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Research paper

The Rhyacian El Cortijo suture zone: Aeromagnetic signature and insights for the geodynamic evolution of the southwestern Rio de la Plata craton, Argentina

Carlos J. Chernicoff [a,b,*], Eduardo O. Zappettini [b], Javier Peroni [b]

[a] *Council for Scientific and Technical Research (CONICET), Argentina*
[b] *Argentine Geological-Mining Survey (SEGEMAR), Argentina*

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A B S T R A C T

The amalgamation of the southern Río de la Plata craton involves two possibly coeval Rhyacian sutures associated with the Transamazonian orogeny, rather than a single one as previously envisaged, i.e. the El Cortijo suture zone and the Salado suture. We circumscribe the Tandilia terrane to the region between these two sutures.

The El Cortijo suture zone runs along a roughly WNW oriented magnetic low aligned along the southern boundary of the Tandilia terrane, i.e. boundary between the Tandilia and Balcarce terranes. This extensive magnetic low, ca. 300 km long, and ca. 90 km wide, would be caused by demagnetization associated with shearing. At a more local scale, the trend of the El Cortijo suture zone often turns toward the E–W. At this scale, WNW trending tholeiitic dykes of Statherian age are seen to cut the Rhyacian El Cortijo suture zone. Spatially associated with the El Cortijo suture zone, there are small magnetic highs interpreted to be related to unexposed basic bodies of ophiolitic nature related to those forming part of the El Cortijo Formation.

We envisage the pre-Neoproterozoic evolution of the Tandilia belt to have been initiated by the extension of Neoarchean (∼2650 Ma) crust occurred during Siderian times (2500–2300 Ma), causing the separation between the Balcarce, Tandilia and Buenos Aires terranes, and the development of narrow oceans at both north and south sides of the Tandilia terrane, accompanied by ∼2300–2200 Ma sedimentation over transitional –continental to oceanic– crust, and arc magmatism developed in the Tandilia terrane. The island arc represented by the El Cortijo Formation was also developed at this time. At late Rhyacian times, it occurred in both the closure of the narrow oceans developed previously, the entrapment of the El Cortijo island arc, as well as anatectic magmatism in the Balcarce terrane.

1. Introduction

The Rio de la Plata craton of southern South America encompasses autochthonous Archean (e.g. Hartmann et al., 2002; Pankhurst et al., 2003; Cingolani, 2010, and references therein) to Paleoproterozoic (e.g. Cordani et al., 2000; Santos et al., 2003; Dalla Salda et al., 2005; Rapela et al., 2007, and references therein) Gondwana basement. Its type outcrop areas occur near the Atlantic margin of the continent, mainly in Uruguay, and also in the Buenos Aires Province of Argentina (Tandilia belt). A very small outcrop of the craton also occurs in the Martín García island located in the Rio de la Plata estuary (see Fig. 1).

Based on geological evidence, it has been proposed that the Tandilia belt comprises two main terranes –Buenos Aires and Tandilia terranes– amalgamated at ca. 2.1 Ga (Transamazonian event; Rhyacian; Ramos et al., 1990; Ramos, 1999). The boundary between the Tandilia terrane and the Buenos Aires terrane would run along the Salado suture indicated by Pángaro and Ramos (2012), as delineated by a curvilinear, roughly WNW trending

* Corresponding author. Council for Scientific and Technical Research (CONICET), Argentina. Tel.: +54 11 47748624.
E-mail addresses: carlos.chernicoff@segemar.gov.ar, cc_jorge@yahoo.com.ar (C.J. Chernicoff).

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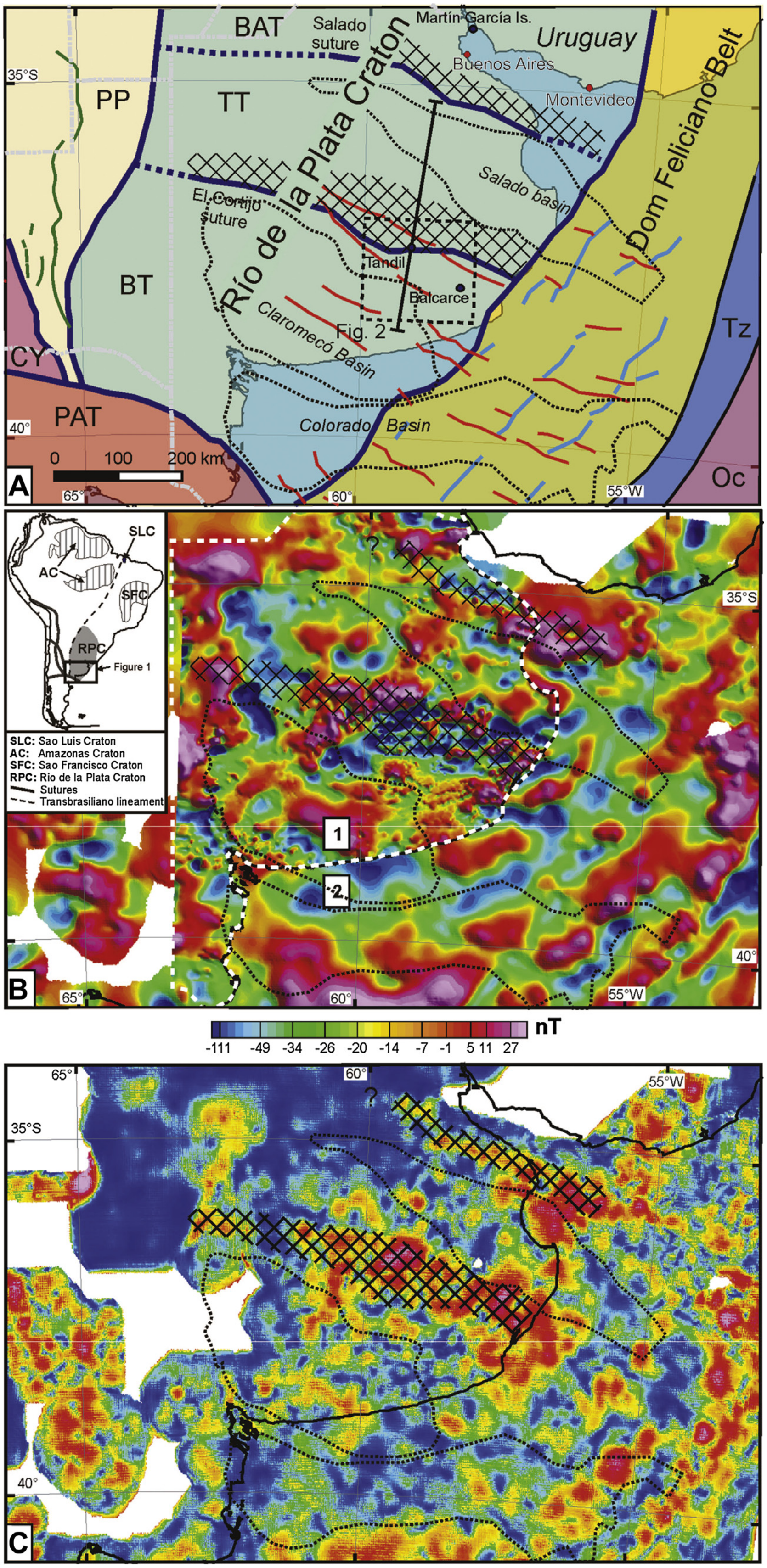

