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REVIEW ARTICLE

The Tandilia System of Argentina as a southern extension of the Río de la Plata craton: an overview

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Abstract The southernmost outcrops of the Río de la Plata cratonic region are exposed in the Tandilia System in eastern Argentina. The geological evolution comprises mainly an igneous-metamorphic Paleoproterozoic basement named Buenos Aires Complex, which is covered by Neoproterozoic to Early Paleozoic sedimentary units which display subhorizontal bedding. The basement of calc-alkaline signature consists mainly of granitic-tonalitic gneisses, migmatites, amphibolites, some ultramafic rocks, and granitoid plutons. Subordinate rock-types include schists, marbles, and dykes of acid and mafic composition. Tandilia was recognized as an important shear belt district with mylonite rocks derived mainly from granitoids. The tectonic scenario seems related to juvenile accretion event (2.25–2.12 Ga) along an active continental margin, followed by continental collision (2.1–2.08 Ga) after U–Pb zircon data. The collisional tectonic setting caused thrusting and transcurrent faulting favouring the anatexis of the crustal rocks. The tholeiitic dykes constrain the time of crustal extension associated with the last stages of the belt evolution. The basement was preserved from younger orogenies such as those of the Brasiliano cycle. After a long paleoweathering process, the Sierras Bayas Group (c. 185 m thick) represents a record of the first Neoproterozoic sedimentary unit (siliciclastic, dolostones, shales, limestones), superposed by Cerro Negro Formation (c. 150–400 m thick, siliciclastics) assigned to Upper Neoproterozoic age. The final sedimentary transgression during Early Paleozoic was the Balcarce Formation (c. 90–450 m thick) deposited over all the mentioned Precambrian units. Based on all the geological background, a tectonic evolution is offered.

Keywords Río de la Plata craton · Argentina · Igneous-metamorphic complex · Paleoproterozoic · Neoproterozoic-Early Paleozoic cover · Tectonic model

Introduction

The Río de la Plata craton is one of the continental blocks placed at the core of western Gondwana (Almeida et al. 1973, 1976, 2000; Cordani et al. 2003). The southernmost outcrops of this cratonic region are exposed in the Tandilia System also called 'Sierras Septentrionales de Buenos Aires' in eastern Argentina (36° 30′- 38° 10′ S—57° 30′- 61° W). These are distributed in a 350-km-long and maximum 60-km-wide northwest-trending orographic belt, located in the central part of the Buenos Aires province (Fig. 1). Marine geophysical studies show also the continuation of the belt toward the continental oceanic platform. The Tandilia belt outcrops are located in between the Salado (filled by Meso-Cenozoic units) and the Claromecó (filled by Neoproterozoic to Paleozoic units) basins known by exploration boreholes (Ramos 1999; Lesta and Sylwan 2005). In geomorphologic aspects, the Tandilia System is characterized by small hills and ranges that stand out 50–250 m over the 'pampa plain' generally covered by modern sediments. The Albión Hill with c. 500 m near Tandil city is one of the highest elevations.

The geological evolution of Tandilia System comprises mainly an igneous-metamorphic Paleoproterozoic basement named Buenos Aires Complex, which is covered by

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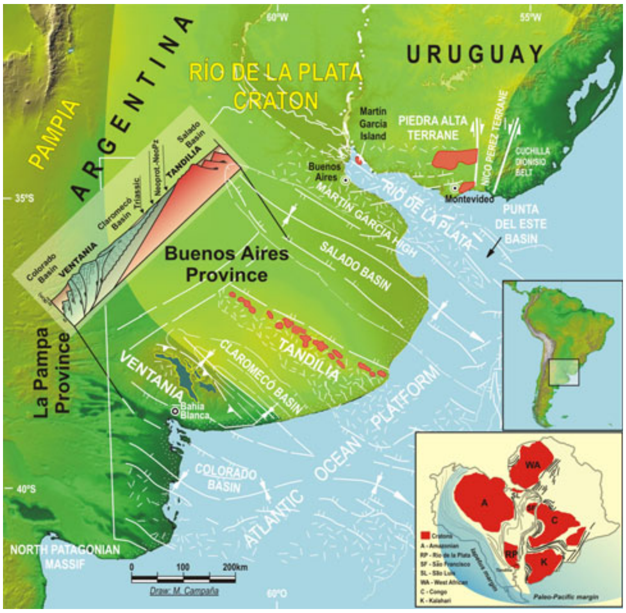


Fig. 1 Location map of the Tandilia System in the Río de la Plata craton of eastern Argentina, showing the extension in between the Salado and Claromecó basins. In *red* color the main outcrops of the Paleoproterozoic rocks in Tandilia, Martin García Island and Piedra Alta Terrane in Uruguay. The profile shows the regional geological relationships (after Ramos 1999). The *inset* maps show in the pre-drift configuration a South America and Africa (Western Gondwana), the location of the Río de la Plata craton amalgamated with Brasiliano belts and the relative position of the Tandilia System in South America

thin Neoproterozoic to Lower Paleozoic sedimentary units which display sub-horizontal bedding (Teruggi and Kilmurray 1980; Iñiguez Rodríguez 1999; Ramos 1999; Cingolani and Dalla Salda 2000 and references therein). As a final event, restricted mafic dykes intrude the sedimentary units.

Paleomagnetic studies have been carried out in Neoproterozoic units of Olavarría and Barker areas. The first data was published by Valencio et al. (1980). Then studies by Rapalini (2006) and Rapalini et al. (2008a, b) on some samples from the Neoproterozoic cover have been permitted to obtain virtual geomagnetic poles and compared with Uruguayan localities within the Río de la Plata craton and some Gondwanan blocks. The obtained polar wander path suggests that the Río de la Plata craton during the Neoproterozoic was localized in intermedian to low latitudes and has been part of Gondwana since 570 Ma.

The Tandilia region constitutes one of the most relevant argentine mining districts (limestones, dolostones, granitoids and several types of clays, among others). For this reason, the permanent quarry activities since the XIX century have facilitated the geological research.

Another point of view is that the Tandilia System could be considered a 'geopark' because it preserved the most ancient rocks of Argentina and Neoproterozoic primitive microorganisms as well as the fossil structures left by them. Many places in Tandilia are true 'natural monuments' that should be preserved as geological world heritage (Cingolani 2008).

The main objective of this paper is to present an update review of the basement and its sedimentary cover of the Tandilia System and to offer a tectonic evolution based in the geological background.

The Tandilia System

The Tandilia geological evolution is relatively well known. Many authors have contributed to the knowledge of the Tandilia basement, sedimentary succession and dynamic events since the pioneering works by Darwin (1846), D'Orbigny (1847), Heusser and Claraz (1863), Aguirre (1879), Backlund (1913), Nágera (1940), González Bonorino (1954). Basement tectonics and general stratigraphic reviews have been provided by Teruggi and Kilmurray (1975, 1980), Dalla Salda et al. (1988), Teruggi et al. (1988), Dalla Salda (1999), Iñiguez Rodríguez (1999), Cingolani and Dalla Salda (2000). After the first recognitions of the sedimentary cover called 'La Tinta Sandsteine' (Heusser and Claraz 1863) or 'La Tinta Formation' (Nágera 1940; González Bonorino 1954) or 'La Tinta Group' (Amos et al. 1972), the most widely accepted stratigraphic scheme for the Neoproterozoic units was proposed by Dalla Salda and Iñiguez Rodríguez (1979) and subsequently modified by Poiré (1987, 1993), Iñiguez et al. (1989); Iñiguez Rodriguez (1999 and references therein). However, Leveratto and Marchese (1983) argued in favor of maintaining for the Tandilia sedimentary cover, the original name of La Tinta Formation deposited as a unique sequence with lateral changes of lithofacies. Several geological aspects as stratigraphy, facies, lithotypes, paleontology, ichnology were investigated and recorded in publications by Borrello (1966), Teruggi and Kilmurray (1980), Iñiguez Rodríguez (1999), Dalla Salda et al. (1988, 2005, 2006) and Poiré and Spalletti (2005). Mineralogical, geochemical, sedimentary provenance and diagenetic-hydrothermal studies were developed on several outcrops of Tandilia (Dristas and Frisicale 1984; Dristas et al. 2003; Zimmermann et al. 2005; Dristas and Martínez 2007; Gómez Peral et al. 2007; Gaucher et al. 2008; Zimmermann and Spalletti 2009).

