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Possible hydrogeological and thermal conditions of the Quilmes Tectonic Trough (Buenos Aires Province, Argentina): a working hypothesis

Posibles condiciones hidrogeológico-termales de la fosa de Quilmes (Provincia de Buenos Aires, Argentina): una hipótesis de trabajo

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ABSTRACT

The proposal of the Quilmes Tectonic Trough (*Fosa tectónica de Quilmes* – FQ) as the extension of the southern end of the Santa Lucía basin in Uruguay and its connection to the Salado basin in Argentina suggest the existence of a large sedimentary volume capable of housing a new aquifer on the La Plata River coast. However, the sedimentary volumes that form the FQ are hidden under a thick, recently deposited cover, and thus, there is a lack of studies on the nature of this formation. Nevertheless, the Uruguayan section of the Meso-Cenozoic depocenter of the Santa Lucía basin has been more thoroughly studied for hydrocarbon exploration, which enabled us to estimate the equivalent tectosedimentary characteristics in the FQ. In the Uruguayan territory, three aquifer systems of the Santa Lucía basin are exploited: the Raigón (Plio-Pleistocene) aquifer, which is the most important source of groundwater for various uses in the south-central region of Uruguay, and the Mercedes (Upper Cretaceous) and Mígues (Lower Cretaceous) aquifers, which are also used, albeit to a lesser extent, for drinking water, irrigation, and industrial purposes. The Mígues aquifer, the least known of the three, shows a variable depth ranging from 100 to 1500 m and considerable stratigraphic sequences of porous and permeable sandstones. These sandstones provide the aquifer with very good qualities as a reservoir rock; as such, the Mígues aquifer has been studied for its potential natural gas reserves and geothermal and water resources. Accordingly, if the same sequences with equivalent sedimentary and hydrogeological qualities are present in the FQ, similar aquifers with interesting properties may remain unidentified along the Buenos Aires coast beneath the intensely explored Puelches, Pampeano and Paraná aquifers. In conclusion, specific exploratory activities may prove the existence and quality of these hydrogeological

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resources, the regional slope toward the southwest from the Uruguayan outcrops, upwelling or semiupwelling conditions and even geothermal energy associated with the deepest cretaceous aquifers.

Keywords: Hydrogeological resources, Quilmes tectonic trough, Buenos Aires Province, Argentina.

RESUMEN

A partir de la propuesta de la fosa tectónica de Quilmes (FQ) como extensión de la prolongación austral de la cuenca Santa Lucía de Uruguay, y su conexión con la cuenca del Salado, de Argentina, se puede considerar como hipótesis de trabajo la existencia de un gran volumen sedimentario, capaz de albergar un nuevo acuífero sobre el litoral rioplatense. Los volúmenes sedimentarios que constituyen la FQ están ocultos debajo de una potente cubierta moderna, por esta razón la falta de estudios de superficie específicos no permite conocer su verdadera naturaleza. Dado que la continuación uruguaya del depocentro meso-cenozoico de la cuenca Santa Lucía está mejor estudiada, a partir de la exploración de hidrocarburos, se pueden estimar características tectosedimentarias equivalentes en la fosa de Quilmes. En el territorio uruguayo se explotan tres sistemas acuíferos que se desarrollan en la cuenca Santa Lucía: el acuífero Raigón (Plio-Pleistoceno), que constituye la fuente de agua subterránea más importante de la región centro-sur de Uruguay, destinada a diversos usos, y los acuíferos cretácicos Mercedes (Cretácico Superior) y Migues (Cretácico Inferior), que también son usados, en menor medida, para el suministro de agua potable, riego y usos industriales. El acuífero Migues es el menos conocido y se desarrolla a profundidades variables (100 a 1500 m), donde exhibe considerables sucesiones de areniscas porosas y permeables que le confieren muy buenas cualidades como roca reservorio, y es objeto de estudio con fines de almacenamiento de gas, recursos geotermales e hídricos. Por esta razón, si las mismas secuencias con cualidades sedimentarias e hidrogeológicas equivalentes están presentes en la fosa de Quilmes, se podría esperar el hallazgo de interesantes acuíferos relacionados, aún desconocidos en el litoral bonaerense, por debajo de los tradicionales Puelches, Pampeano y Paraná. De comprobarse la existencia y calidad de estos recursos hidrogeológicos a partir de la realización de actividades exploratorias específicas, la pendiente-gradiente regional hacia el sudoeste desde los afloramientos de Uruguay, se podrían esperar condiciones de surgencia o semisurgencia natural, e incluso geotermalismo asociado a los acuíferos cretácicos más profundos.

Palabras clave: Recursos hidrogeológicos, fosa tectónica de Quilmes, Provincia de Buenos Aires, Argentina.

1. INTRODUCTION

The identification and interpretation of the Quilmes Tectonic Trough (*Fosa Tectónica de Quilmes* – FQ) as the southern extension of the Santa Lucía basin in Uruguay and its connection to the Salado basin in Argentina (Rossello et al., 2011) suggest the existence of a large sedimentary volume capable of housing several unknown aquifer systems on the La Plata River coast (Santa Cruz, 1972; Sala and Hernández, 1993; Santa Cruz et al., 1997; Auge, 2005; Amato and Silva Busso, 2006), which is the working hypothesis of this study.

The area of the western extension of the Santa Lucía basin (De Santa Ana et al., 1994) remains uncertain due to its location on the international boundary between Argentina and Uruguay and a general lack of data (Figure 1). Nevertheless, through joint interpretations, studies from both countries have identified evidence of Meso-Cenozoic infills on the northern coast of the Buenos Aires province (the FQ), which are consid-

ered the extension of the Santa Lucía basin into the Argentinian territory (Rossello et al., 2017, 2018).

Rossello et al. (2017, 2018) provided potential arguments that weaken the hypothesis of a first-order tectonic boundary, originally proposed by the geologist Alberto Mingramm in *Umbral de Martín García* [Martín García Swell] (Zambrano, 1974). Since then, most researchers have continued to support this interpretation, designating the structure as Martín García High (*Alto de Martín García*), based on a lack of data for the Santa Lucía basin in the Argentine territory. This tectonic feature was assumed to be an uplifted sector of the crystalline basement from the projection of Martín García Island, the outline of which is located in the La Plata River and almost matches the international boundary between Argentina and Uruguay. Thus, the Martín García High became a physical western boundary in the Mesozoic records of the Santa Lucía basin and was even projected onto the Atlantic continental shelf as the La Plata River High (*Alto del Plata*).

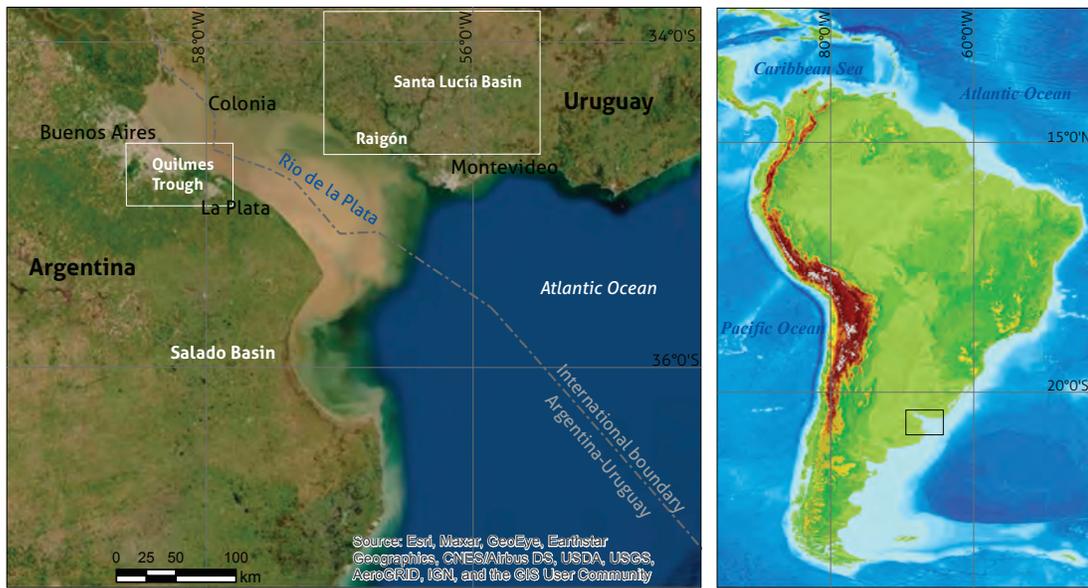


Figure 1. Regional location of the study sector on a satellite image of the La Plata River (left) and on a map of South America (right)
Source: Earth Sciences and Image Analysis Laboratory, NASA - <https://eol.jsc.nasa.gov/>