Figure 1. (A) Tectonostratigraphic terranes of the broader study region, with key structural lineaments, modified after Ghidella et al. (2001), Chernicoff and Zappettini (2004) and Pángaro and Ramos (2012). Salado basin after Pángaro and Ramos (2012), Claromecó and Colorado basins after Introcaso et al. (2008). (B) Magnetic map of the broader study region combines: (1) grid of total magnetic field of the province of Buenos Aires (SEGEMAR, 2012), and (2) global magnetic grid (EMAG2) (grids 1 and 2, separated by short white dashes). (C) Analytic signal

Bouguer anomaly high associated with the Salado Mesozoic episutural basin, in turn covered by Quaternary sediments. No actual basement exposures of the Tandilia or Buenos Aires terranes occur near the Salado suture.

About 200 km to the south of the Salado suture, the occurrence of an assemblage of metacherts, metawackes and metabasites of Rhyacian age (El Cortijo Formation) near the city of Tandil has been proposed to represent remnants of oceanic crust obducted during a collisional event (Teruggi et al., 1988; Ramos et al., 1990; Ramos, 1999).

In this article we analyze the geological, geochronological and geophysical information available for the Tandil area, reinterpreting it as forming part of a larger suture zone –El Cortijo suture zone– coeval with the Salado suture. We herein present the aeromagnetic data, plus local scale 3D modeling, that have guided us to delineate the location and extent of the El Cortijo suture zone. As part of the broader revision of all the available geological information, we have also reinterpreted the pre-Neoproterozoic evolution of the southwestern portion of the Rio de la Plata craton.

2. Geological framework

The Precambrian basement exposed in the Tandilia region comprises an igneous-metamorphic assemblage referred to as the Buenos Aires Complex assigned to the Transamazonian cycle –Paleoproterozoic age– (Marchese and Di Paola, 1975; Dalla Salda, 1999; Cingolani and Dalla Salda, 2000; Dalla Salda et al., 2006; Bossi and Cingolani, 2009; Cingolani, 2010, and references therein), covered by thin Neoproterozoic to lower Paleozoic sedimentary units displaying sub-horizontal bedding (e.g. Iñiguez Rodríguez, 1999; Ramos, 1999; Cingolani and Dalla Salda, 2000; Cingolani, 2010, and references therein).

The Buenos Aires Complex mostly consists of gneisses, migmatites, amphibolites and minor ultramafic rocks, intruded by tonalitic/granitic and leuco-monzogranitic plutons. There are also subordinate amounts of schists, marbles, metavolcanic units, and dykes of acid and mafic compositions. Particular attention is herein given to the presence of an association of low-grade metamorphic rocks comprised by metacherts, metagreywackes and metabasites (El Cortijo Formation) since it is thought to represent a slice of oceanic crust (Teruggi et al., 1988; Ramos, 1999).

The emplacement of the mostly I-type granitoid plutons in the thick gneissic sequence of the Tandil area is thought to be broadly coeval with the regional high-temperature metamorphism, mylonitization and anatexis (Cingolani, 2010 and references therein). In the Balcarce area, Massonne et al. (2012) have recently estimated the onset of migmatization at ca. 2073 Ma, as indicated by U-Th-Pb dating of monazite in a partially migmatized metapelite.

Zircon U-Pb SHRIMP ages for gneissic rocks and granitoids of the Tandil area determined by Hartmann et al. (2002) and Cingolani et al. (2002, 2005) yielded Paleoproterozoic (Rhyacian) ages in the range of 2234–2065 Ma, with inheritance at 2368 Ma (Siderian), 2185 (early Rhyacian) and 2657 Ma (Neoarchean).

Preliminary Hf isotope determinations on SHRIMP dated zircon crystals from tonalitic-monzonitic granitoids and gneisses of the Tandil-Balcarce area average Hf model ages (crustal) of ca. 2646 Ma with positive epsilon hafnium values, i.e. coincident with the oldest inheritance in one of the dated tonalitic gneisses, hence providing strong evidence for the juvenile Neoarchean derivation of the Transamazonian calc-alkaline magmatism (Cingolani et al., 2010). These Hf isotope determinations are consistent with the Sm-Nd model ages of ca. 2.4–2.7 Ga of granitoids, reported by Hartmann et al. (2002) and Pankhurst et al. (2003). These Hf and Nd isotopic data unequivocally point to the occurrence of Neoarchean crust in the southwestern portion of the Rio de la Plata craton.

The early magmatic arc plutonic rocks would have been largely juvenile (mantle-derived), as indicated by the initial $^{87}Sr/^{86}Sr$ ratios between 0.702 and 0.706 of the tonalitic-granitic suite, also consistent with the preliminary Hf isotope determinations referred to above, in contrast with the late leucogranitic suite that yielded a high initial $^{87}Sr/^{86}Sr$ value of 0.7181 (Varela et al., 1988), reflecting large crustal recycling.

In contrast to previous views, Massonne et al. (2012) have recently invoked the occurrence of underthrusting of oceanic crust without eclogitization, as opposed to subduction leading to continental collision, for the Paleoproterozoic peak pressure metamorphism in the Balcarce area. According to the latter authors, the heating generated by this process at mid crustal levels would have caused widespread anatexis at 2.07 Ga.