Some review works on different aspects of Tandilia System were published by Cingolani and Dalla Salda (2000), Andreis (2003), Pankhurst et al. (2003), Rapela et al. (2007), Poiré and Spalletti (2005), Dalla Salda et al. (2005, 2006), Poiré and Gaucher (2009), Gaucher et al. (2009), Bossi and Cingolani (2009).

The Paleoproterozoic basement

The igneous-metamorphic Buenos Aires Complex (Marchese and Di Paola 1975a, b; Teruggi and Kilmurray 1980; Dalla Salda et al. 1988; Cingolani and Dalla Salda 2000; Dalla Salda et al. 2006 and references therein) assigned to 'Transamazonian' or Paleoproterozoic age (Fig. 2) consists mainly of granitic-tonalitic gneisses, migmatites, amphibolites, some ultramafic rocks, and granitoid plutons. Subordinate rock-types include schists, marbles, and dykes of acid and mafic composition. Conspicuous features are wide belts of mylonites mentioned for a first time by Backlund (1913). Metavolcanic units within the Buenos Aires Complex have been described by Lema and Cucchi (1981, 1985) and also by Dristas (1983).

Another aspect to mention is following Teruggi et al. (1988), the presence of a low-grade metamorphic rocks differentiated as El Cortijo Formation and exposed only in Tandil region, consisting of metacherts, metagreywackes and metabasites that could represent a slice of oceanic crust.

The igneous-metamorphic complex is partially covered by two marine platform sedimentary units: the oldest was described as of Neoproterozoic age, and the youngest was assigned to an Ordovician–Silurian age. However, the Punta Mogotes borehole near the city of Mar del Plata revealed more than 80 m of slightly deformed metapelites beneath the c. 400-m-thick quartz-arenites (Borrello 1962; Di Paola and Marchese 1974; Marchese and Di Paola 1975b). According to Cingolani and Bonhomme (1982), the metamorphic event was dated by K–Ar in illitic fine fractions at around 600 Ma, and these metapelites are the only rock-types that could be correlated with the Brasiliano cycle (Ramos, 1988) in the eastern Uruguay (Cuchilla Dionisio Belt). The Rocha Formation that outcrops in this belt shows a similar detrital zircon pattern than that of the Punta Mogotes Formation according to a recent study by Rapela et al. (2008).

Regional geophysical data (gravity and magnetism) allowed to evaluate the geometry, depth, and composition of the Tandilia continental crust (Kostadinoff 1995), which reaches a thickness of about 40 km. The positive gravity Bouguer anomalies registered in this region would indicate a slight thinning of the crust and a series of regional alignments. Also it is possible to interpret the boundaries of tectonic blocks associated with post-deformation main tectonism. The record of gravity anomalies in the Balcarce-Mar del Plata region is in accord with the presence of a c. 500-m-thick sedimentary sequence in Punta Mogotes borehole (Kostadinoff 1995; Dalla Salda et al. 2006).

After the first geochronological data by Hart et al. (1965), it is well known that in general the basement rocks of Tandilia were assigned to the 'Transamazonian' age/cycle (Almeida et al. 1973). It has been very common the usage of the mentioned term (Hurley et al. 1967) as event, cycle or orogeny to cluster all the geological processes during the Paleoproterozoic (2000 ± 400 Ma). On the other hand, in the local nomenclature, it was also proposed as the 'Tandiliano cycle' (Ramos 1999 and references therein). Brito Neves (2009) discussed and proposed to

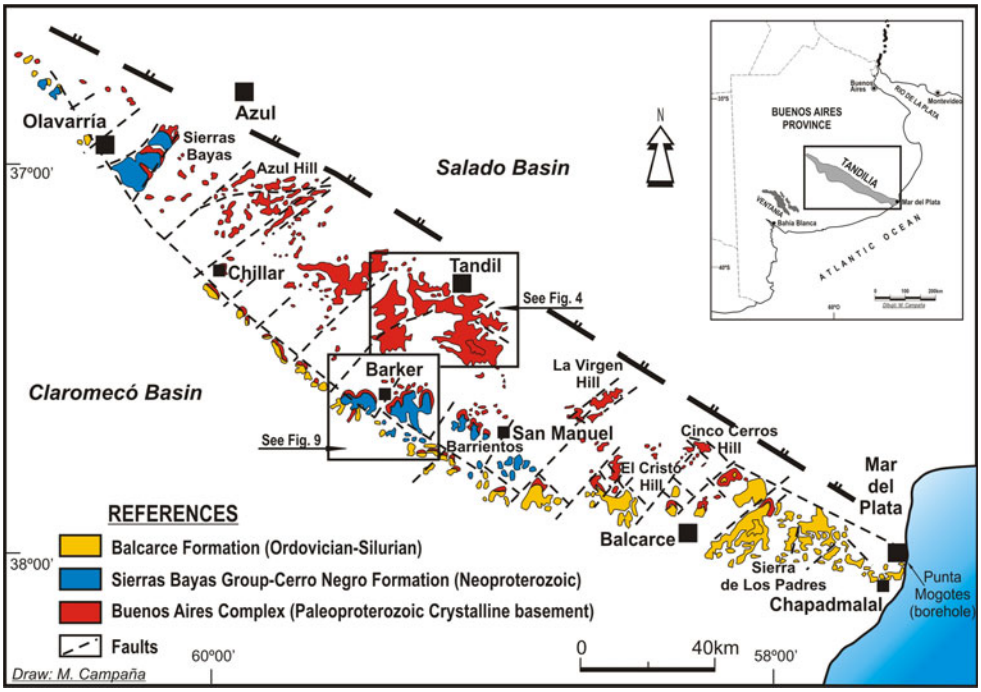


Fig. 2 Geological map of the Tandilia System showing the main outcrop distributions of the Paleoproterozoic crystalline basement (Buenos Aires Complex) and the Neoproterozoic-Lower Paleozoic sedimentary units (Iñiguez et al. 1989). Note the position of the Punta Mogotes borehole at the Atlantic border. Two main areas (Tandil and Barker) were selected to show more detailed maps

abandon the Transamazonian term and to use the four Periods suggested by the International Stratigraphic Chart published by IUGS-UNESCO on 2004 for the Paleoproterozoic: Siderian (2.5–2.3 Ga), Rhyacian (2.3–2.05 Ga), Orosirian (2.05–1.8 Ga) and Statherian (1.8–1.6 Ga). In this overview paper, we intend to use this terminology in the interpreted tectonic model for the Tandilia System evolution.

Metamorphic rocks

Metamorphic rocks are conspicuous in the southern and south-eastern third of the Balcarce area. These are gneissic rocks related to granulite facies (Fig. 3) with orthopyroxene and hornblende; schists (El Quebracho Hill); olivine marbles (Punta Tota, Bachicha Hill); pyroxene-rich ultramafic rocks (Cinco Cerros and Punta Tota); and migmatites. Detailed studies carried out in the El Cristo Hill near the town of Balcarce (Dalla Salda 1975, 1999; Cortelezzi et al. 1999; Ribot et al. 2000) showed that the main metamorphic event reached the garnet grade of the amphibolite facies that locally underwent retrograde metamorphism.