However, the true nature of the sedimentary volumes that form the FQ and that may eventually become suitable aquifers for various uses (drinking water, agricultural-industrial uses, geothermal purposes and fluid storage) is poorly known due to the current lack of specific subsurface studies (Rossello et al., 2017, 2018). This region lacks detailed geophysical surveys and sufficiently deep exploratory wells because the potential exploration targets are hidden under a deep and modern cover. For this reason, in this study, assuming that the FQ is the extension of the depocenter of the Santa Lucía basin into the territory of Buenos Aires, the possibility of examining and analyzing the existence of large aquifers located in Cretaceous continental siliclastic sequences is proposed as a working hypothesis.

Thus, the main objective of this study is to propose a working hypothesis that will generate interest in promoting exploration activities and basic research to confirm or reject this new hydrogeological potential located at greater depths and beneath the structure commonly known as the Puelches aquifer.

2. METHOD

The geological arguments that support the hypothesis that new deeper aquifers may be found in the FQ based on gravimetric and shallow well data available in the literature are summarized in this study.

To compare the possible sedimentological, petrophysical and hydrogeological characteristics of the deepest aquifers in the FQ, a general tectono-stratigraphic correlation is performed between the Santa Lucía basin to the east (Veroslavsky, 1999; Rossello et al., 2011; Rodríguez et al., 2020) and the Salado basin to the west (Yrigoyen, 1975; Tavella and Wright 1996; Yrigoyen, 1999; Tavella, 2005; Raggio et al., 2012).

A review of the sedimentological, petrophysical and hydrogeological characteristics of different aquifers located in the sedimentary infill and basement of the Santa Lucía basin provides the expected data for the FQ.

The regional structural deepening trend of sedimentary sequences capable of supporting upwelling aquifers and the observed geothermal capacity from Uruguay to the Salado basin is established based on simplified schemes.

3. REGIONAL GEOLOGICAL FRAMEWORK

The waters of the La Plata River divide the Argentinian and Uruguayan territories, the coasts of which are characterized by extensive plains covered by recent sediments that have been partly or fully deposited on pediment areas of the Precambrian basement, constituents of the La Plata River Craton and the Mesozoic depocenters of the Salado and Santa Lucía basins (Rossello et al., 2017, 2018). In the Argentinian territory, excluding

the outcrops of the Tandilia Mountain Ranges, the only inlier of this basement on the Martín García Island consists of amphibolites, gneisses and schists, which indicates a sedimentary protolith with a greater overall planar anisotropy in the NE direction (Dalla Salda, 1981), in line with observations for the southeastern Uruguayan basement (Oyhantçabal et al., 2011).

3.1 Quilmes tectonic trough

Based on a limited number of old wells in Buenos Aires, the province basement has been located at varying subsurface depths (Figures 2 and 4), which according to the data available at the time, were quite shallow (Artaza, 1943; Groeber, 1945). For example, drilling at La Piedad church (located along the current streets of Bartolomé Mitre and Paraná in Buenos Aires) revealed lithologies attributed to the crystalline basement 283 m below the wellhead (m.b.w.h.) (Figure 2). In the city of Olivos, Buenos Aires Province, the same lithologies were found

at 245 and 401 (when drilling at La Noria Bridge (Groeber, 1945). Farther south, at Vucetich Park, in the city of La Plata, Groeber (1945) mentioned in a profile of San Nicolás - Monte Veloz that the basement was found 485.35 m.b.w.h. and included a well in Hudson (10.25 m above sea level (m.a.s.l.)); below approximately 200 m of sediment, gneissic material was identified at 369.95 m.b.w.h.; further, this formation was originally described as *el Rojo Mesopotámico inferior* [Red Lower Mesopotamic] and subsequently termed the Olivos Formation (Oligocene-Lower Miocene, continental), the *Verde Mesopotámico superior* [Green Upper Mesopotamic] and the Paraná Formation (Upper Miocene, marine) and was ultimately overlain with the Puelches and Pampeano aquifers and had good hydrogeological conditions (González Bonorino, 1965; Santa Cruz et al., 1997).

The Hudson well is located on the central axis of the proposed FQ (Figure 2). As in other wells drilled at that time

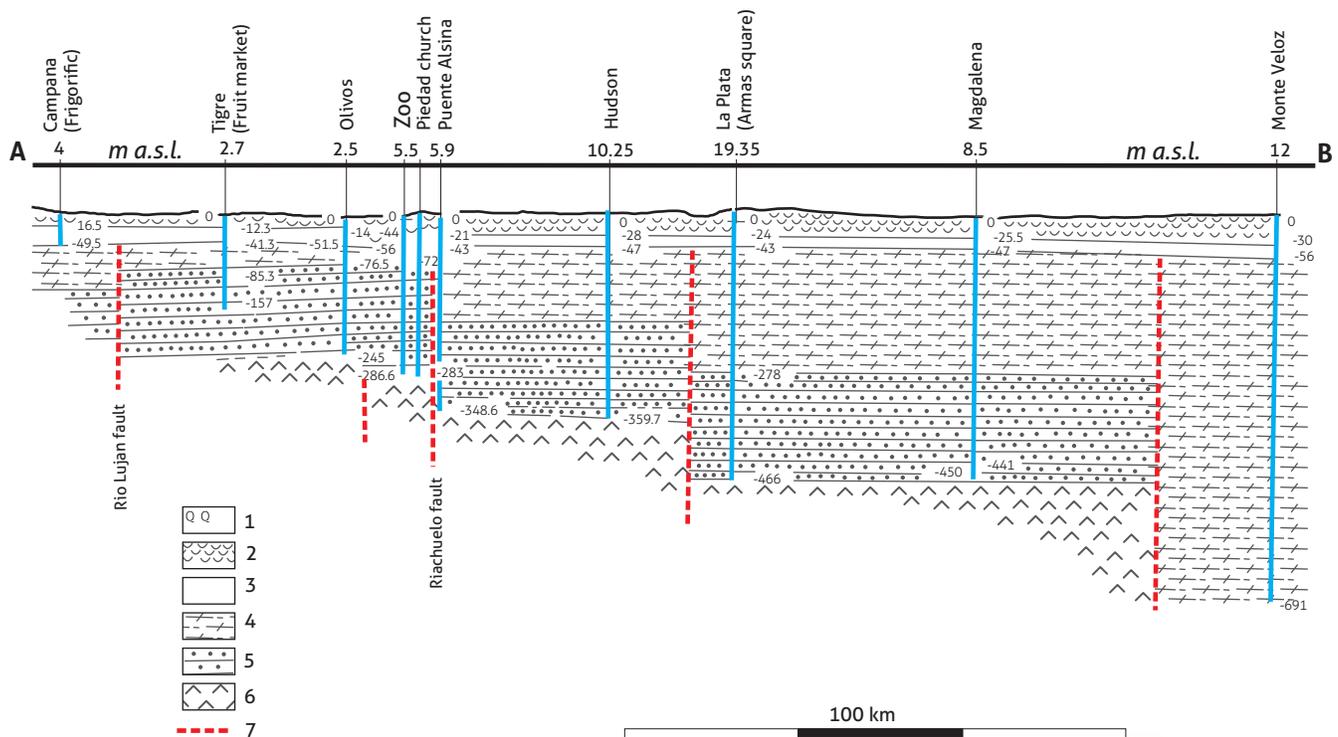


Figure 2. Reproduction of the San Nicolás - Monte Veloz profile along the Buenos Aires coast of the La Plata River (see the location in Figure 4) Location and depth in meters and lithologies crossed by wells drilled in the 1940s to provide drinking water. 1: Querandino; 2: Pampeano; 3: Puelches; 4: Verde Mesopotámico superior; 5: “Rojo Mesopotámico inferior”; 6: basement; 7: fault. Source: retrieved from Groeber (1945).