The Buenos Aires Complex is highly deformed, and it is characterized by the occurrence of wide mylonitic belts developed in a transpressive tectonic setting (Dalla Salda, 1981a,b; Teruggi et al., 1988; Ramos, 1999); the mylonitic belts would have been formed in connection with a collisional event. This dynamic event reached amphibolite facies and locally the granulite facies, though some mylonitic rocks were partially retrograded to greenschist facies (Frisicale et al., 2012). The predominant vergence of the contractional component of the belts is toward the north-northwest. In this context, the oceanic rocks of the El Cortijo Formation (Teruggi et al., 1988) would be related to the partial obduction of a suture zone.

The record of multiple events of deformation and intrusive magmatism in Tandilia has led to suggest that the Transamazonian orogeny involved continent–continent collision (tonalitic-granitic plutons) as well as post-collisional generation of leucogranites plus conspicuous transcurreent faulting (e.g. Dalla Salda et al., 2006; Cingolani, 2010, and references therein).

The only available geochronological data for the highly radiogenic and typically post-collisional leucogranites in Tandilia come from a Rb-Sr isochron age of 1770 ± 88 Ma (Varela et al., 1988) obtained from the Tigre and Alto de Vela ranges, where they are associated with acidic metavolcanic rocks, and jointly emplaced in wrench faults (Dalla Salda, 1981b; Ramos et al., 1990).

The Buenos Aires Complex is intruded by two unmetamorphosed dyke swarms: (i) A calc-alkaline dyke swarm trending mainly E–W has been dated by $^{40}Ar/^{39}Ar$ step-heating plateau ages of emplacement at 2020 ± 24 and 2007 ± 24 Ma (Teixeira et al., 2002), and (ii) a younger, tholeiitic dyke swarm trending WNW–ESE dated at 1588 ± 11 Ma (U-Pb on baddeleyite; Teixeira et al., 2002).

The calc-alkaline dyke swarm developed with a thickness of 0.5–10 m, and a bimodal, andesitic to rhyolitic composition. It is considered to be contemporaneous with the early post-collisional intrusions occurred in the transtensional stage of the Paleoproterozoic orogeny, yet preserving a magmatic arc chemical signature (e.g. Hartmann et al., 2002; Teixeira et al., 2002, and references therein).

According to Teixeira et al. (2002), the tholeiitic dyke swarm constrains the time of crustal extension at the Paleo-Mesoproterozoic boundary during which basin-formation tectonics and anorogenic magmatism took place worldwide within a stabilized Paleoproterozoic lithosphere. The same authors also

(total gradient) of the magnetic data. References: dark-blue lines: terrane boundaries; light-blue lines: structures associated with the Dom Feliciano belt; red lines: lineaments associated with Gondwanan (Permian) structures; green lines: structures associated with the Pampia terrane. Oc: oceanic crust; Tz: transitional zone; BAT: Buenos Aires terrane; TT: Tandilia terrane; BT: Balcarce terrane; PAT: Patagonia terrane; PP: Pampia terrane; CY: Cuyania terrane. NNE–SSW regional transect is indicated. Projection: UTM-20, Datum WGS84.

indicate that this diachronous extensional event within the South American continent initiated shortly after the Transamazonian orogeny (e.g. Florida tholeiitic dyke swarm in Uruguay dated at 1.73 Ga, coeval with anorogenic granitoids intruded both in Tandilia and Uruguay) and lasted for ca. 140 Ma (up to ca. 1.59 Ga), mirroring the evolution of the Eburnean orogeny in the African counterpart of Gondwana. The Transamazonian + Eburnean orogenies would have played an important role for juvenile crustal accretion, followed by the dispersion of the stabilized continental fragments during the Mesoproterozoic, prior to Rodinia assembly.

3. Aeromagnetic modeling

3.1. Magnetic domains and fabrics

A broader inspection of the geophysical data available beyond the study area, e.g. SEGEMAR's aeromagnetic data over the La Pampa region, marine aeromagnetics presented by Ghidella et al. (2001), processed satellite gravity data presented by Pángaro and Ramos (2012), allows to recognize the tectonic domains flanking the Rio de la Plata craton (Fig. 1A), i.e. the Dom Feliciano domain, to the east, and the Pampia domain, to the west, as well as the Patagonia terrane, to the south.

The Dom Feliciano domain corresponds to the southern segment, both onshore and offshore, of the late Neoproterozoic Dom Feliciano orogen (e.g. Porada, 1979, 1989; Fragoso-Cesar, 1980; Oyhantçabal et al., 2009). Within the range of latitudes shown in Fig. 1, this domain shows an NE oriented magnetic fabric (which turns toward the NNE to the north of the present region). In addition, a set of WNW trending lineaments related to the Permian Gondwanide orogeny can also be picked out within this domain, crosscutting the Dom Feliciano fabric (e.g. Pángaro and Ramos, 2012). Since the Dom Feliciano Belt is a late Neoproterozoic mobile belt or orogen, it bears no common structural legacy with the Rio de la Plata craton prior to Phanerozoic.

The Pampia domain corresponds to the southeastern portion of the Pampia terrane (e.g. Ramos et al., 2010; Chernicoff et al., 2012) shown in Fig. 1A. This domain follows a roughly N–S magnetic trend, as clearly identified by aeromagnetic data (Chernicoff and Zappettini, 2004).

The northern boundary of the Patagonia terrane is delineated by an arcuate-shaped to roughly E–W trending regional magnetic and gravimetric high (Chernicoff and Zappettini, 2004) that cuts at high angle the terrane boundaries located to the north.

Within the southwestern portion of the Rio de la Plata craton considered in this article, we separate the Buenos Aires, Tandilia and Balcarce terranes. We herein take the boundary between the Buenos Aires and Tandilia terranes (Salado suture) from that indicated by Pángaro and Ramos (2012) based on satellite gravity data, plus an adjustment based on the analytic signal of the integrated aeromagnetic data of the province of Buenos Aires (SEGEMAR, 2012; see Fig. 1A).