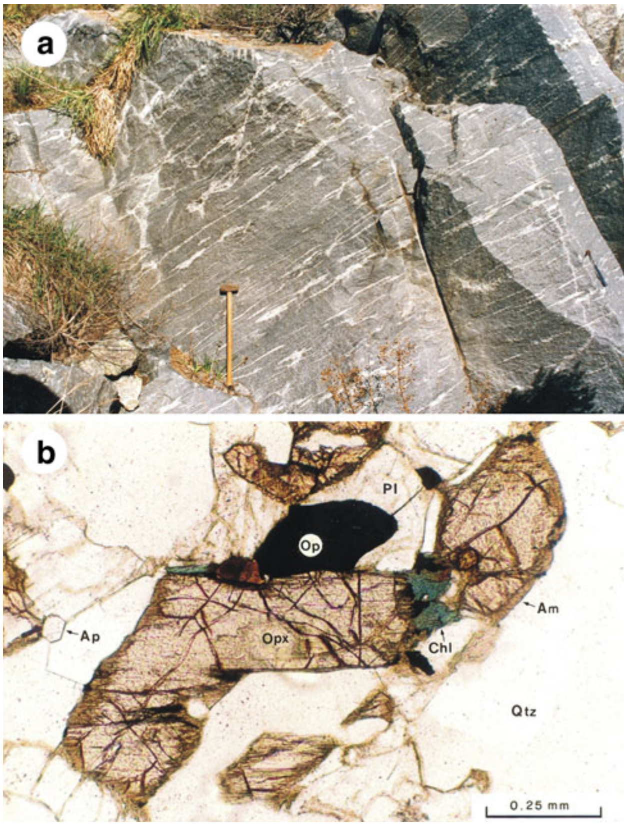


Fig. 3 **a** Othopyroxene rich gneisses exposed at El Cristo Hill (Balcarce area); the migmatic lensoids (*white color*) are evident. **b** Photomicrograph of the mentioned rock showing *Opx* orthopyroxene, *Pl* plagioclase, *Am* amphibole, *Qtz* Quartz, *Ap* Apatite, *Chl* Chlorite and *Op* opaque mineral (courtesy of A. Ribot)

Although non-granitic rocks are rare in the Tandil area, there occur acid metavolcanic rocks, locally with porphyroblasts and comparable to rocks observed at the Vela and at La Ribulia Hills to the South of the city of Tandil (Fig. 4). A wollastonitic skarn has been described in the San Miguel area. Amphibolites are observed in the Tandil area, especially in the southern and central regions. Granulites and charno-enderbites have been found in the Azul and Olavarría areas to the NW of the System (Dalla Salda et al. 1988, 2005; Hartmann et al. 2002b).

The metamorphic evolution of dolomitic marbles and associated calc-silicate rocks from the interesting Punta Tota outcrop (Balcarce region) has been reevaluated by Delpino and Dristas (2008) through petrographic, geothermobarometric, and fluid inclusion studies. These authors described garnet migmatites showing a great abundance of pegmatitic segregates, overlain by biotite—garnet gneisses. Metamorphic conditions are estimated at 750–800°C and 5–6 kb, followed by near isobaric cooling to about 500–450°C and 5.5–6.5 kb. The studied metamorphic reactions indicate a petrological evolution along a counterclockwise P–T path. These authors have proposed two probable geotectonic settings: thinning of the crust and overlying supracrustal basin in an ensialic intraplate tectonic setting and development of a marginal back-arc basin.

Granitoids

The above-mentioned metamorphic rocks have been intruded by several granite plutons. These are typically gray granitoids (with amazonite K-feldspars), except in the northernmost part of the complex where the granitoid rocks are reddish as can be observed in the Sierra Chica and other quarries near Olavarría city. In the central region of the Complex (Tandil area) occurs a wide belt (Fig. 4) consisting of tonalites, granodiorites, granites (partially mylonitized), with magmatic arc affinities, possibly representing syn to post-tectonic phases of the Paleoproterozoic (‘Transamazonian’) orogeny (Dalla Salda et al. 1987, 1988). The Alta de Vela and Montecristo leucogranites were related to the final phase of the main orogenic event. Furthermore, the presence of epidote-rich granite suggests a thickening and/or a crust that was in rapid vertical motion uplift. Geochemical tectonic discrimination analysis revealed some S-type granite bodies (Dalla Salda et al. 1988, 2006), and the analysis of the texture presence of feldspars, micas, and epidote suggests a protracted thermal evolution.

Calc-alkaline and mafic—tholeiitic dyke swarm

The Buenos Aires Complex has a widespread unmetamorphosed dyke swarm described by Quartino and Villar Fabre (1967), Teruggi et al. (1974b), Lema and Cucchi

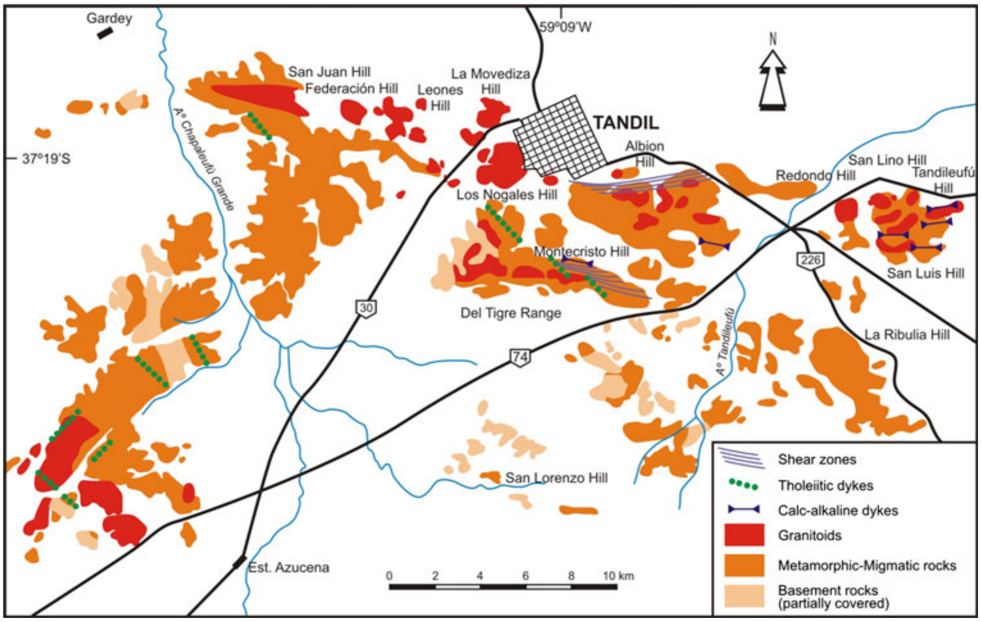


Fig. 4 Geological map for the Tandil region (Dalla Salda et al. 1988, 2006) where the granitoids intruded the metamorphic rocks. Note the main distribution of the calc-alkaline and tholeiitic dyke swarm and the main shear zones (mylonites)

(1981, 1985), Dristas (1983) and Kilmurray et al. (1985). The study of these dykes is important for an understanding of source mantle characteristics in the Paleoproterozoic times, as well as for insights of the processes for craton stabilization. The oldest dykes known in Tandilia (Fig. 4) are calc-alkaline with a bimodal composition and of Paleoproterozoic age (Fernández and Echeveste 1995; Iacumin et al. 1999, 2001; Teixeira et al. 2002), integrated by andesitic to rhyolitic compositions with mainly an east–west orientation. These calc-alkaline dykes have developed with a thickness of 0.5–10 m and depict gray colors and have a $^{40}Ar/^{39}Ar$ plateau age of emplacement of 2020 and 2007 Ma, contemporaneous with post-collisional intrusions (Varela et al. 1988; Dalla Salda et al. 1992; Hartmann et al. 2002b). They originated during a transtensional stage of the Paleoproterozoic orogeny. The calc-alkaline character has been interpreted as representing a magmatic arc tectonic setting (Teixeira et al. 2002). Youngest dykes from c. 1600 Ma have mafic and tholeiitic signature (Echeveste and Fernández 1994; Iacumin et al. 2001) separated in two sub-groups, dolerites or low-TiO_2 dykes (Teruggi et al. 1974b) that outcrop in Azul and Tandil regions and high-TiO_2 basaltic dykes recorded in Tandil area (Teruggi et al. 1988). Dolerite dykes have a wide geographic distribution (Fernández et al. 2001) as a subvertical bodies up to 50 m thick (trending N 30° W), some with more than 5 km long. The high-TiO_2 basalt dykes have been recognized in the Tandileufú Hill (Fig. 4) with porphyritic texture. The phenocrysts are plagioclase, augite, with high contents of TiO_2 (1.2–1.4% by weight) and pigeonite (Dalla Salda et al. 2005). The tholeiitic dykes, with east–west orientation cross-cutting mylonite belts and leuco-monzogranites, indicate a significant change in the regional stress field of the crust, with a location shift into a final Paleoproterozoic extensional tectonic regime accompanied by an anorogenic igneous activity.