(Artaza, 1943), the Hudson well ends at the point when the drill cuttings generated by percussion drilling methods in the typical crystalline basement lithologies (gneisses, granites and amphibolites) are recovered. However, these drill cuttings, presumably derived from the tops of the basement blocks, could have also been generated by intercalations of conglomeratic levels formed by granitic clasts. Levels with these petrographic characteristics form the outcrops of the Cañada Solís and Mi-gues formations in the western region of Minas and the exploratory wells of the Santa Lucía basin (Veroslavsky et al., 2004). Thus, considering the last alternative, these findings match the interpretation supported by gravimetry, which suggests a much deeper sedimentary infill than that supplied by the Hudson well (Rossello et al., 2011; Rodríguez et al., 2020). In turn, Perdomo et al. (2017) performed vertical electrical sounding, measured gravity values in the Buenos Aires partido [county] of La Plata and assessed depth variations of up to 200 m in the basement proposed for the Vucetich Park well (Figure 2), with a block morphology delimited by extensional faults arranged in a NE-SW direction.

Although neither seismic data nor sufficiently deep wells are available yet in this riparian sector of the La Plata River, in the province of Buenos Aires, gravimetric data and regional correlations suggest that the FQ is the western extension of the Santa Lucía basin into Argentinean territory (Rossello et al., 2011, 2017). Based on the available tectosedimentary data, the sedimentary infill has an average depth of approximately 200 m and essentially consists of continental Cretaceous sequences that merge from the Santa Lucía basin directly into the Salado basin and are then covered by a Cenozoic sedimentary cover (Figure 3).

Based on gravimetric data acquired on the NE coast of Buenos Aires and between Buenos Aires and Magdalena (Gianibelli and Ríos, 1989; Gianibelli et al., 1989; Cabassi et al., 1996) and combined with other data from the geodetic bases of the Argentinean National Geographic Institute (*Instituto Geográfico Nacional de la República Argentina* – IGN), new gravimetric models were generated and processed using the GM-SYS software. These models made it possible to identify a depocenter occupying approximately 20000 km² under the

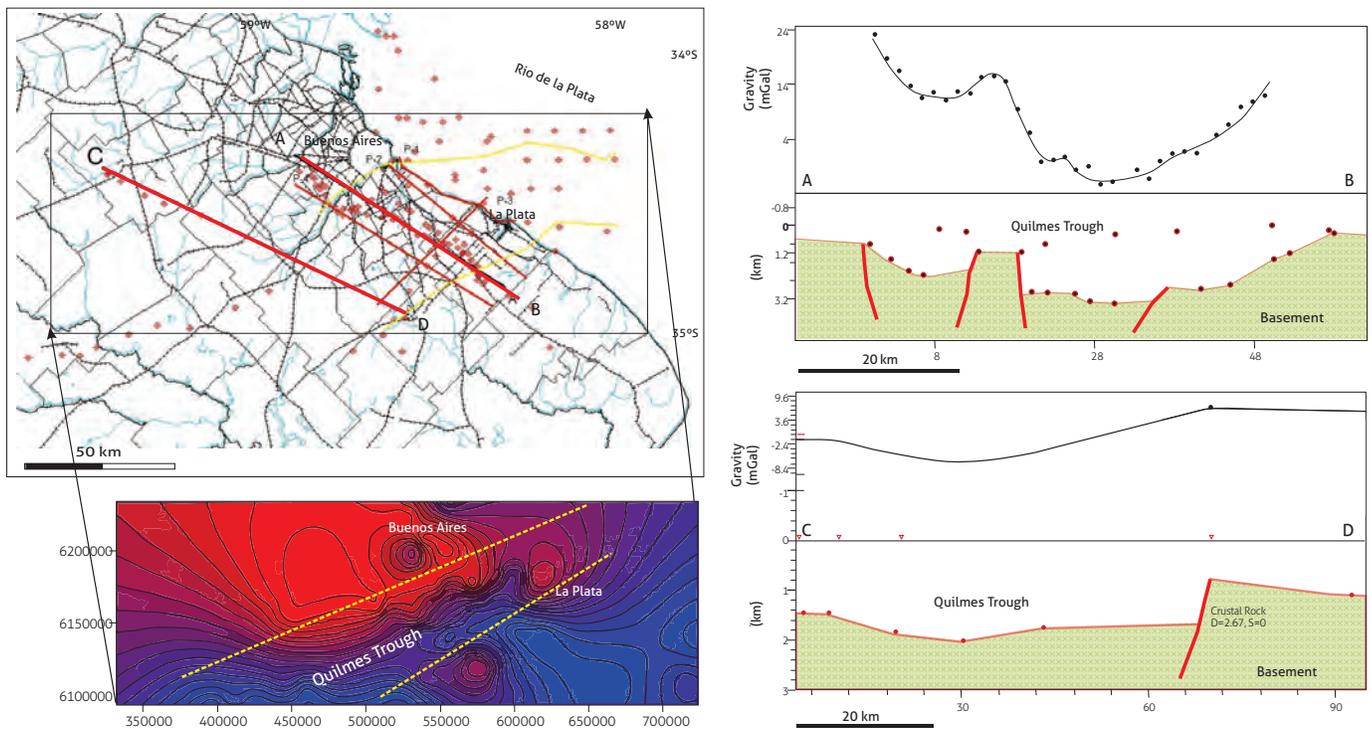


Figure 3. Bouguer anomaly map of the province of Buenos Aires and gravity cross-sections obtained using data from the Military Geographic Institute (*Instituto Geográfico Militar* – IGM) collected on the Buenos Aires shore of the La Plata River and from the GM-SYS model
Source: retrieved from Rossello et al. (2011)

recent sedimentary cover of the continental and fluvial Buenos Aires territories. Rossello et al. (2011) identified first-order structural features with subparallel highs and lows and matching general ENE-WSW directions in the basement, similar to those in the Santa Lucía basin, and with extensional tectonics related to the Gondwana breakup and the early opening of the Atlantic Ocean (Figure 3). This structuring is considered to be one of the factors responsible for the 3.8-degree earthquake recorded approximately 20 km south of Buenos Aires on November 30, 2018, with an estimated epicenter of approximately 4.5 km (Rossello et al., 2020).

3.2 The Santa Lucía basin

The Santa Lucía basin (CSL, for its acronym in Spanish) covers an area of nearly 6000 km² in the Uruguayan territory, has a slightly triangular geometry and is filled with almost 2500 m of sequences from the Jurassic to the present day. These sequences most likely continue in equivalent units in the FQ (Figure 4).

The CSL derives from an intracratonic pull-apart depositor (Veroslavsky, 1999; Rossello et al., 2001) that is spread through the main zones of crustal weakness in the crystalline basement, particularly those that determine the main boundaries of the sedimentary infills and internal highs arranged in E-NE directions.