On the basis of the integrated aeromagnetic data of the province of Buenos Aires (SEGEMAR, 2012), we have identified an elongated, roughly WNW oriented magnetic low aligned along the southern boundary of the Tandilia terrane, i.e. boundary between the Tandilia and Balcarce terranes, and refer to it as the El Cortijo domain, or El Cortijo suture zone. This broad trend can also be seen in the total magnetic gradient map (analytic signal map; Fig. 1C). We interpret the extensive magnetic low, ca. 300 km long, and ca. 90 km wide, to be caused by demagnetization associated with shearing at the Tandilia terrane's southern boundary, as transpressive shearing is well known to be pervasive in all of the basement exposures of the region (see Section 2 Geological framework, above). It is worth noting that the identified magnetic low does not coincide with any sedimentary basin (see Fig. 1A). At a more local scale, the trend of the El Cortijo suture zone often turns toward the E–W (see Fig. 2). A key relationship picked out at this local scale is WNW trending tholeiitic dykes of Statherian age cutting the Rhyacian El Cortijo suture zone, which clearly points to the ancient age of this suture. Spatially associated with the El Cortijo suture zone, there are small magnetic highs (Fig. 1B) interpreted to be related to unexposed basic bodies of ophiolitic nature related to those exposed and forming part of the El Cortijo Formation.

The western end of the El Cortijo suture zone is masked by Phanerozoic sediments, though it is likely to reach the western boundary of the Río de la Plata craton (Fig. 1A; see also aeromagnetic interpretation given by Chernicoff and Zappettini, 2004).

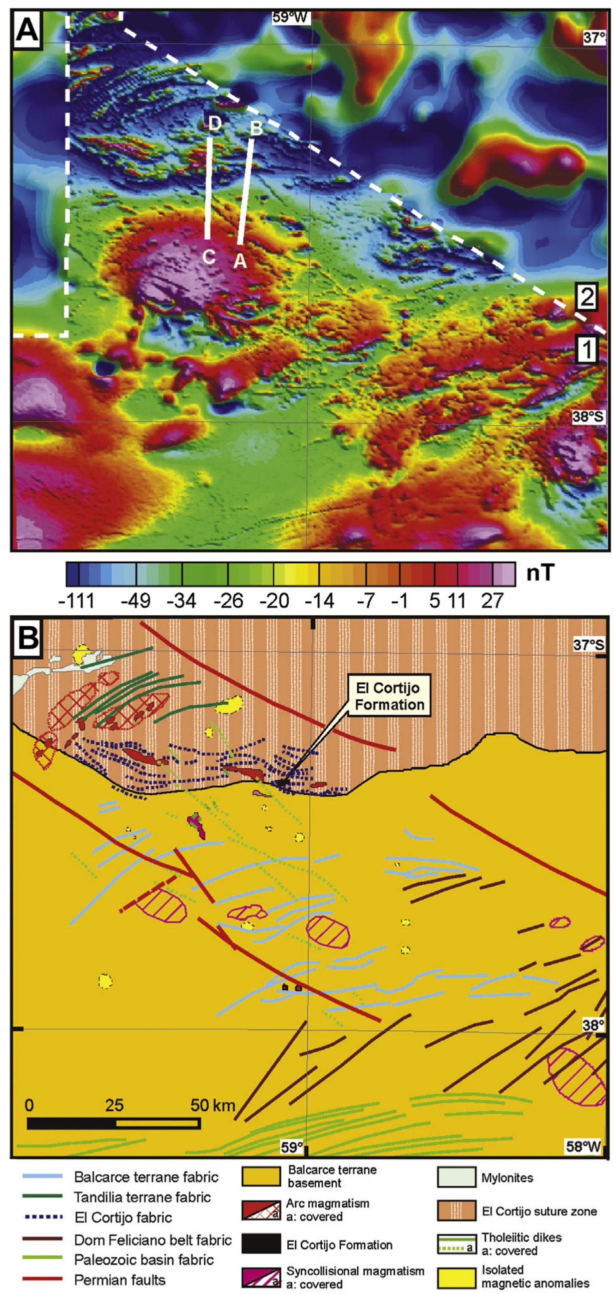

Figure 2. (A) Local aeromagnetic map of a selected area, combines (1) high-resolution aeromagnetic grid of the Tandil area (SEGEMAR, 2005), and (2) grid of total magnetic field of the province of Buenos Aires (SEGEMAR, 2012). (B) Geological interpretation of the local magnetic map. A–B and C–D: line paths of profiles extracted from the aeromagnetic grid (see modeling, in Fig. 3B).

Its eastern end is cut by the NE-trending magnetic fabric of the Neoproterozoic Dom Feliciano Belt in the proximity of the Atlantic coast (see e.g. Fig. 7 in Pángaro and Ramos, 2012; and Fig. 1B and C, this article).

Furthermore, the aeromagnetic survey has allowed to remap the previously known, WNW oriented Statherian tholeiitic dykes but at their full length, i.e. significantly more extensive (>50 km) than depicted by conventional geological mapping (Figs. 2B and 4). Within the Tandilia and Balcarce terranes, fragile Permian structures follow the orientation of these Statherian dykes (Fig. 2B).

With the purpose of gaining additional structural/lithologic information usable for the overall geotectonic interpretation, the aeromagnetic data were modeled. Theoretical magnetic modeling was carried out: (1) for a regional, ca. 400 km long, profile extracted from the integrated aeromagnetic data of the province of Buenos Aires (SEGEMAR, 2012): regional profile oriented NNE–SSW (see Figs. 2 and 3a) for two local, ca. 30 km long, profiles extracted from the high-resolution aeromagnetic survey of the Tandil area (SEGEMAR, 2005): profile A–B, oriented NNW–SSE and profile C–D, oriented N–S, (see Fig. 3b; see also block diagrams presented in Fig. 4). The topography along the regional profile was taken from the SRTM data (e.g. Farr and Kobrick, 2000), whereas that along the local profiles was taken from the digital elevation model derived from the aeromagnetic survey (SEGEMAR, 2005). The commercial modeling package used is ModelVision™.

3.2. Regional profile

The regional trend is represented by a fourth degree polynomial curve that might reflect the effect of heterogeneities seated at the base of the crust. The central part of the profile cuts across the El Cortijo suture zone, whose width averages 90 km. It is characterized by a large wavelength magnetic low representing a zone of demagnetization formed at the expense of the Tandilia terrane, magnetic susceptibility: 0.001 SI, plus small wavelength magnetic highs representing basic bodies, magnetic susceptibility 0.07 SI. Though this model is based on the total magnetic field (Fig. 1B), the analytic signal (Fig. 1C) emphasizes the delineation of this suture zone, as often the analytic signal (total magnetic gradient) helps defining the boundary between bodies differently magnetized.