Mylonites and shear zones

The mylonites were derived mainly from granitoids. In Azul region, a mylonitic belt is developed in about 40 km east–west long and 3 km wide (Gonzalez Bonorino et al. 1956; Frisicale 1999; Ribot 2000). Another belt was recognized south of Tandil (Fig. 4) with outcrops 25 km long from Albión Hill to Del Tigre Range with similar east–west orientation with some ramifications toward the west-northwest (Dalla Salda 1981); other exposures occur in Alta de Vela Range (Teruggi et al. 1973). Mylonites, proto-mylonites and fault rocks are the main litho-types. Feldspatic and amphibolitic blastesis related to these shear zones were also described. After Ribot (2000), the main deformation event in granitoids of the Azul region was in medium-grade conditions (c. 450°C) followed by hornblende alteration (rehydratation). The Azul shear zone was interpreted based on kinematic indicators as dextral (Gonzalez Bonorino et al. 1956) or sinistral (Ribot 2000). Nevertheless, Frisicale et al. (2001, 2005) concluded that the mylonites were developed during lower greenschist to amphibolite facies with scarce asymmetric rotated porphyroclasts showing both sinistral and dextral senses of shear. After these authors, the Azul shear zone is probably related to the late Paleoproterozoic orogenic cycle and may be due to NNE–SSW tectonic convergence. Deformation temperatures from mineral assemblages are in the range of 400–450°C, and the pressures are more than 6 kb.

In the Sierras de Tandil shear zone, Dalla Salda (1981) interpreted a sinistral horizontal movement. However, at the Albión Hill, D'Angiola et al. (1992) found dextral kinematic indicators. Based on cross-cutting relationship, the age of the shear zones is in between 1,600 and 2000 Ma during a Paleoproterozoic orogeny.

Geochemical and isotopic data interpretation

Dalla Salda et al. (1988, 2006) and Pankhurst et al. (2003) offer some geochemical data based on major and trace elements which indicate that the basement igneous-metamorphic rocks are of calc-alkaline composition. Rapela et al. (2007) present also a complete set of geochemical data, but from rocks obtained in boreholes located outside more than 800 km to the north-west of the Tandilia System. The isotopic data coupled with the geochemical characteristics obtained by these authors indicate that these rocks are associated with intra-oceanic subduction systems or in primitive continental arc settings.

The geochemical available data compiled by Dalla Salda et al. (1988, 2005, 2006) show that the granitoids are generally metaluminous but with a tendency to peraluminosity in more acid varieties. Together with the predominance of hornblende, as the main mafic phase and the absence of peraluminous minerals, the parent magmas were interpreted as I-Type (Pankhurst et al. 2003) that is, derived by melting of preexisting igneous source rocks. However, several processes and sources are involved in active margins. In the tectonic discrimination diagram of Batchelor and Bowden (1985), the majority of samples plot in the subgroup of pre-plate collision, destructive plate margin, subduction regime with a trend toward subgroups of syn-collision or anatectic melting zone and post-orogenic granites. These processes could all be involved as part of a sequence of events beginning in a subduction-related environment and culminating with intense deformation and anatexis during a subsequent collisional phase. However, the same geochemical trend extends in the other direction for the mafic enclaves and could equally imply a coherent geochemical and petrogenetic process for the whole suite, such as variable partial melting of a simple mafic (tholeiitic) source or simple mixing between tholeiitic magma and a uniformly evolved crust.

As were shown by Rapela et al. (2007), the juvenile geochemical and isotopic characteristics are common in 2.0–2.2 Ga rocks in the Brazilian shield corresponding to the Paleoproterozoic ('Transamazonian') orogenic cycle (Cordani et al. 2000). Studies of the major and trace elements and Sr isotope analyses on rocks collected from the El Cortijo Formation have given rise to the view that some of the granitoid plutons in the Tandil area are related to a collision type tectonic setting (Dalla Salda et al. 1987; Ramos 1988; Varela et al. 1988; Teruggi et al. 1988). The collision favored thrusting and transcurrent faulting which constituted a favorable condition for the initial development of anatexis. Furthermore, it can be suggested that the emplacement of the granite plutons in the thick gneissic sequence in the Tandil area was coeval with the regional high-temperature metamorphism, mylonitization and anatexis. Some leucogranites (Alta de Vela Hill) are heterogeneous with high radiogenic signature and typically post-collisional.

The calc-alkaline dykes (Iacumin et al. 2001; Teixeira et al. 2002) have primitive mantle-normalized trace element patterns enriched in Rb, Ba, K, La, Ce and Nd and significant Nb and Ti anomalies, whereas the low-TiO_2 tholeiitic dykes have low incompatible element contents and primitive normalized-incompatible element patterns with slightly positive or negative Nb, mainly reflecting derivation from a depleted source mantle. High-TiO_2 tholeiitic dykes have more enriched incompatible elements-primitive mantle patterns of an enriched source mantle.

Isotopic data and its consequent interpretation were obtained in Tandilia System basement rocks, as described below.

K–Ar, Ar–Ar, and Rb–Sr

The oldest K–Ar ages from Tandilia are c. 2200–2000 Ma published by Hart et al. (1965) and Halpern et al. (1970). Other data vary between 2000 and 1500 Ma (Linares and Latorre 1968; Teruggi et al., 1974a, 1988), but most are younger, often less than 1000 Ma (Hart 1966; Cazeneuve 1967; Linares and González 1990). The first Rb–Sr data for Tandilia were presented by Halpern and Linares (1970) who gave a calculated age of 1947 ± 44 Ma for rocks in the Olavarria area. Granites and microgranites from the San Miguel quarry east of Tandil gave an age of 2120 ± 10 Ma (Halpern et al. 1970; Umpierre Urquhart and Halpern 1971). The pattern of such data has been interpreted by Teruggi and Kilmurray (1980), Dalla Salda (1981), and Ramos (1985) as representing a series of Precambrian events that start with sedimentation, mafic volcanism, and nappe formation in the 2200–2000 Ma interval; followed by intense deformation, metamorphism, and migmatization at times c. 1800 Ma; and then granite emplacement, folding, and low-grade events during the Neoproterozoic. Varela et al. (1988) presented a more comprehensive study with Rb–Sr data for several areas in the Tandilia System and obtained ages of 2154 ± 28, 2001 ± 60, 1971 ± 398, and 1770 ± 88 Ma. Based on this isotopic information, Dalla Salda et al. (1988, 1992) and Cingolani and Dalla Salda (2000) have distinguished main intrusive episodes. Pankhurst et al. (2003) obtained new Rb–Sr whole-rock data for granitoids and orthogneisses from the western part of the Tandilia System yielding an 'errorchron' of 2009 ± 71 Ma.

K–Ar age of 1750 ± 50 Ma for a dolerite dyke near Tandil was obtained by Teruggi et al. (1974b). Biotites from hornfelses adjacent to calc-alkaline (andesite–rhyolite) dykes southeast of Azul have yielded ^{40}Ar–^{39}Ar ages of 2020 ± 24 and 2007 ± 24 Ma (Teixeira et al. 2001, 2002). Plagioclase from tholeiitic dykes indicate much younger K–Ar and ^{40}Ar–^{39}Ar ages of 800–1100 Ma, which is considered to reflect hydrothermal activity (Teixeira et al. 2002).

Sm–Nd and U–Pb

Pankhurst et al. (2003) presented for granitoid samples from Olavarría region a Sm–Nd isochron of 2140 ± 88 Ma (initial ^{143}Nd/^{144}Nd: 0.50977) that could record the age of emplacement of igneous protoliths. Sm–Nd model-ages averaging 2620 ± 80 Ma indicate that the principal rock-forming events were a Late Archaean. Because it is likely that these evolved granitic rocks were derived only indirectly from mantle sources, with an earlier stage of crustal differentiation, 2600–2700 Ma is considered a maximum possible age for the original extraction of continental crust from the mantle.

The Sm–Nd T_{DM} model-ages obtained by Hartmann et al. (2002b) range between 2.7 and 2.4 Ga. The εNd values slightly below cero (−1, 27 to −3, 30) are another argument for a crustal source for most of the Tandilia granitoids, but this crustal source cannot be much older than the magmatism.

Initial εNd values of 2.3–2.4 in calc-alkaline dykes (Iacumin et al. 2001) indicate slightly more crustal contamination or prehistory than that of the granitoids analyzed by Pankhurst et al. (2003) mostly 2.1–2.2. These dykes are essentially contemporaneous with granite emplacement in a transtensional stage during a restricted Paleoproterozoic orogenic activity. An upper intercept U–Pb age on two baddeleyites from tholeiitic dyke places the intrusion at 1588 ± 11 Ma after data obtained by Teixeira et al. (2002).

