordeste. d'Orbignyana – Corrientes, vol 2 1–50.

Hirata, R., Geisicki, A., Sracek, O., Bertolo, R., Giannini, P.C., Aravena, R., 2011. Relation between sedimentary framework and hydrogeology in the Guarani Aquifer System in São Paulo state, Brazil. J. S. Am. Earth Sci. 31 (4), 444–456.

Iriondo, M.H., 1991. El Holoceno en el Litoral. Comunicaciones Museo Provincial de Ciencias Naturales "F. Ameghino" (Nueva Seire), 3 (1) 1–40.

Iriondo, M.H., Krohling, D., Orfeo, O., 1998. Tropical realm (provinces of Corrientes and Misiones). Loess in Argentina: Temperate and Tropical (Iriondo, M., Chairman), Paraná, Argentina, Excursion Guide Nº 4 (27 pp.).

Jordan, T.E., Isaacks, B., Ramos, V.A., Allmendiger, R.W., 1983. Mountain building in the Central Andes. Episodio 3, 20–26.

Lagorio, S.L., Leal, P.R., 2005. Niveles peperíticos intercalados en los derrames lávicos de Serra Geral, provincia de Misiones. XVI Congreso Geológico Argentino, Actas 1, pp. 847–850 (La Plata).

LEBAC, 2008. Informe Final de Hidrogeologia do Projeto Aquífero Guarani. Coord.: Gastmans, D. & Chang, H.K. Equipe: Paula e Silva, F.; Correa, S.F.; Informe Técnico — Consórcio Guarani. Rio Claro, 172 pp.

Mariani, P., Braitenberg, C., Ussami, N., 2013. Explaining the thick crust in Paraná basin, Brazil, with satellite GOCE gravity observations. J. S. Am. Earth Sci. 45, 209–223. http://dx.doi.org/10.1016/j.jsames.2013.008.

Mársico, D., 2013. Aportes a la perspectiva geológica e Hidrogeológica regional en el sector centro Este de la cuenca chacopampeana. Ph. D University of La Coruña, Spain.

Milani, E.J., 2004. Comentários sobre a origem e a evoluçao tectónica da Bacia do Paraná. In: Mantesso-Neto, V., Bartorelli, A., Carneiro, C.D.R., Brito-Neves, B.B. (Eds.), Geologia do Continente Americano: Evoluçao da Obra de Fernando Flávio Marques de Almeida. Becca Produçoes Culturais, Sao Paulo, Brazil, pp. 265–295.

Milani, E., GonçalvesdeMelo, J., AlvesdeSouza, P., Fernandes, L., França, A., 2007. Bacia do Parana. B. Geoci. Petrobras, Rio de Janeiro, v. 15, n. 2 265–287.

Mingramm, A., 1965. Abandono del pozo estratigráfico F. MB. 1 — Mariano Boedo (Formosa). YPF, Buenos Aires. Inédito.

Mingramm, A., Russo, A., 1972. Sierras Subandinas y Chaco salteño. In: Leanza, A.F. (Ed.), Geología Regional Argentina: 185–211. Academia Nacional de Ciencias, Córdoba (869 pág.).

Mira, A., 2012. Modelo conceptual hidrogeológico del Sistema Acuífero Guaraní con énfasis en el sector Argentino. M. Sc. Thesis Polythecnic University of Cartagena, Spain (244 pp.).

Moritz, H., 1980. Geodetic Reference System 1980. Bull. Géod. 54, 495–505.

Nettleton, L., 1971. Elementary Gravity and Magnetics For Geologist and Seismologist. In: Wuenchel, P. (Ed.), Society of Exploration Geophysic.

Oleaga, A.B., 2002. Contribución a la hidrogeología del acuífero Guaraní en el sector Uruguay. Un enfoque integral. Disertación Universidad Nacional Autónoma de México, Ciudad de México (119 pp.).

Orfeo, O., Georgieff, S., Anis, K., Rizo, G., 2011. Depósitos sedimentarios modernos y antiguos del Río Paraná (Corrientes, Argentina): Un Análisis Comparativo XXIII Congreso Nacional del Agua Resistencia, Chaco, Argentina, pp. 101–109.

Padula, E., Mingramm, A., 1967. Informe de terminación del pozo Cha.LB.-x-2, Las Breñas, Chaco. YPF S. A., Buenos Aires.

Padula, E., Mingramm, A., 1969. Permian subsurface beds of the Chaco–Mesopotamian Region, Argentina, and their relatives in Brazil, Paraguay and Uruguay. International Union of Geosciences Gondwana Stratigraphy Symposium. Earth Sciences, 2. United Nations Educational, Scientific and Cultural Organization (UNESCO), París, pp. 1041–1051.