Toward the north of the El Cortijo suture zone, the transect reaches a large wavelength magnetic high representing an unaffected portion of the Tandilia terrane (magnetic susceptibility: 0.008 SI), plus basic bodies (magnetic susceptibility: 0.03 SI). The latter bodies are interpreted to be related (and physically connected) with the basaltic sills known to occur at the base of the Salado basin. Sediments pertaining to the latter basin are modeled by a tabular body of very low magnetic susceptibility (0.001 SI) at the top of this terrane. Note: within the Tandilia terrane, our modeling does not discriminate between the basement and the Neoproterozoic to lower Paleozoic sedimentary sequences.

The southern tract of the profile traverses the Balcarce terrane that is broadly associated with a large wavelength magnetic high representing basement rocks with moderately high magnetic susceptibility (0.01 SI), plus small wavelength magnetic highs possibly representing granitoid bodies (magnetic susceptibility 0.009 SI). The northern end of the Balcarce terrane traversed by this profile would correspond to a zone of demagnetized rocks (magnetic susceptibility descends down to 0.002 SI) possibly representing the sheared terrane boundary. Straddling the boundary between the latter demagnetized zone and the unaffected portion of the Balcarce terrane, it stands out a higher magnetic susceptibility body (0.025 SI) bound to postdate the timing of demagnetization.

The regional profile does not reach the Salado suture, localized to the north of it (Fig. 1A). As mentioned before, the location of this suture indicated by Pángaro and Ramos (2012) has herein been adjusted (shifted) based on the analytic signal of the integrated aeromagnetic data of the province of Buenos Aires (SEGEMAR, 2012; see Fig. 1C), hence now being located at the northern border of the Salado basin (Fig. 1A).

3.3. Local profiles

At a local scale, two additional profiles modeled small magmatic bodies 'stitching' the boundary between the El Cortijo suture zone and an unaffected portion of the Balcarce terrane (see location in Fig. 2A).

A total of ten bodies were modeled. The strike and length of these bodies were inferred from the total magnetic gradient (analytic signal). The magnetic susceptibility values of the four types of modeled lithologies were taken from published tables (Dobrin, 1960; Telford et al., 1976; Clark, 1999) since most of these bodies subcrop beneath thin Quaternary sediments, and have no topographic expression. The shape of the bodies was obtained by means of a trial and error approach, and by using the inversion method.

Within the El Cortijo domain, two parallel ENE-trending, 20 km long, subcropping tabular bodies identified in the two profiles were modeled. These bodies give rise to a local magnetic anomaly of approximately +50 nT localized within the wider magnetic low of −100 nT that characterizes the portion of the El Cortijo domain herein analyzed at detailed scale. The magnetic susceptibility assigned to these bodies is 0.07 SI, possibly corresponding to unexposed basic bodies of ophiolitic nature related to those exposed and forming part of the El Cortijo Formation, see reference to oceanic character of the El Cortijo rock assemblage, proposed by Teruggi et al. (1988) and Ramos (1999), in Section 2 Geological framework, above.

A granitic body that was also modeled within this domain has almost negligible expression in the magnetic grid, and its magnetic susceptibility was estimated at 0.0025 SI.

In the central portion of both profiles, four bodies related with a series of isolated magnetic anomalies were modeled, and assigned a magnetic susceptibility of 0.04 SI.

Finally, two 32 km long tabular bodies were modeled in the southern end of both profiles. Their orientation is NW to WNW, and are clearly related to a series of magnetic lineaments that coincide with locally exposed tholeiitic dykes. A magnetic susceptibility of 0.06 SI was assigned to these tabular bodies.

3.4. Interpretation

We have identified a 90 km wide suture zone running for ca. 300 km in a roughly WNW to E–W direction at the southern end of the Tandilia terrane. The latter suture zone is herein referred to as the El Cortijo suture zone, and it is characterized by an elongated magnetic low caused by demagnetization associated with shearing at the Tandilia terrane's southern boundary. Notably, when analyzed at local scale, WNW trending Statherian extensional structures, tholeiitic dykes herein mapped for as much as 50 km long, cut the Rhyacian El Cortijo suture zone.

It is also worth noting that the WNW orientation of the tholeiitic dyke swarm is closely followed by the orientation of Gondwanide (Permian) fragile structures in the study region. Indeed, the Permian orogeny would be responsible for the WNW oriented, fault-bounded uplift of the basement of the Tandil hills (e.g. Cingolani, 2010 and references therein) that would then follow a Statherian structural weakness.

Spatially associated with the long wavelength magnetic low of the El Cortijo suture zone, there is a small number of shorter wavelength magnetic highs interpreted to be related to unexposed