Reliable ages for gneissic and granitoids rocks have been determined by Hartmann et al. (2002b), Cingolani et al. (2002 and 2005) using the robust U–Pb SHRIMP isotope methodology (Fig. 5). More than 60 zircon crystals were analyzed for samples obtained from the Azul, Tandil and Balcarce areas.

After Hartmann et al. (2002b) regardless of composition and structure, the magmatic ages of all zircon samples are Paleoproterozoic (Rhyacian) in the range of 2234–2065 Ma, with inherited ages determined in the cores of a few zircon crystals that suggest 2368 Ma (Siderian) to 2185 (Early Rhyacian) for the source, with only one Neoarchean age c. 2657 Ma in a tonalite from the Tandil region. Internal structure of zircon crystals is suggestive of metamorphic recrystallization but the ages are entirely Paleoproterozoic. A lack of recrystallization or new zircon (Fig. 5) growth in the Neoproterozoic suggests that the Tandilia belt was preserved from younger orogenies such as those of the Brasiliano cycle. The main tectonic activity has been linked to the 2.25–2.12 Ga accretionary event ('Encantadas') and to the 2.1–2.08 collisional overprint ('Camboriu'). This geological evolution can be correlated with the Piedra Alta terrane (Uruguay), where Rb–Sr, Sm–Nd and U–Pb data show a similar signature (Cingolani et al. 1997; Preciozzi et al. 1999; Hartmann et al. 2002a; Oyhantçabal et al. 2009, 2010) during Paleoproterozoic times.

Hf isotopes

Preliminary Hf isotope analysis (Cingolani et al. 2010c) on zircon crystals (Fig. 6) was carried out using a laser-ablation microprobe, attached to a plasma multi-collector ICP-MS at Macquarie University, Sydney (Australia). From all studied samples taken in Tandil and Balcarce regions suggest that the depleted mantle model age is Neoarchean 2.65 Ga, less old than the crystallization age. Positive εHf obtained data show also derivation from juvenile material. An alternative interpretation could be a mixing with juvenile (2.27 Ga?) and crustal (more than 2.65 Ga) magmatic components. The average of 28 Hf model-ages (c.2.6 Ga) is almost coincident to the age of the only one inherited zircon on granitoid sample from Tandil area, showing strong evidence supporting the derivation from a Neoarchean crust. The Hf isotope study confirms the Sm–Nd data published by other authors. These results are in agreement with precise U–Pb dating of the craton in western Uruguay and southernmost Brazil, which also indicate a relatively short-lived Paleoproterozoic orogeny.

The Neoproterozoic-Lower Paleozoic sedimentary cover

After more than 800 Ma Tandilia sedimentary processes start with an unconsolidated arkosic saprolite that records a palaeoweathering basement surface (Poiré 1987; Dristas et al. 2003; Zalba et al. 1993). This altered level less than 4 m thick was registered in the Olavarría and Barker areas. In the currently accepted (Fig. 7) stratigraphic scheme (Dalla Salda and Iñiguez Rodríguez 1979; Manassero 1986; Iñiguez et al. 1989; Poiré and Spalletti 2005; Gómez Peral et al. 2007; Poiré and Gaucher 2009), the Sierras Bayas Group (c. 185 m thick) is a Neoproterozoic sedimentary cover comprising—from base to top- the Villa Mónica, Colombo Diamictite, Cerro Largo, Olavarría-Las Aguilas and Loma Negra units superposed by Cerro Negro Formation (c. 150–400 m thick) and the final sedimentary

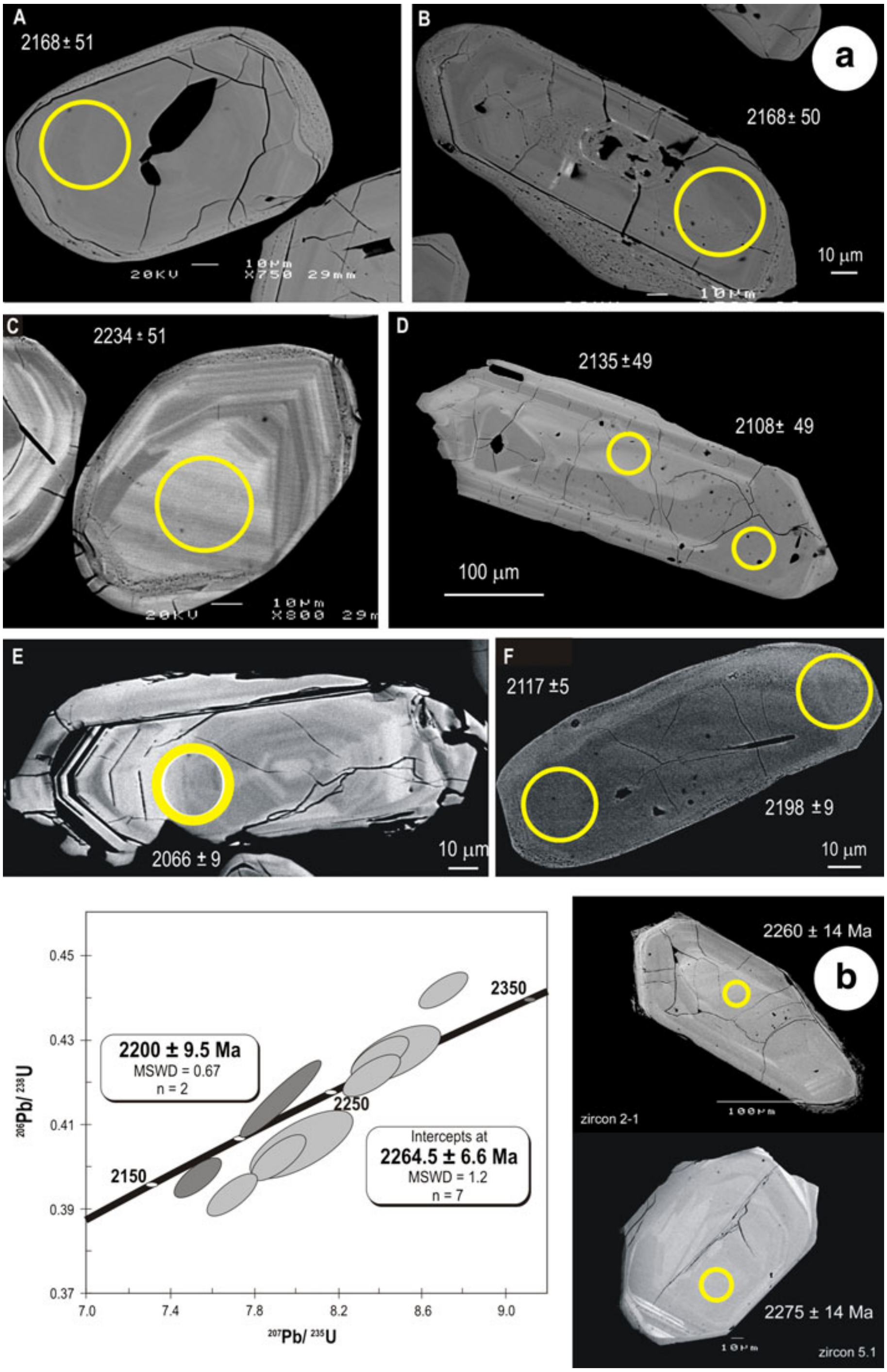


Fig. 5 **a** Backscattered electron images of zircon crystals analyzed by Hartmann et al. (2002b). Samples *A* and *B* Punta Tota (Balcarce area) banded garnet granitoid. *C* Villa Mónica quarry (Olavarría) *gray* charno-endeberbite. *D* Boca de la Sierra (Azul) syenogranite. *E* Villa Mónica quarry red monzogranite. *F* Triunfo Hill (Balcarce) mafic charnockite gneiss. **b** U–Pb SHRIMP concordia diagram for zircon crystals of the Ta5 granitoid sample from Montecristo quarry (Tandil region). On the *right* backscattered electron images of two analyzed zircons (Cingolani et al. 2005)

event at the Lower Paleozoic with c. 100–400 m of the Balcarce Formation (Iñiguez et al. 1989; Iñiguez Rodríguez 1999; Poiré et al. 2003; Poiré 2004; Gómez Peral et al. 2007). Depositional sequences currently recognized (Andreis and Zalba 1998; Poiré et al. 2003; Poiré and Spalletti 2005) and provenance studies (Zimmermann et al. 2005; Zimmermann and Spalletti 2009) could be synthesized as follow.