As shown by subsurface surveying for hydrocarbon exploration involving gravimetric and 2D seismic surveys with wellhead control, the Santa Lucía basin has a morphostructural conformation typical of a pull-apart rift generated by dextral transpression, with uplifted basement blocks and intermediate troughs with syn-sedimentary infills (Rossello et al., 2001). The Santa Lucía basin shows an asymmetric profile generated by a conjugated system of synthetic and antithetic listric normal faults defining successive grabens and horsts of different scales (Figure 5). This arrangement highlights two subbasins separated by the crystalline Santa Rosa High (*Alto de Santa Rosa*) (Veroslavsky et al., 2004).

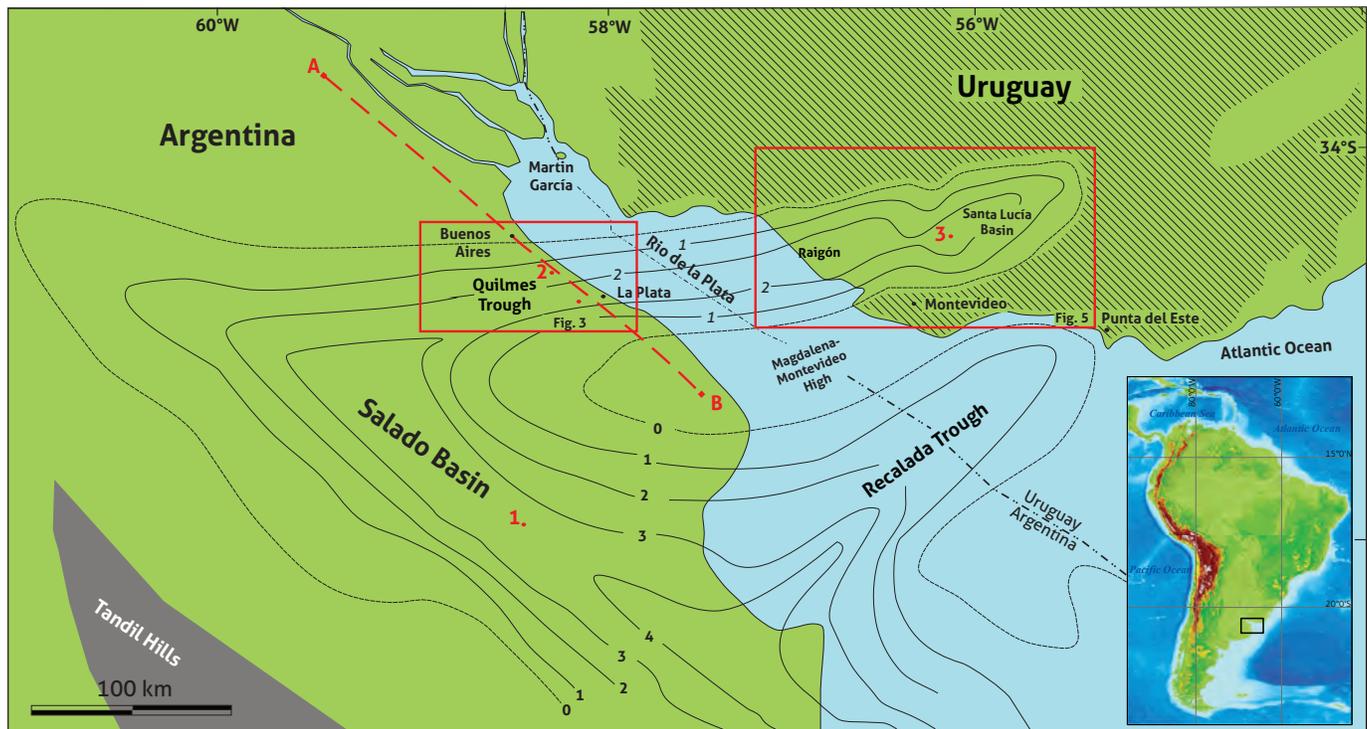
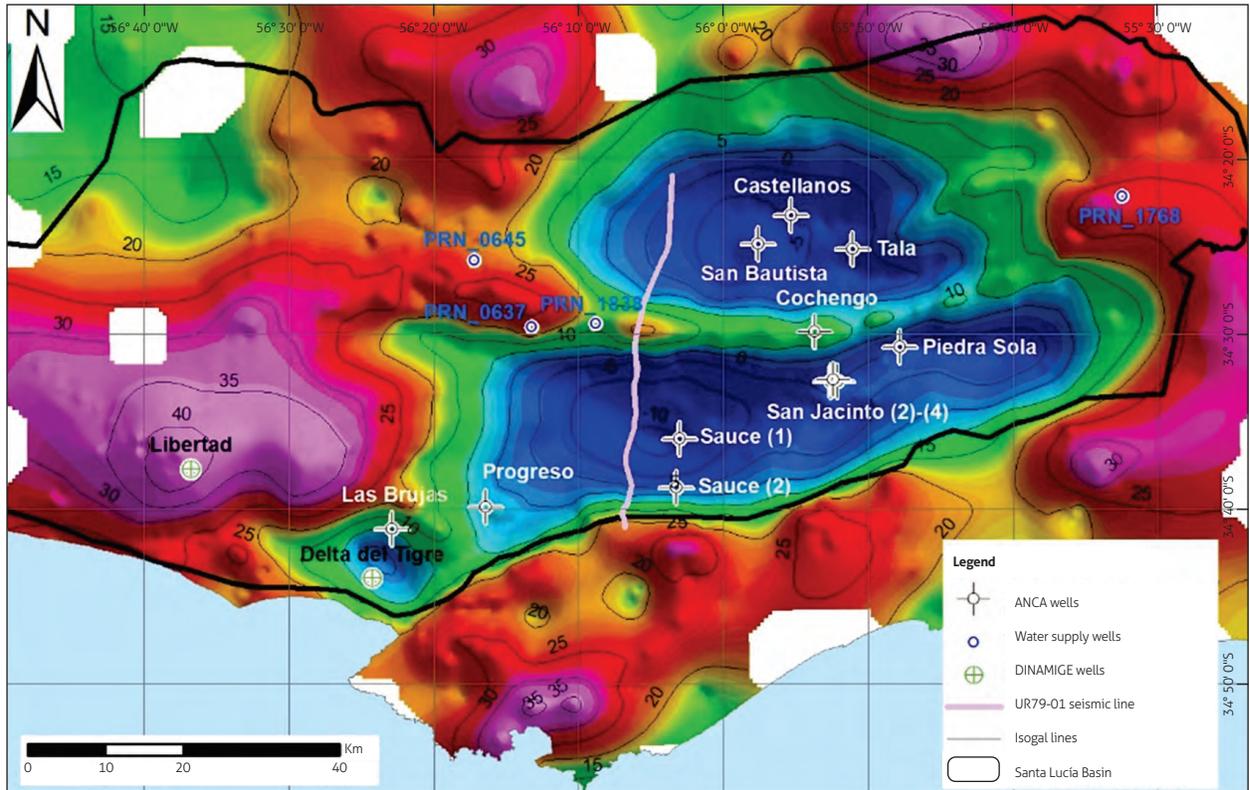


Figure 4. Schematic isopach map of Meso-Cenozoic sedimentary records showing the location of the FQ and the Recalada trough and their relationships with the Salado and Santa Lucía basins. The striped sectors correspond to crystalline basement outcrops. The red dashed A-B line indicates the approximate position of the profile in Figure 2. The red circles indicate the positions of the 1) General Belgrano, 2) Hudson and 3) Sauce wells. Source: retrieved from Rossello et al. (2017).