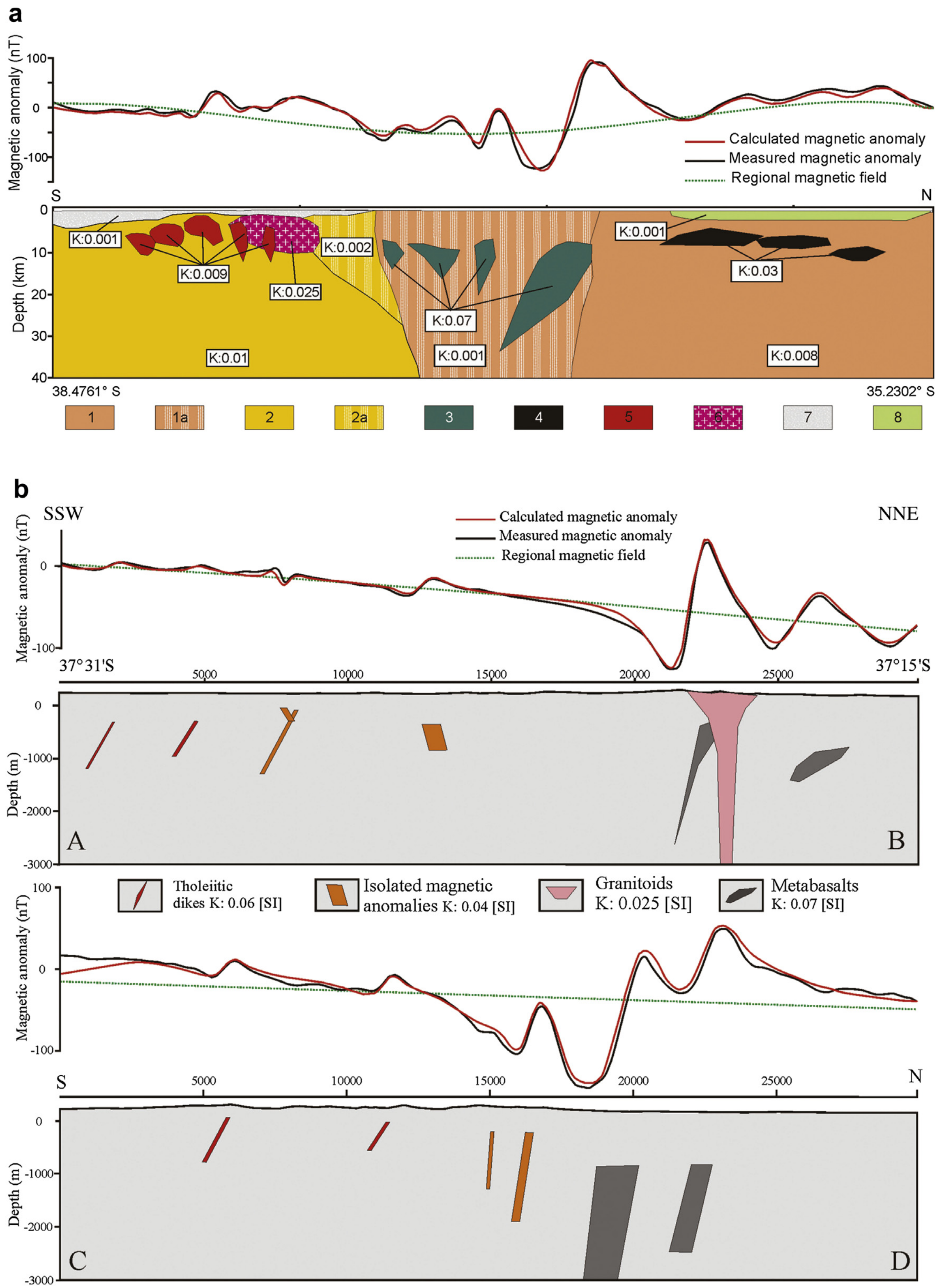

Figure 3. (a) Modeled magnetic profile of regional scale (see location in Fig. 1). References: 1: Tandilia terrane; 1a: El Cortijo suture zone; 2: Balcarce terrane; 2a: demagnetized portion of Balcarce terrane; 3: basic bodies; 4: basic bodies; 5: granitoid bodies; 6: granitoid body; 7: Paleozoic sediments; 8: Mesozoic–Tertiary sediments. (b) Modeled magnetic profiles of local scale (A–B and C–D) (see location in Fig. 2). See good match between calculated and measured magnetic anomalies. Abscissa: distance given in meters. K: magnetic susceptibility.

basic bodies of ophiolitic nature associated to those exposed and forming part of the El Cortijo Formation. The western end of the El Cortijo suture zone is obliterated by Phanerozoic sediments, though it is likely to reach the boundary between the Rio de la Plata craton and the Pampia terrane, whereas its eastern end is cut by the late Neoproterozoic Dom Feliciano Belt.

We name Balcarce terrane to that occurring to the south of the El Cortijo suture zone, up to the northern boundary of Patagonia.

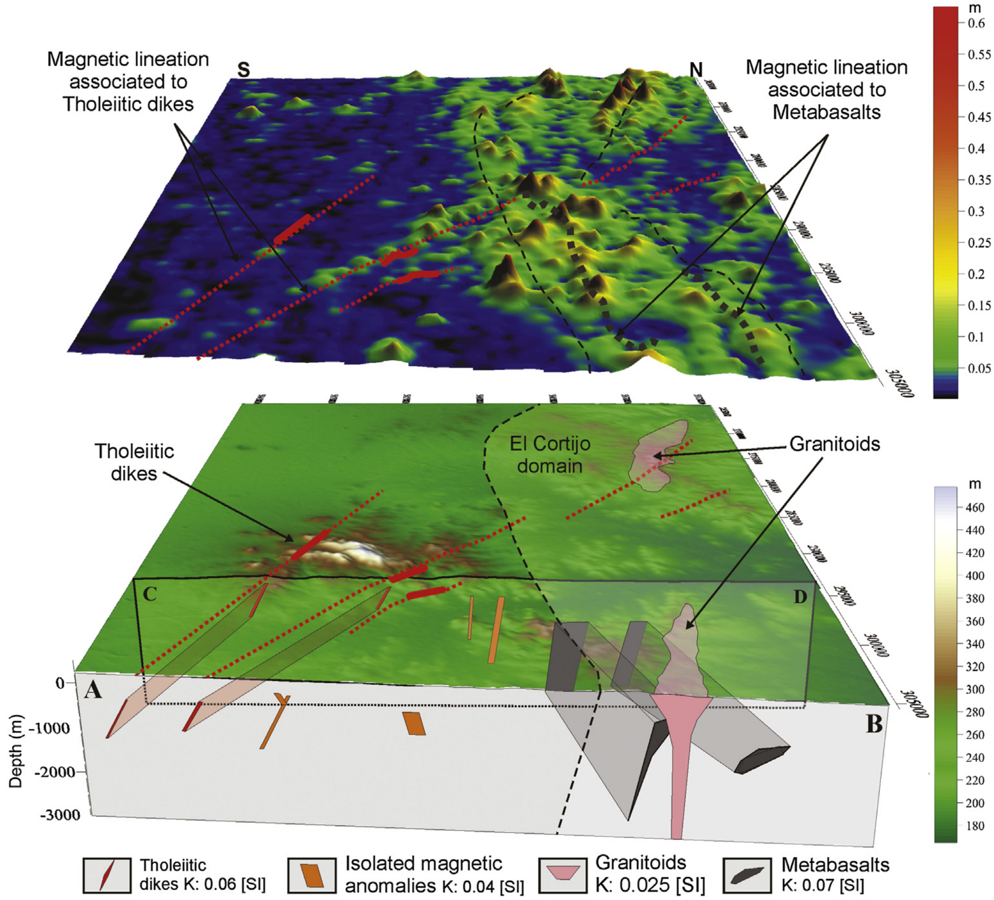

Figure 4. Block diagrams (view from east) of the local magnetic profiles modeled in Fig. 3B. Upper diagram: analytic signal grid (total magnetic gradient) with the interpretation of the main magnetic lineaments, and the delimitation of the El Cortijo domain (thin dashed lines). Lower diagram: digital elevation model of the same area, with indication of exposures of tholeiitic dykes and granitoids. See good match between exposed tholeiitic dykes and NW to WNW magnetic lineaments, and the association of metabasalts with magnetic anomalies within the El Cortijo domain. K: magnetic susceptibility; m: meters; please note that the analytic signal grid (total magnetic gradient) has no units.