The first marine transgression (Villa Mónica Formation)

It was defined as the "Lower Quartzites" and "Dolostones" (50–70 m thick) and bears some phosphate levels and rich stromatolite assemblages (Poiré 1993) suggesting a Tonian-Cryogenian age (c. 850 Ma). The main outcrops are localized in the Olavarría and Barker areas. The basal member is composed of shallow-marine siliciclastic rocks

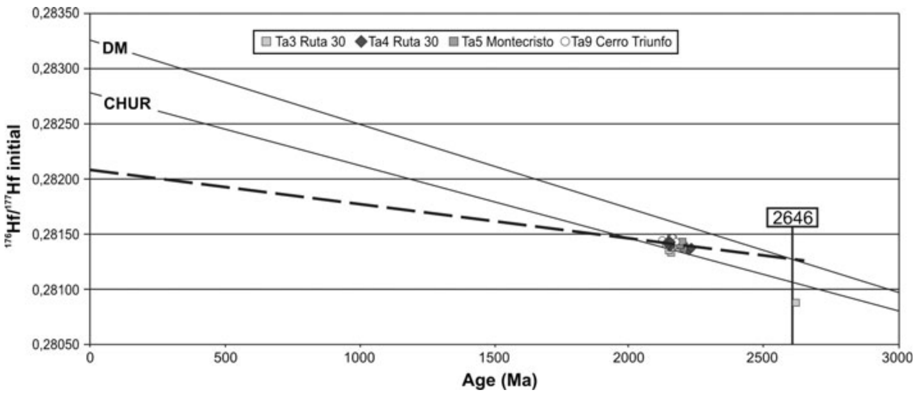


Fig. 6 Plot of ^{176}Hf/^{177}Hf ratios versus ages on dated zircon crystals of samples from Balcarce and Tandil regions (Cingolani et al. 2010c). The depleted mantle model age is Neoarchean (*c*. 2.65 Ga)

(conglomerates, quartz-arenites, arkoses, diamictites and shales), the upper member is characterized by shallow-marine stromatolitic dolostones and shales (Poiré and Spalletti 2005). The first record of acritarchs (Gaucher et al. 2005a) in greenish pelites assigned to *Leiosphaeridia* represents the oldest fossils reported for the Tandilia System (Fig. 7). The contact with the underlying palaeosols (saprolite) is well exposed in some quarries in the Olavarría area (Poiré 1993). Gómez Peral et al. (2005) and Poiré et al. (2005) reported hydrothermal pyrophyllite in shales of the upper part of the siliciclastic member. The overlying dolostone member includes stromatolites representing a platform in an intertidal environment. Gómez Peral et al. (2007) have obtained carbon and oxygen isotopic data, combined with a detailed diagenetic study from dolostones that provide a new record of chemostratigraphic variations useful for regional and global correlations.

Rb–Sr geochronology of illitic shales within the dolostones yielded an age of 793 ± 32 Ma (Cingolani and Bonhomme 1988). Detrital zircon geochronology on three samples (Rapela et al. 2007; Gaucher et al. 2008; Cingolani et al. 2010a), show a unimodal population of Palaeoproterozoic age. This is a clear indication that sandstones from different areas were mostly derived from the underlying Buenos Aires Complex, which has a restricted Paleoproterozoic age range (Fig. 8).

Dristas et al. (2003) described minerals associated with advanced argillic alteration deposits near Barker town, and Zalba et al. (2010) have shown a complex history of weathering and diagenesis of this unit in the La Juanita Range, Barker area (Fig. 9). These authors also described well-preserved microbially induced structures (biosignatures). Above the mentioned unconformity, predominantly diamictitic deposits of 8 m thick occur. This event recently was recognized as a separate unit by Poiré and Gaucher (2007).

The second transgression (Cerro Largo Formation)

This second 40-m-thick marine transgression (Poiré 1993; Poiré and Gaucher 2009) presents finely bedded, varicolored, glauconitic sandstones, hetherolithic facies and cross-bedded quartz-arenites (Fig. 7). The coarsening and shallowing upward sequence represents the transition from subtidal nearshore to shoreface environments. *Chuaria, Synsphaeridium* and *Leiosphaeridia* are the most important microfossils found in this unit (Pöthe de Baldis et al. 1983; Gaucher et al. 2005a). Simple trace fossils have been reported from sandstones but were reinterpreted as desiccation cracks associated to biomats (Porada and Bourgouri 2008).

According to provenance geochronological studies (Gaucher et al. 2008), the sandstones (Fig. 8) are characterized by a dominant Palaeoproterozoic detrital zircon population, but also important Archean to lowermost Paleoproterozoic and Mesoproterozoic ages occur. The presence of Archean detrital zircons in sandstones of this section of the Sierras Bayas Group points to the Nico Pérez Terrane (Uruguay), as a probably source of detritus, which was closer to Tandilia than it is today (Gaucher et al. 2008), and the absence of Neoproterozoic detrital zircons confirms the deposition in a stable continental margin probably opened to the east and south.

Shallow-marine deposits (Olavarría and Las Aguilas units)

In the Olavarría region quartz-arenites of the Cerro Largo Formation pass transitionally into siltstones and claystones of the so-called Olavarría Formation (Andreis et al. 1996) with a maximum thickness of 37 m. Rb–Sr ages on illitic shales point to a Neoproterozoic age (Bonhomme and Cingolani 1980). Paleoenvironmental interpretations suggest shallow-marine deposits in a transgressive system tract.

At the Aguilas Range in Barker area (Fig. 9), three lithofacies occur in the homologous Las Aguilas Formation, from base to top (Zalba et al. 1988; Andreis 2003; Poiré and Gaucher 2009): silicified calcareous breccias with oolites and peloids; reddish to whitish claystones; and a coarsening-upward, heterolithic sequence. Several sedimentary structures (ripples, hummocky cross bedding and