a



b

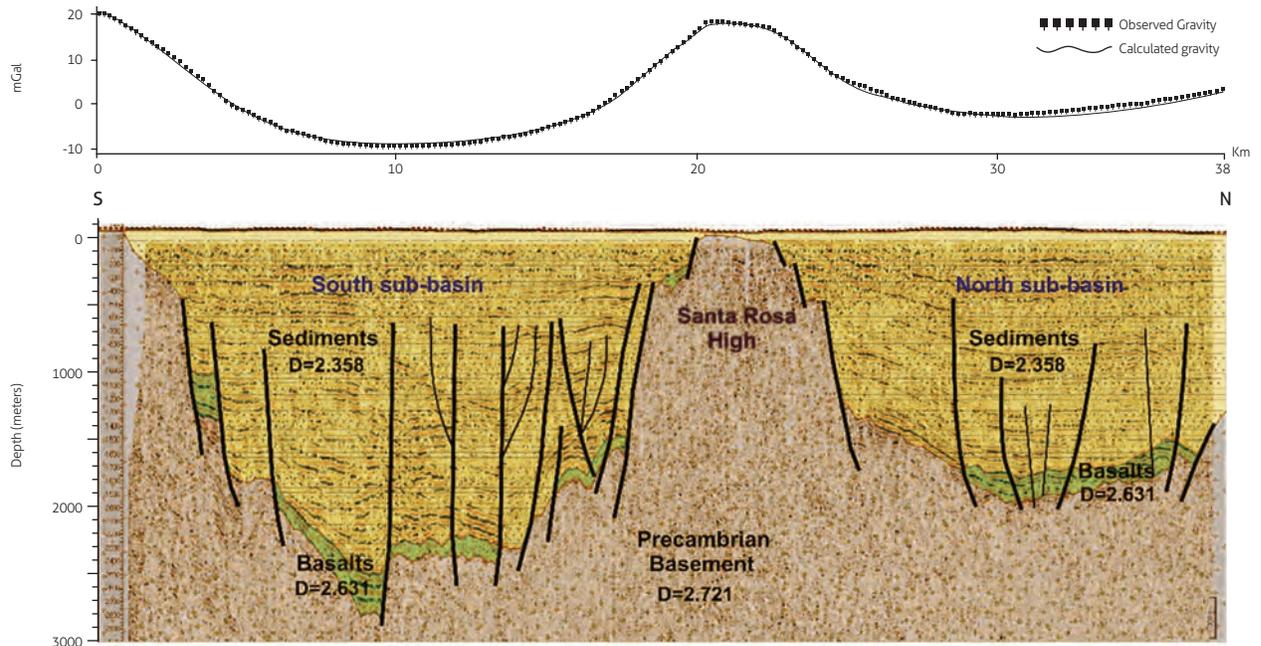


Figure 5. a) Bouguer anomaly map of the Santa Lucía basin, showing the arrangement of the two subbasins separated by the Santa Rosa high. b) Cross-sections of the 2D gravity model, supported by seismic line UR76-01
Source: adapted from Rodríguez et al. (2020)

Based on surface information, seismic surveys and several exploratory wells, Veroslavsky et al. (2004) proved the presence of pre-rift and rift records, which are assigned to the Upper Jurassic and Lower Cretaceous (Figure 6). Their rocky records, which exceed 2300 m in the Sauce 1 well, begin with a few basaltic eruptions that correspond to the Puerto Gómez Formation, which overlays the Precambrian basement in some sectors. These basalts are interspersed with thick continental sedimentary rocks of the Cañada Solís Formation that are interpreted as alluvial systems and are laterally and vertically related to the sandstones, conglomeratic sandstones and subordinate pelites of the Migues Formation. These lithological terms are interpreted as deposits of river and lake systems, with some associated wind episodes. The Castellanos Formation developed in the central sector of the basin, particularly in the domain of the northern subbasin, and consists of a sequence of pelites, claystones and gray sandstones, with occasional intercalated levels of anhydrite, the facies associations and paleontological content of which indicate a primarily lacustrine origin and an Aptian Albian age (Veroslavsky, 1999; Campos, 1998).

The structural configuration of the basin reveals potential stratigraphic traps (pinchout) combined with closure against a fault (particularly against the Santa Rosa high and other sectors with strong structural compartmentalization, *e.g.*, the Sauce depocenter of the southern subbasin, Figure 5).

Toward the Upper Cretaceous, the sedimentation changed to a continental siliciclastic sequence developed in a post-rift setting that exceeded the boundaries of the basin that controlled the sedimentation during the Lower Cretaceous. In the geographical area where the Santa Lucía basin developed, these continental records do not exceed 100 m and essentially gather fluvial deposits that meet in a) the Mercedes Formation, which consists of white and pink sandstones and conglomeratic sandstones of varied granulometry, with conglomeratic, pelitic and calcareous intercalations in strongly silicified sectors, and b) the Asencio Formation, which consists of whitish, fine, massive and laminated sandstones and has been affected by intense ferrification processes near the top (Figure 6). Some authors have included the limestone deposits caused by intense calcretization processes associated with the Mercedes Formation in the Queguay Formation (Spoturno et al., 2004).

From the Oligocene to the present, the Cretaceous sequences have been covered by continental and transitional sedi-

mentary rocks, including pelites, fine-to-coarse sandstones and clays of the formations shown in Figure 6.

The Fray Bentos Formation is the first Cenozoic depositional event and is characterized by siliciclastic continental Oligocene deposits linked to arid and semiarid conditions, interspersed with short humid periods, including the following main lithologies: fine-to-medium-coarse sandstones, pinkish and somewhat sandy loessic silts, lutite and conglomerate and conglomeratic sandstone lenses (Spoturno et al., 2004). The sandstones and silts are generally cemented by calcium carbonate, which is either pulverulent or in sandstones with irregular shapes. In the basin, the unit has a thickness ranging from a few meters to slightly over 100 m and develops as a wedge that thickens toward the west (Spoturno et al., 2004).

The Camacho Formation corresponds to preserved, Upper Miocene marine transgressions, which are thicker (30-35 m) in the southwest region of the CSL, and is traditionally correlated with the Paraná Formation in the Argentinian territory (del Río and Martínez, 1998). This formation is represented by silty claystones, claystones with hues ranging from greenish gray to black, mudstones with a clayey siltitic matrix and sand, gravel and bivalve mollusk clasts with hues ranging from greenish dark gray to black, detrital and biodetrital sediments of lumachelles with a grayish fine-to-medium-coarse sandy matrix and fine-to-very-fine sandstones with a clayey matrix and calcareous cement.

The Raigón Formation encompasses fluvial and transitional continental Plio-Pleistocene sediments of sand and gravel, different from the Fray Bentos Formation but similar to the Camacho Formation, which is covered by the Libertad Formation. The Raigón Formation is located in the departments of Montevideo, Canelones, San José and Colonia in Uruguay, which support the important homonymous aquifer and display a gradual subsidence toward the SW (Figure 7).

The depth of the Raigón Formation peaks in the coastal areas, ranging from approximately 40 to 45 m, and has minimum values between 5 and 10 m in the continental zones (Pena et al., 2013). The main lithological compositions of the Raigón Formation in more than 70 wells include white, feldspathic fine-to-medium-coarse sands, thick arkosic sands, chippings, gravels and polymictic pebbles and boulders, all of which are interstratified with more or less continuous lenses of clays and fine clayey sands with hues ranging from brown to green (Heinzen et al., 1986; Carrión et al., 2011).