Otherwise, the boundary between the Tandilia terrane, herein more circumscribed than in previous models, and the Buenos Aires terrane is marked by the Salado suture (Pángaro and Ramos, 2012; plus adjustment indicated in this article). Both the El Cortijo and Salado sutures are bound to be roughly coeval, i.e. Rhyacian.

A further outcome of our interpretation is the possible location of Mesozoic basic bodies unexposed in the Tandilia terrane, which could be physically connected with the basaltic sills occurring at the base of the Salado basin, which are thought to be related with the Serra Geral large igneous province.

4. Final considerations: new interpretation of the pre-Neoproterozoic tectonic evolution of the southwestern Rio de la Plata craton

Whereas aeromagnetics have guided us to delineate the location and extent of the El Cortijo suture zone, the identification of this Rhyacian suture is part of our reinterpretation of the available geological and geochronological information that actually lead us to revise the pre-Neoproterozoic evolution of the southwestern portion of the Rio de la Plata craton (i.e. Tandilia belt).

The following pre-Neoproterozoic basement evolution of the Tandilia area (see Fig. 5) makes the configuration of the southwestern portion of the Rio de la Plata craton dealt with in this article, as depicted by aeromagnetic data, compatible with the satellite gravity data used by previous authors (Pángaro and Ramos, 2012). It also reconciles two different geologic models presented by previous workers, i.e. Cingolani (2010 and references therein) on the one hand, and Massonne et al. (2012), on the other hand.

4.1. Pre-Transamazonian (>2.2 Ga)

Concurrent evidence indicates that the Transamazonian calc-alkaline magmatism in the Tandilia belt derives from Neoarchean crust, as pointed out both by zircon inheritance, average Hf model ages in zircons, as well as Nd model ages, all of them clustered at ~2650 Ma (Hartmann et al., 2002; Pankhurst et al., 2003; Cingolani, 2010; Cingolani et al., 2010).

This enables to infer the existence of precursor Neoarchean crust in the proto-Río de la Plata craton, from which the once single Tandilia plus Balcarce terranes may have inherited their structural fabric. The presence of Neoarchean detrital zircons such as those identified e.g. in the Ventana Group (Uriz et al., 2010) and Las Piedras Formation (Chernicoff et al., 2010) also point to the occurrence of Neoarchean rocks in the southern Río de la Plata craton.

We envisage the Neoarchean proto-Río de la Plata craton to have been subject to an early extensional stage after 2650 Ma, at Siderian times. This extensional regime may have started coevally with the intracontinental rifting occurred in the San Francisco craton at the end of the Neoarchean (ca. 2500 Ma), and lasting for more than 100 Ma (e.g. Teixeira et al., 2000; Barbosa and Sabaté, 2004). Coeval extensional regimes are also known to have occurred in other