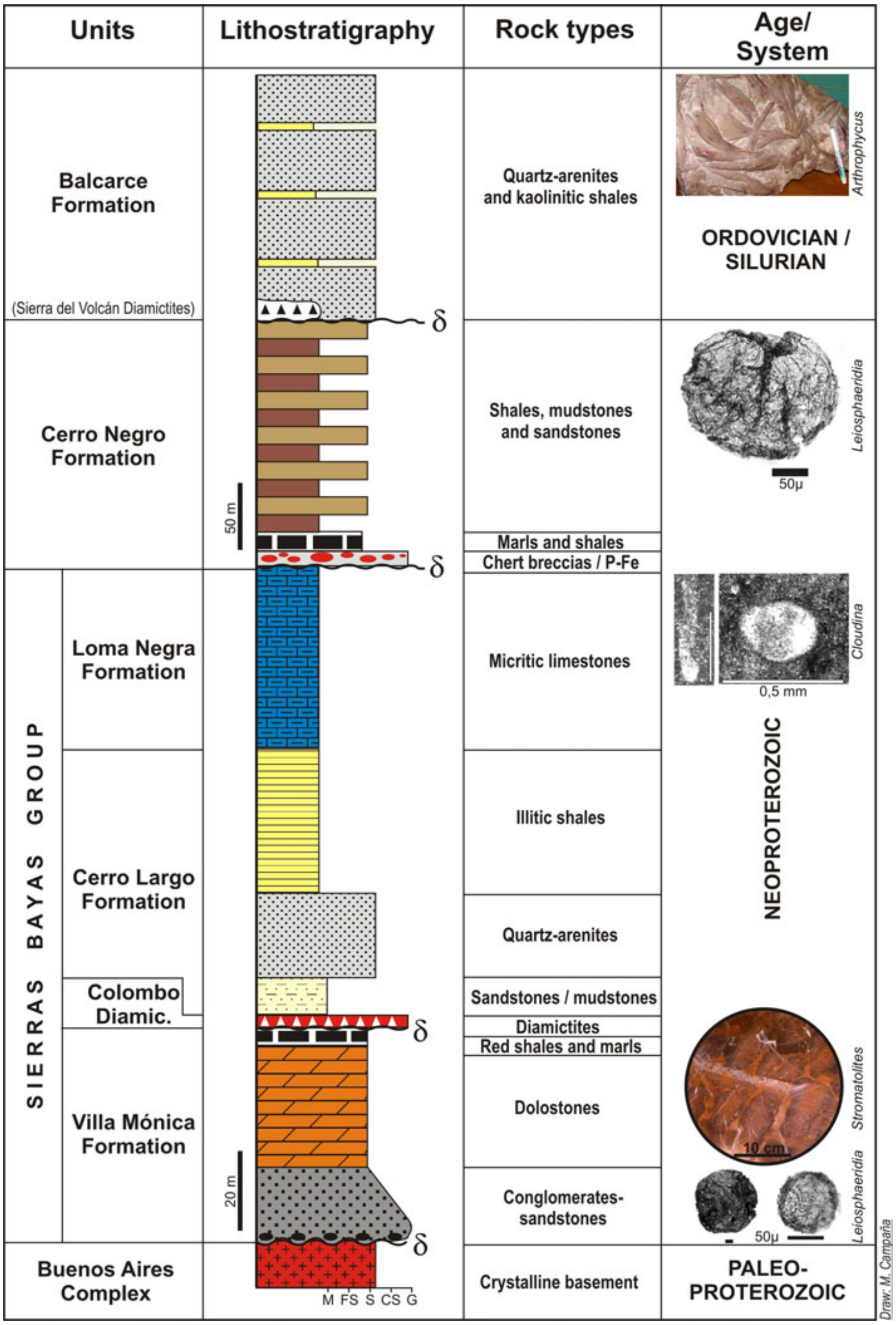


Fig. 7 Integrated lithostratigraphic column of the Neoproterozoic-Early Paleozoic Sierras Bayas Group, Cerro Negro and Balcarce Formations showing the main rock types and unconformities based on Poiré and Gaucher (2009). Examples of microfossils (*Acritarchs*) from Villa Mónica and Cerro Negro units (*scale bars* = 50 µm) and the probable *Cloudina* cf. *C. riemkeae* (*scale bar* 0.5 mm) in thin sections of micritic limestones of the Loma Negra are after Gaucher et al. (2005a, b). Photographs of stromatolites (in dolostones of Villa Mónica unit) and *Arthrophycus* ichnogenus (Balcarce Formation) are from the author

synaeresis and desiccation cracks) were described. Also in the Barker area, the middle part of the unit comprises red claystones with high iron content (32–70% Fe_2O_3) up to 9 m in thickness, which could be correlated with others late Neoproterozoic iron deposits in SW Brazil and Uruguay (Gaucher 2000; Gaucher et al. 2003, 2004). The stratigraphic position of the Las Aguilas Formation below the Loma Negra limestones were defined by Poiré and Spalletti (2005) following as first suggested in Leveratto and Marchese (1983) geological mapping (Fig. 9).

Open marine ramp and lagoons (Loma Negra Limestone). Regression, karstic surface and new transgression (Cerro Negro unit)

The Loma Negra Limestone unit was proposed by Borrello (1966). It is the youngest depositional sequence of the Sierras Bayas Group (Fig. 7) and has been mined for a century by the cement industry. It is outcropping in quarries localized in the Olavarría and Barker areas (Fig. 9). The Loma Negra Formation with 40–45 m thick is composed

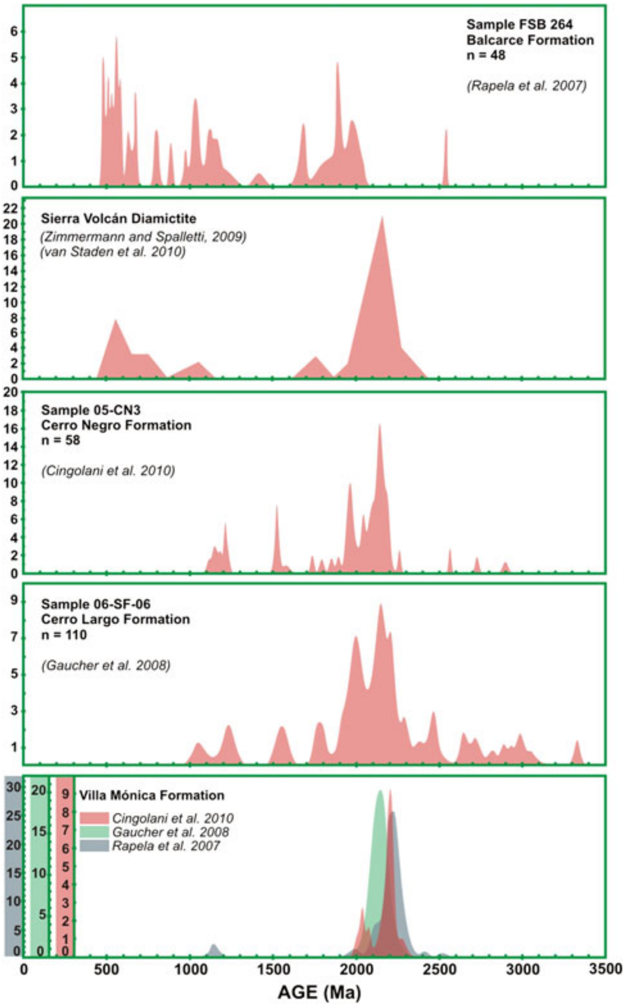


Fig. 8 Comparative diagram of frequencies vs. ages for detrital zircons for Villa Mónica Formation (Rapela et al. 2007; Gaucher et al. 2008; Cingolani et al. 2010a), Cerro Largo Formation (Gaucher et al. 2008); Cerro Negro Formation (Cingolani et al. 2010a); Sierra del Volcán Diamictite (van Staden et al. 2010; Zimmermann and Spalletti 2009) and Balcarce Formation (Rapela et al. 2007)

almost exclusively of reddish and black micritic limestones, deposited by suspension fall-out in open marine ramp and lagoonal environments. In these limestones, several diagenetic processes were recognized by Gómez Peral et al. (2007) and after chemostratigraphical studies the Loma Negra Formation fits in global δ13C and ^{87}Sr/^{86}Sr trends (Kawashita et al. 1999) that range the Ediacaran age, which is regionally important since it places constraint on the continuity of Neoproterozoic basins in south-western Gondwana.

On the top of the Loma Negra Formation a regional unconformity occurs (Leanza and Hugo 1987; Barrio et al. 1991), which has been recently named "Barker Surface" (Poiré and Gaucher 2007; Poiré 2008) and correlated with other Gondwanan sequences. This surface has been related to a sea-level drop pointing to a marine regression that exposed the Loma Negra shelf. In the micritic limestones Gaucher et al. (2005a) reported the occurrence of *Cloudina cf. C. riemkeae* (Fig. 7) and a probable medusoid resting traces (Poiré et al. 2003). These entire data and the chemostratigraphic signature (Kawashita et al. 1999; Gaucher et al. 2005a; Gómez Peral et al. 2007) suggest a Neoproterozoic (Ediacaran) age for the upper section of the Sierras Bayas Group. The correlation with the Arroyo del Soldado Group (Nico Perez terrane, Uruguay) was described by Poiré et al. (2003) and Gaucher et al. (2004).