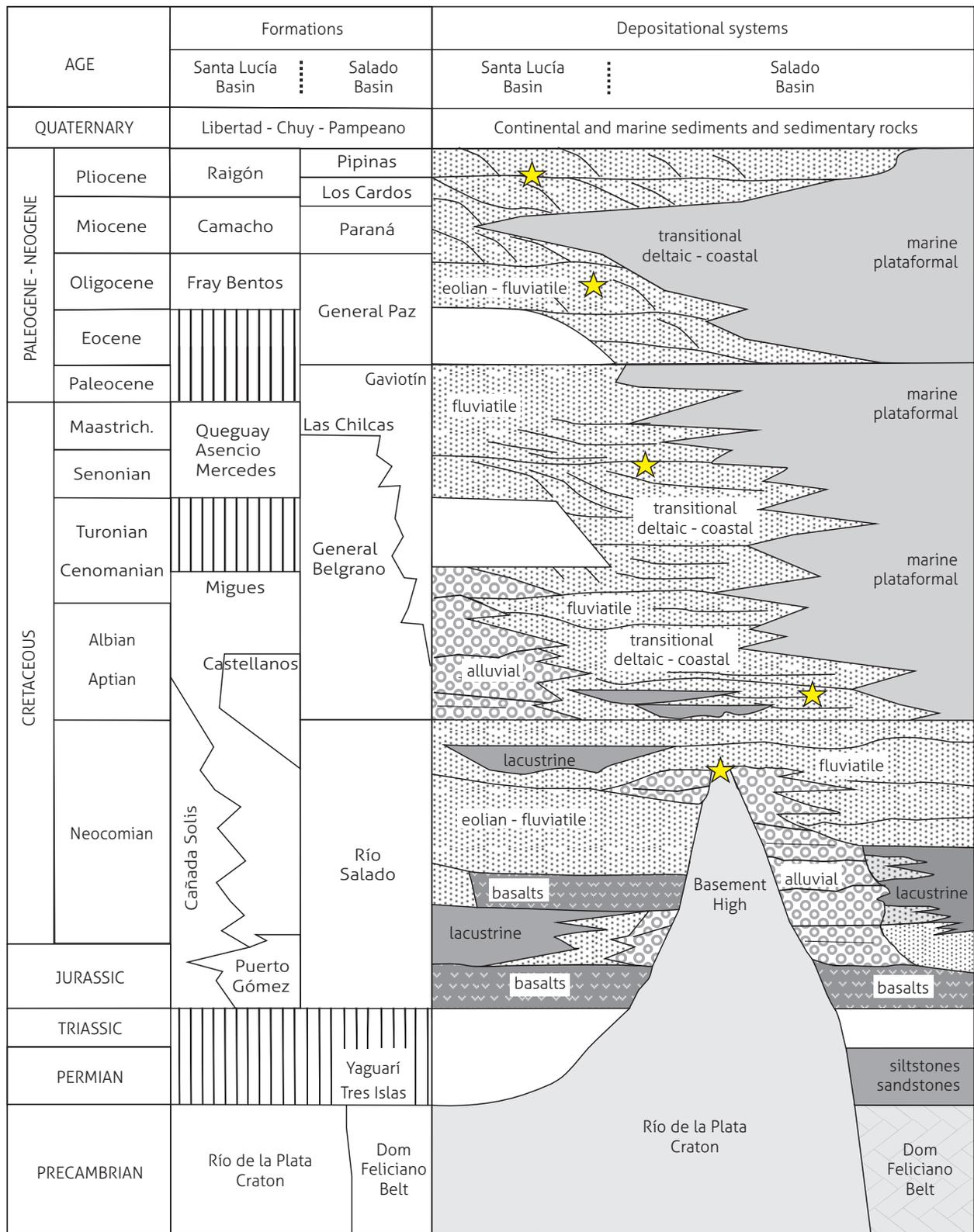


Figure 6. Chronolithostratigraphic columns of the Santa Lucía and Salado basins showing a tendency to develop more distal and deeper facies toward the south; the yellow stars in column A indicate the location of the levels with petrophysical quality that likely function as aquifers
Source: Rossello et al. (2017)

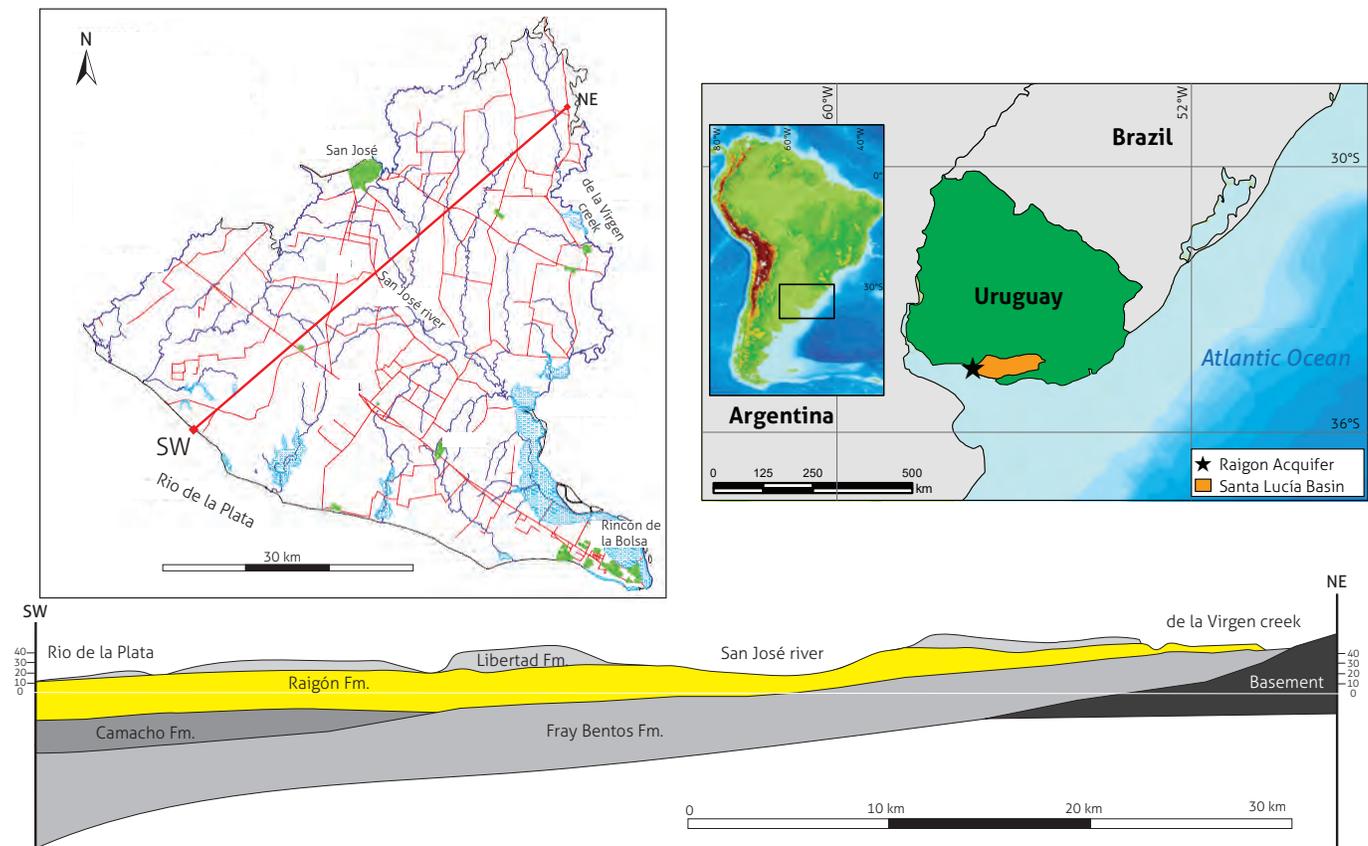


Figure 7. Location of the Raigón aquifer on the Uruguayan coast of the La Plata River (see its location in Figure 1) and a schematic cross-section. The cross-section shows the gradual subsidence of the sequences toward the SW. Source: adapted from Los Santos-Gregorashchuk and Hernández García (2013)

3.3 Salado basin

The Salado basin is a Meso-Cenozoic depocenter that developed both inland and offshore in the province of Buenos Aires, extends for more than 700 km and has been explored for hydrocarbon resources (Tavella and Wright 1996; Yrigoyen, 1999; Tavella, 2005; Raggio et al., 2012). Among other deep wells, the General Belgrano well, drilled in 1948, ultimately bottomed out at 4012 m.b.w.h. in Cretaceous sequences without reaching the basement. In addition, exploratory seismic data on hydrocarbons in the domain of the Salado basin show a sustained and likely gradual deepening toward the Samborombón Bay, forming its deep Meso-Cenozoic depocenter (Figure 6).