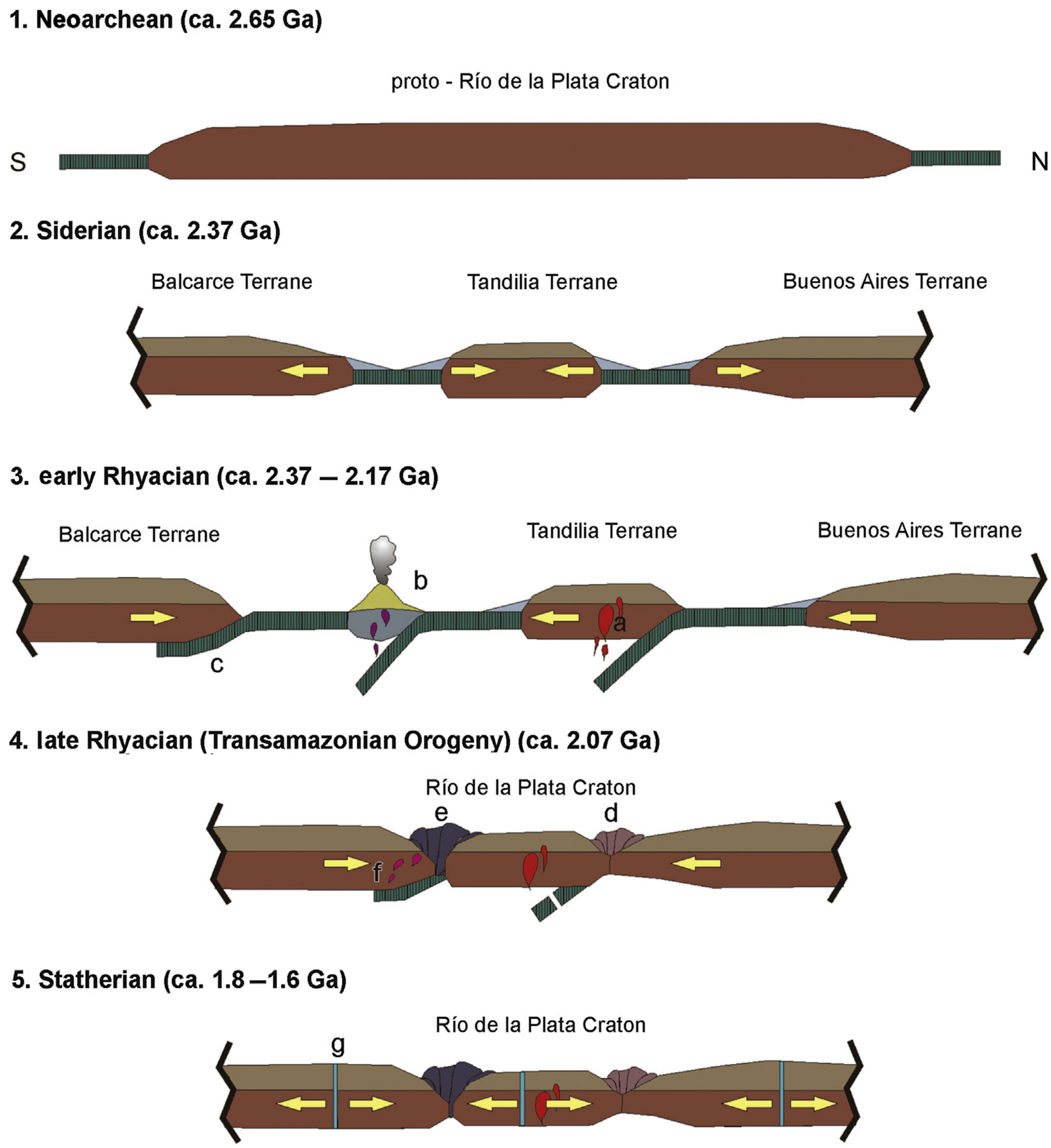

Figure 5. Pre-Neoproterozoic tectonic evolution of the broader study region. References: a: calc-alkaline magmatism, b: El Cortijo island arc, c: underthrusting of oceanic crust (after Massonne et al., 2012), d: Salado suture, e: El Cortijo suture zone, f: anatectic granitoids, g: tholeiitic dykes. Sketch not to scale.

Archean cratonic fragments like, e.g. in the Superior and Karelian cratons, where 2450 Ma mafic dykes are associated with early Paleoproterozoic rifting of the Archean basement (Hölttä et al., 2008). Indeed, on a global scale, the time range considered in this section falls in between peaks (i.e. in a 'valley') of zircon crystallization ages, regarded to be associated with zircon-poor basaltic magmatism predominant during breakup of supercontinents (e.g. Hawkesworth et al., 2009).

The extensional event herein considered must have caused the separation between the Balcarce, Tandilia and Buenos Aires terranes. Aeromagnetic data indicate that the Tandilia and Balcarce terranes have similar geophysical properties (magnetic susceptibility 0.008 SI and 0.01 SI, respectively), whereas no record of geophysical properties of the Buenos Aires terrane precludes assessing the early relationship between the Tandilia and Buenos Aires terranes.

During the time range considered herein, oceanic crust must have developed both to the north and south (present-day coordinates) of the Tandilia terrane, followed by sedimentation (between 2300 and 2200 Ma) in the new basins.

It is worth noting that during the 2450–2200 Ma time range, the sedimentation regime over the emerged Neoarchean cratonic fragments is thought to have started with major basal unconformities due to a global-scale drop in sea level (Eriksson and Condie, 2012) caused by the 'magmatic slowdown' event (2450–2200 Ma) of Condie et al. (2009). Eriksson and Condie (2012) have indicated that this process would have resulted in highly elevated freeboard for cratons, thereby enhancing erosional processes at the cost of significant deposition. This may well have occurred in our case of interest, i.e. in the proto-Río de la Plata craton, where ~2300–2200 Ma supracrustal deposits may represent rift-related sedimentation developed above a major basal unconformity underlain by transitional –continental to oceanic– crust. Such type of deposits may be coeval e.g. with the ca. 2316 Ma rift-related deposits identified above a major basal unconformity in the Kaapvaal craton (Duitschland Formation; Eriksson and Condie, 2012).

The extensional event herein considered must have come to an end by ca. 2370 Ma, it being succeeded by the onset of subduction (see following section). The age of ca. 2370 Ma is herein inferred from the youngest magmatic zircon inherited by the Rhyacian gneisses (Cingolani et al., 2002).

4.2. ca. 2370–ca. 2166 Ma

The spread in the narrow oceans developed at both sides of the Tandilia terrane was reversed, with south-dipping subduction being initiated both: (a) at the northern margin (present-day coordinates) of the Tandilia terrane (i.e. development of continental magmatic arc represented by I-type calc-alkaline granitic to tonalitic magmatic rocks in the Tandilia terrane) and (b) intraoceanic subduction to the south of the Tandilia terrane (i.e. development of island arc magmatism in between the Tandilia and Balcarce terranes, represented e.g. by metabasalts). In both cases, subduction must certainly have occurred between ca. 2230 and ca. 2166 Ma (e.g. Cingolani et al., 2002), possibly extending back to 2370 Ma. This stage would have occurred coevally with the accretionary Encantadas orogeny of Hartmann et al. (2002).

4.3. ca. 2070 Ma (Transamazonian orogeny)

Continued subduction led to the consumption of the oceanic crust. At ca. 2.07 Ga, the collision between the Tandilia and Balcarce terranes took place causing crustal thickening, high-temperature metamorphism, mylonitization and, at the late kinematic transtensional stage, calc-alkaline, EW oriented dyking, locally parallel to the El Cortijo suture zone. During this event, the El Cortijo island arc was trapped between the colliding crustal blocks, as attested by the occurrence of metacherts, metagreywackes and metabasalts metamorphosed at low greenschist facies. This event would be coeval with the collisional Camboriú orogeny of Hartmann et al. (2002).

It cannot be discarded that the process causing high grade metamorphism and anatexis at ca. 2.07 Ga in the Tandilia terrane differed from that occurred coevally further south, in the Balcarce terrane, as envisaged by Massonne et al. (2012), for whom underthrusting of oceanic crust provided the necessary heat at mid crustal levels to cause widespread anatexis (i.e. not subduction leading to continental collision). In any case, even if Massone et al.'s option was applicable to explain the anatectic granites in the Balcarce terrane, it would still not necessarily contradict the roughly coeval trapping of the El Cortijo island arc in between the Tandilia and Balcarce terranes.

The collision between the Tandilia and Buenos Aires terranes along the Salado suture (Pángaro and Ramos, 2012) is bound to have occurred coevally with the events associated with the El Cortijo suture, though no information other than gravimetric data, and the episutural nature assigned to the Mesozoic Salado basin (Pángaro and Ramos, 2012), has been obtained so far.

4.4. ca. 1800–1600 Ma

At this time range, the collapse of the Transamazonian orogen began, with the development of extensive WNW trending tholeiitic dykes (1.59 Ga), and intrusion of S-type post-collisional leucogranites (e.g. Teixeira et al., 2002). The tholeiitic dyking pertains to a diachronous extensional event that, elsewhere in the Río de la Plata craton, has been dated back to shortly after the Transamazonian orogeny, e.g. 1.73 Ga Florida tholeiitic dyke swarm of western Uruguay (Teixeira et al., 2002).

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