Parasnis, D., 1997. Principles of Applied Geophysics, 5th edition. Prentice and Hall (437 pp.).
Peate, D.W., 1997. The Paraná–Etendeka province. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Igneous Provinces: Continental Oceanic and Planetary Flood Volcanism. Geophysical Monograph, 100. American Geophysical Union, pp. 215–245.
Preciozzi, F., Spoturno, J., Heinzen, W., Rossi, P., 1985. Carta Geológica del Uruguay a escala 1:500.000. Dirección Nacional de Minería y Geología.
Putzer, H., 1962. Geologie von Paraguay. Beiträge zur Regionalen Geologie der Erde.Gebrüder Borntraeger, Berlin (182 pp.).
Ramos, V.A., 2000. The Southern Central Andes. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America. XXXI International Geological Congress (561–606 pp. Brasil).
Rossello, E., Veroslavsky, G., Santa Ana, H., Fúlfaro, V.J., Fernández Garrasino, C., 2006. La dorsal Asunción-Río Grande: un altofondo regional entre las cuencas Paraná (Brasil, Paraguay, Uruguay) y Chacoparanense (Argentina). Rev. Bras. Geocienc. 36, 181–196.
Russo, A., Archangelsky, D., Andreis, R., Cuerda, A., 1987. Cuenca Chacoparanense. Subcomisión Internacional del Carbonífero, Proyecto 211 del Proyecto Internacional de Correlación Geológica (PICG), Academia Nacional de Ciencias. In: Archangelsky, S. (Ed.), El Sistema Carbonífero en la República Argentina, pp. 197–212 (Córdoba).
Santa Ana, H., Veroslavsky, G., 2003. La tectosecuencia volcanosedimentaria de la Cuenca Norte de Uruguay. Edad Jurásico–Cretácico Temprano. In: Veroslavsky, G., Ubilla, M., Martínez, S. (Eds.), Cuencas sedimentarias de Uruguay: geología, paleontología y recursos naturales — Mesozoico. Facultad de Ciencias, Dirac, pp. 51–74.
Santa Cruz, J., 1981. Bases Hidrogeológicas Generales de la Provincia de Corrientes. VIII Congreso Geológico Argentino. Actas, IV, pp. 231–242 (San Luis, Argentina).
Scherer, C., 2002. Preservation of aeolian genetic units by lava flows in the Lower Cretaceous of the Paraná Basin, southern Brazil. Sedimentology 49, 97–116. http://dx.doi.org/10.1046/j.1365-3091.2002.00434.x.
Schmidt, S., Götze, H.J., 1998. Interactive visualization and modification of 3D models using GIS functions. Phys. Chem. Earth 23 (3), 289–295.
Schmidt, S., Götze, H.-J., Alvers, M., Fichler, C., 2010. IGMAS+ a new 3D Gravity, FTG and Magnetic Modeling Software. In: Zipf, A., Behncke, K., Hillen, F., Schefermeyer, J. (Eds.), (Hrsg.) : Die Welt im Netz (Geoinformatik 2010, Kiel, 17.3. - 19.3.2010). Akademische Verlagsgesellschaft AKA GmbH, Osnabrück. ISBN: 978-3-89838-335-6, p. S. 57-63.
Schobbenhaus, C., Bellizzia, A., 2001. Mapa geológico de América del Sur, 1:5.0000.000. CGMW - CPRM – DNPM – UNESCO, Brasilia.
SEGEMAR-DIGEOMIN, 2002. Evaluación del Recurso Geotérmico en la zona de Leandro N. Alem, Provincia de Misiones. Proyecto de Perforación Termal, 2ª etapa, estudio geofísico.
Silva Busso, A., 1999. Contribucíón al Conocimiento de la Geología e Hidrogeología del Sistema Acuífero Termal de la Cuenca Chacoparanense Oriental, Argentina. Ph.D. Thesis Facultad de Ciencias Exactas y Naturales, Bueno Aires (2v. 351 pp.).
Tankard, A., Uliana, M., Welsink, H., Ramos, V., Turic, M., França, A.B., Milani, E., De Brito Neves, B., Eyles, N., Skarmeta, J., Santa Ana, H., Wiens, F., Cirbian, M., Lopez Paulsen, O., Germs, G., De Wit, M., Machacha, T., Miller, R. Mc G., 1995. Structural and tectonic controls of basin evolution in Southwestern Gondwana during the Phanerozoic. In: Tankard, A., Suárez Soruco, R., Welsink, H. (Eds.), Petroleum Basins of South America. American Association of Petroleum Geologists Memoir, 62, pp. 5–52 (Tulsa).
Tófalo, O., Marengo, H., Wilson, C., 2008. Las Formaciones Guichón y Mercedes (Cretácico), en la provincia de Corrientes. Actas XII Reunión Argentina de Sedimentología. Buenos Aires.
Wildner, W., Hartmann, L., Lopes, R., 2007. Serra Geral magmatism in the Paraná Basin, a new stratigraphic proposal, chemical stratigraphy and geological structures. Gramado. Problems in the Western Gondwana Geology, I Workshop – South America – Africa, v. 1, pp. 189–197.
Winn Jr., R.D., Steinmetz, J.C., 1998. Upper Paleozoic of the Chaco–Paraná basin, Argentina, and the great Gondwana glaciation. J. S. Am. Earth Sci. 11 (2), 153–168.
Zalán, P.V., Wolff, S., Astolfi, M.M., Vieira, I.S., Conceição, J.C., Appi, V.T., Neto, E.V., Cerqueira, J., Marques, A., 1990. The Paraná Basin, Brazil. In: Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J. (Eds.), Interior Cratonic Basins. Amer. Assoc. Petrol. Geol. Memoir, N°51, pp. 681–708.