The Salado basin infill shows two characteristic, predominantly continental lithofacies with maximum recorded thicknesses of 886 m: a) the first Neocomian lithofacies, with a sharp syn-rift character and thick clastic sequences, such as red beds, is represented by the Salado River Formation, and b) the se-

cond lithofacies is represented by post-rift levels of the General Belgrano Formation that are attributed to the Aptian-Santonian and overlay the previous formation with a well-marked angular unconformity in the seismic sections, albeit the lithological differentiation of the well samples is less pronounced.

These lithofacies are followed by the marine units of the Las Chilcas Formation (Maastrichtian-Paleocene) that are gradually overlaid with regressive, continental red beds assigned to the Eocene-Oligo-Miocene of the General Paz and Olivos-Los Cardos Formations, reaching depths of up to 800 m and transiently becoming deltaic and marine deposits toward the east and ultimately completely dominant before reaching the continental slope. The analysis of the offshore seismic sections shows a conformation that begins with Eocene deposits of the proximal platform and gradually, upwardly changes to a set of deltaic facies, which became alluvial plain deposits in the late Oligocene.

Another major marine advance occurred between the early and mid-Miocene. Similar to the previous marine advance in the Maastrichtian-Paleocene, this advance also transgresses deeply into this part of the continent, as represented by the Paraná Formation, with a maximum recorded thickness of 815 m. The Salado basin displays a gradual transition between the Miocene marine deposits and the underlying units; however, near the coast, this relationship is pseudoconcordant based on the clear evidence of a fracturing episode that dislocated the Olivos Formation without affecting the Paraná Formation and the loosely overlapping boundaries of previous continental deposits (Yrigoyen, 1999).

The Cenozoic sedimentary record ends at a depth of approximately 125 m, as represented by the inland continental clastic accumulations. There is a gradual marine influence toward the ocean. Reddish-brown terrigenous deposits (correlated with the Arroyo Chasicó Formation) have also been differentiated and assigned to the lower Pliocene for their rich faunal content, culminating in the upper Pliocene with the Puelches Formation, which is characterized by a conspicuous deposit of light and yellowish-brown quartz sands at a depth of a few tens of meters. Lastly, silts and loesses, assigned to the Pampeano Formation, top the stratigraphic column in the Quaternary and broadly cover the edaphic surface that dominates the Buenos Aires plain.

4. HYDROGEOLOGICAL FRAMEWORK OF THE AQUIFERS OF THE SANTA LUCÍA BASIN

The Santa Lucía basin contains three main aquifers that are used for various purposes, including drinking water, livestock water, agricultural irrigation and industrial uses (Dinamige, 2009).

The Raigón Aquifer System (*Sistema Acuífero Raigón* – SAR) is the most important system in a wide region of southwestern Uruguay due to its high levels of extraction (Besouat et al., 2000). This aquifer consists of a Plio-Pliocene sequence of sandstones, sands and gravels, interspersed by thin levels of pelites and claystones, which occasionally act as confining or semiconfining units. The Camacho Formation in the south region and the Fray Bentos Formation to the north form the base of this aquifer. Although the Camacho Formation is considered impermeable, some perforation data suggest the existence of permeable zones within this formation, which enables hydraulic connection to the Raigón aquifer (Instituto

Nacional de Investigación Agropecuaria, 2019). Therefore, based on its lithological and hydraulic characteristics, the Raigón aquifer may operate as a system of multiple interrelated layers (Gestión Sostenible del Acuífero Raigón, Uruguay, 2005).

The best aquifer conditions are found in the extreme southwest of the Santa Lucía basin (San José department) where the continuity, depth and hydraulic conductivity of the strata, the existence of considerable recharge and the well-defined physical boundaries enable the development of the SAR (INIA, 2019). In the region south of the city of San José, the minimum thickness of the aquifer ranges from 0.5 to 2 m, with low yields (2 to 5 m³/h). The hydrogeological characteristics of the Santa Lucía basin change in the south-central region, where the yields reach high values (60-80 m³/h), and the wells produce up to 10 m³/h. In general, the thickness does not exceed 20 m, and the base of the aquifer is always less than 100 m from the ground surface. The transmissivity ranges from 100 to 2200 m²/d, with values between 300 and 1400 m²/d prevailing throughout the SAR. The storage coefficient ranges from 1.10-5 to 1.10-2 (Carrión et al., 2011; Gestión Sostenible del Acuífero Raigón, Uruguay, 2005).

The other two aquifers in the Santa Lucía basin, the Migues aquifer and the Mercedes aquifer, consist of Cretaceous geological units (Dinamige, 2009; Bossi et al., 1999; Montaña et al., 2006). Their groundwater layers are the most relevant antecedent streams for analyzing the performance of the Cretaceous aquifer units in the CSL, particularly in the central region of the department of Canelones.

The Mercedes aquifer is found at the surface and subsurface at shallow depths, with variable thicknesses, and has the characteristics of a free and semiconfined aquifer (Dinamige, 2009). In the central region of the basin, the aquifer consists of sandstones and conglomeratic sandstones, ranging from consolidated to friable and occasionally with strong silicification and carbonation processes, and acts as a partly porous and partly fissured aquifer. The Mercedes aquifer shows, in general, low discharges, ranging from 2 to 4000 l/h, except in areas of intense fracturing. According to Montaña et al. (2006), in the central region of the department of Canelones, the Mercedes aquifer performs as a free aquifer, and its average thickness is approximately 10 m, with mean transmissivity (T) values of approximately 50 m²/day, ranging from 3 to 100 m²/day, and a mean permeability (K) ranging from 1 to 10 m/day.

The Migues aquifer develops almost exclusively in the subsurface, and its main hydrogeological and hydrochemical

characteristics are only known up to depths of approximately 150-200 m due to the depth limitations of water well drilling companies; thus, its groundwater potential at greater depths remains unknown. Bossi et al. (1999) stated that, in some sectors, this aquifer can accumulate large volumes of groundwater, with discharges reaching 30 m³/h at depths ranging from 40 to 80 m. The quality of this water can be good, although it is occasionally high in salinity. In the Juanicó region, Montaño et al. (2006) highlighted the presence of a sandy, semiconfined and multilayer aquifer, with occasional sandy conglomeratic levels and depths ranging from 30 to 120 m, that essentially consists of the Migues aquifer and the Mercedes aquifer in the first meters. In this region, the discharge of most wells ranges from 10 to 15 m³/h, but several wells have discharges that exceed these values.

Although the hydrogeological characteristics of the Migues aquifer under shallow, semiconfined and confined conditions

are somewhat known, its economic potential as a reservoir could be even higher at greater depths. The exploratory wells drilled in search of hydrocarbons, particularly in the southern subbasin, show the development of vast and considerably thick sandy bodies, which display excellent porosity and permeability characteristics for reservoir rocks at variable depths (Veroslavsky, 1999). Based on the study of well cores, cuttings and Sauce well logging (2450 m), Tomasini et al. (2019) reported good reservoir properties in at least three levels, with tops at depths ranging from 900 to 1500 m. The reservoir levels are outlined by the sandstones of the Migues Formation, with large thicknesses (> 100 m), mean porosities of 22% and permeability values ranging from 150 to 460 mD. These characteristics have led to several studies of these deep reservoirs aimed at analyzing their viability for gas storage (methane, hydrogen and CO₂) and as a geothermal resource (Tomasini et al., 2019).

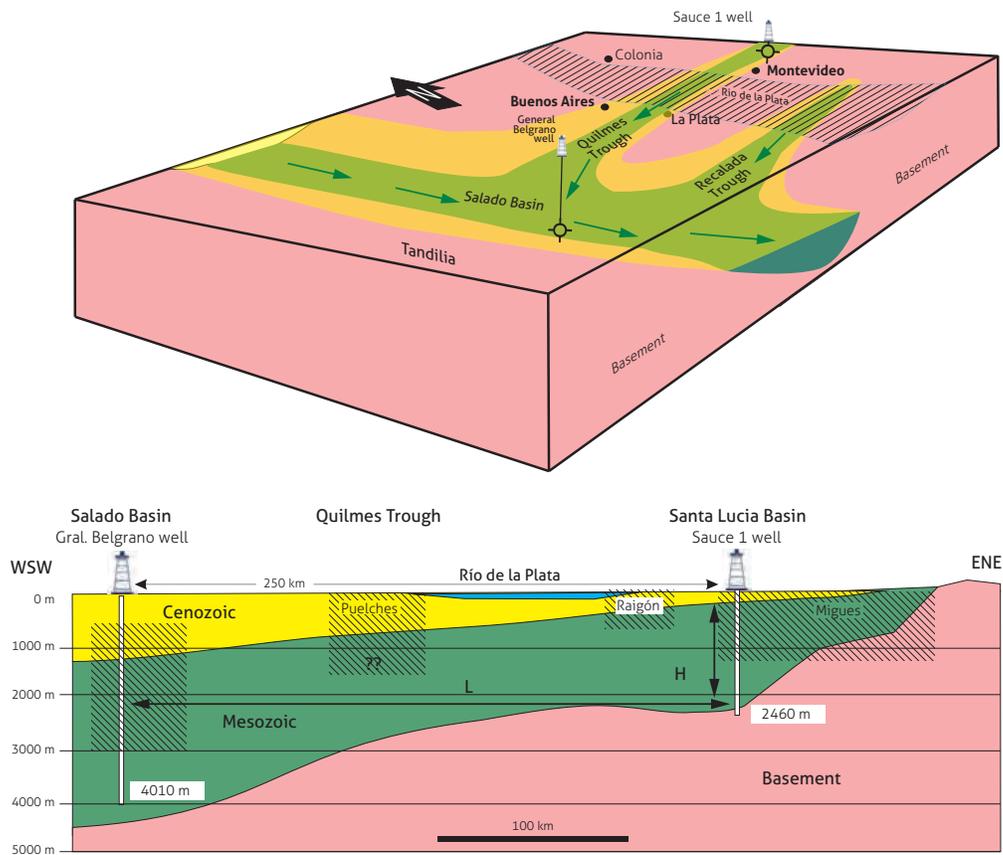


Figure 8. Above: three-dimensional diagram of the connection between the Santa Lucía Basin-FQ and the Recalada Trough with the Salado Basin. Below: schematic cross-section of the regional subsurface through the La Plata River. This cross-section shows the deepening of the Meso-Cenozoic sequences from the Santa Lucía basin (Sauce well 1) to the Salado basin (Gral. Belgrano well). L: distance between control wells; H: difference in level. Source: Modified from Rosello et al. (2017).

5. DISCUSSION

A schematic correlation of the characteristics of the previously described sedimentary infills of the Santa Lucía and Salado basins reveals a regional slope in the pre-Mesozoic basement that deepens toward the southwest until reaching level differences of more than 1000 m (Figure 8). In the latter depocenter, excluding the Cretaceous and Oligocene-Pliocene formations, the sedimentary facies are more distal and are related to other sources located toward the NW (Rossello, 2018), which are generally thinner and show evaporitic intercalations. Therefore, given its unfavorable petrophysical conditions, the FQ is unlikely to have the hydrogeological conditions expected in the deepest sectors.

If the gravimetric surveys available for the FQ (Rossello et al., 2011; Perdomo et al., 2017) can be compared with those described in the Santa Lucía basin (Rodríguez et al., 2020), block tectonics, expressed as uplifted basement blocks separated by sedimentary volumes, may be active in the FQ.

If the favorable petrophysical characteristics of the aquifers known in Uruguay continue in the FQ, albeit at greater depths, conditions of natural upwelling and considerable geothermal temperatures could occur in this trough because the water from the aquifers of the Santa Lucía basin flows through saturated porous and permeable materials toward levels that are deeper than the infiltration levels. Due to the presence of superimposed sealing units, these discharges could naturally re-emerge as springs upon well drilling, in line with the vertical flow dynamics in a saturated porous medium established by Darcy's law (see definitions in Custodio and Lamas, 1976). Groeber (1945) recognized the upwelling and partial upwelling character of the aquifers in the sequences termed "Mesopotámico rojo" [Red Mesopotamic] reached by the wells drilled by Artaza (1943); however, no further petrophysical and hydrodynamic descriptions are available.

In the FQ, the aquifer would likely encompass levels with more proximal depositional characteristics, correlated with the



Figure 9. Estimated location of the possible aquifers in the FQ underneath the traditional Puelches and Pampeano aquifers in the metropolitan area of Buenos Aires
Source: Taken from Rosello et al. (2018).

Salado River and General Belgrano Formations, and favorable petrophysical characteristics for an aquifer.

If the FQ harbors deep aquifers below the well-known Puelches, Pampeano and Paraná aquifers (Santa Cruz, 1972; Santa Cruz et al., 1997; Amato and Silva Busso, 2006), with hydraulic, physical and chemical conditions similar to those of the aquifers of the Santa Lucía basin, these aquifers could be an excellent supply of alternative or complementary hydrogeological resources for the metropolitan area of Buenos Aires, where the trough is located (Figure 9).

6. CONCLUSIONS

The interpretation of the FQ as a depocenter with Mesozoic and Cenozoic sedimentary infills that reach an average depth of almost 900 m suggests the presence of significant sandstone and conglomeratic intervals that could be suitable for new hydrogeologic reservoirs that are deeper than current reservoirs, when compared to neighboring areas in Uruguay. Currently available gravimetric surveys allow us to establish a morphotectonic analogy with the Santa Lucía basin, which is much better known for its subsoil data from the exploration of its hydrocarbon resources.

New deep aquifers will likely be discovered based on knowledge of the petrophysical characteristics of the equivalent units of the Santa Lucía basin, the hydrodynamic conditions of which range from 12 to 15% effective porosity, with stratigraphic traps (pinchout) combined with (closure against a fault) and overlapped by fine sediments of excellent quality that can act as seals.

In addition, the FQ connects similar sedimentary sequences of the Santa Lucía basin with those of the Salado basin at deeper positions, likely providing favorable conditions for upwelling aquifers and even hydrothermalism. Based on the deepening upward sequences that are most likely to form aquifers, a topographic difference of approximately 700 to 900 m is calculated, which should generate an adequate gradient to facilitate underground flow from groundwater recharge zones located in Uruguay.

Considering the arguments described above, a specific hydrogeological study supported by noninvasive, rapid, low-cost geophysical exploration methods, such as magnetotellurics (MT), audio-frequency MT (AMT), the horizontal-to-vertical spectral ratio (HVSr) and transient electromagnetics (TEM), must be performed to complement the knowledge on the geo-

logical configuration of this region, which has been limited by the scope of gravimetric models. Drilling the necessary exploratory wells will enable us to determine if the spatial conditions and geochemical qualities of the deep aquifers can host the FQ.

For this reason, the present working hypothesis is proposed, which justifies the logistical costs of exploratory drilling in the FQ to verify the existence of thermal groundwater, its hydraulic, physical, chemical and isotope characteristics and, consequently, the technical-economic potential of this proposed aquifer system. Locating this aquifer system is very important given its strategic location below the large population centers in and around Buenos Aires.

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