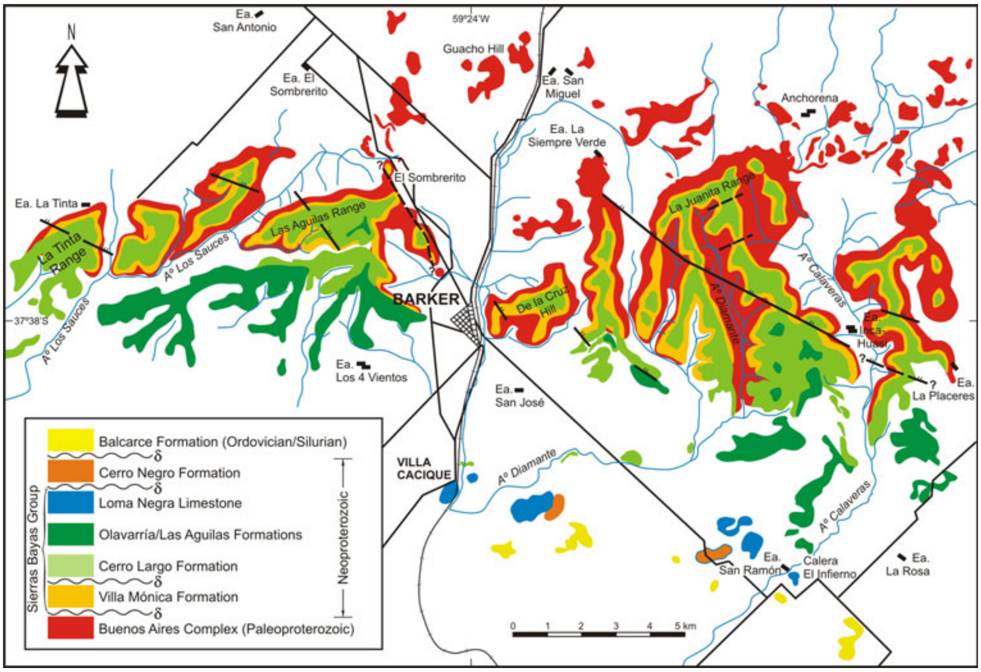
In the Olavarría region, Iñiguez and Zalba (1974) described the Cerro Negro Formation as a 150 m thick unit made up of illite-chlorite rich, green and reddish pelites (Fig. 7). This unit unconformable overlies the Loma Negra Formation. Meteoric dissolution of carbonates led to an expressive karstic surface, in which residual clays and brecciated cherts accumulated. At the base of the Cerro Negro Formation, Leanza and Hugo (1987) described a "phosphate member" that suggests the infilling paleovalleys of a flat basin on a paleosurface of the Loma Negra Formation during a marine regression. New quarry outcrops and exploration boreholes suggest c. 400 m thick for this unit (Poiré and Gaucher 2009) characterized by reddish, greenish or brown-olive-black claystones and heterolithic facies, mainly deposited in upper to lower intertidal conditions. The upper contact with the Balcarce Formation is not exposed covered by Quaternary deposits but it was recognized in quarries exploration boreholes in Barker region (Fig. 9). The Cerro Negro Formation yielded abundant acritarchs in organic matter rich shales mainly assigned to *Leiosphaeridia and Synsphaeridium*, which are consistent with an Ediacaran age for the unit (Cingolani et al. 1991; Gaucher et al. 2005a). However, Rb–Sr radiometric data (Bonhomme and Cingolani 1980) on illitic shales suggest a Neoproterozoic age (c. 730 Ma).

Detrital zircon U–Pb ages obtained from samples located at the base of the unit show similar polymodal pattern reported for the Cerro Largo Formation (Fig. 8) but a minor Archean zircon grains provenance is evident (Cingolani et al. 2010a).

Deformation of the Neoproterozoic rocks and tangential tectonic event

In general, the Tandilia Neoproterozoic sedimentary rocks were slightly deformed and remained flat-lying (Iñiguez et al. 1989). However, some deformation was described by González Bonorino (1954) in the Olavarría (Sierras Bayas) region. Recently in a detailed work by Massabie and Nestiero (2005) found two fold systems, F1 (NE) and F2 (NW) which define domes and basins pattern on Sierras Bayas Group. Also ductile deformation locally observed could be associated with a tectonic reactivation of the

Fig. 9 Geological map of the Barker area modified after Leveratto and Marchese (1983). The sedimentary unit nominations were modified after Poiré and Spalletti (2005)



basement (Buenos Aires Complex), furnished by preexisting planar anisotropies of the mylonitized granitic rocks. This folding is considered a result of tectonic activity occurred during Late Precambrian to Lower Early Paleozoic and predates the last marine transgression of the Balcarce Formation.

As we mentioned earlier, the Punta Mogotes Formation (metapelites) with K–Ar metamorphic age of c. 600 Ma (Cingolani and Bonhomme 1982) could be correlated with the Rocha Formation that outcrops in the Cuchilla Dionisio terrane, Uruguay (Bossi and Gaucher 2004). The docking of the Cuchilla Dionisio terrane occurred in the Cambrian (Gaucher et al. 2005a) by means of tangential tectonics represents one of the last events of Gondwanan amalgamation. If this is correct, the Sierra Ballena Shear Zone (c. 535 Ma) that separates this terrane from the Nico Perez terrane could be extended through the Tandilia Atlantic coast (Punta Mogotes borehole). Concomitant faulting block systems (Kostadinoff 1995) has produced a deepening of the Early Paleozoic siliciclastic basin toward the East.

New shallow-marine open shelf basin: lower Paleozoic Balcarce unit with pyroclastic and glacial events

The last sedimentary cycle, represented by the Balcarce Formation, crops out along the southern edge of Tandilia from the Olavarría area to Mar del Plata at the Atlantic coast (Fig. 2). The thickest sections are exposed between Balcarce and Mar del Plata. The Balcarce Formation unconformable overlies all the Precambrian units (Fig. 7). Its average thickness is 75–90 m, reaching c. 450 m in the Punta Mogotes borehole near Mar del Plata. In general, this unit is composed of quartzites, fine-grained quartzitic conglomerates and kaolinitic shales. Locally at the base of the sequence, some pyroclastic levels were described. One of these levels was recorded at the Cerro del Corral area, which was affected by hydrothermal solutions (Dristas and Frisicale 1988, 2003, among others).

The sedimentological studies (Del Valle 1987a, b; Poiré and Gaucher 2009 and references therein) suggest an epicontinental, shallow-marine open shelf with sedimentary facies developed in the nearshore and inner shelf environments of a tide-dominated and storm influenced platform. The progradation to the south of the clinoforms reported by Poiré et al. (2003) confirms that the margin of the Balcarce basin was located to the north of the Tandilia region (Teruggi, 1964; Dalla Salda and Iñiguez Rodríguez 1979). The Balcarce Formation contains abundant and diverse trace fossils of the "Cruziana ichnofacies" (Borrello 1966; Poiré et al. 1984; Del Valle 1987b; Cingolani et al. 1985; Poiré and Del Valle 1996; Spalletti and Poiré 2000; Seilacher et al. 2002). The age of the Balcarce Formation has been considered as early Palaeozoic. Trace fossils broadly constrain the age between Ordovician and Lower Silurian. In the ichnostratigraphic correlation work, Seilacher et al. (2002) described from some localities between Balcarce and Mar del Plata outcrops, the occurrence of *Cruziana ancora angusta, C. bonariensis, Diplichnites isp., Gyrochorte zigzag, Arthrophycus alleghaniensis* among other ichnospecies (Fig. 7).

Rapela et al. (2007) reported U–Pb detrital zircon ages (Fig. 8) from Los Pinos quarry sample with different provenance pattern compared with the old sequences and as young as 475–480 Ma (Early Ordovician) for the Balcarce Formation, suggesting also a Late Ordovician to Lower Silurian sedimentation age.

After the mineralogical, geochemical and detailed provenance studies by Zimmermann and Spalletti (2009), the Balcarce Formation comprises mainly detrital material derived from old upper crustal material that excludes a reworking of the older successions of the basement of the Río de la Plata craton, and includes Cambrian rift-related granites of South Africa and the Sierra de la Ventana (Eastern Argentina), as main suppliers of detritus. The sources were magmatic, sedimentary, and subordinated felsic metamorphic terranes. High concentrations of tourmaline and Ti–rich heavy minerals, including zircon and nearly euhedral chromite, are common. The delivery of chromite may be associated with convergent tectonics causing the obduction of oceanic crust during pre-Upper Ordovician times (from El Cortijo Formation?). Trace element geochemistry of recycled pyroclastic material, associated with the quartz-arenites, also suggests volcanic arc sources.

Recently, Cingolani et al. (2010b) present U–Pb zircon ages by ID-TIMS on samples taken from kaolinitized pyroclastic levels outcropped in Cerro del Corral (Dristas and Frisicale 1988). The studied zircon crystals show mainly idiomorphic bi-pyramidal type characteristics, suggesting acidic igneous origin and reveal a very few transport from the source. The analyzed zircons indicate much older ages than the Ordovician–Silurian age of Balcarce sedimentation. Most of ^{207}Pb/^{206}Pb ages are close to 2.1 Ga, suggesting a main Paleoproterozoic source area for these crystals, representing the typical age of the Tandilia basement. Among the 18 analyzed zircon fractions, extracted from volcaniclastic layers, no evidence of an Ordovician–Silurian volcanic episode was obtained, suggesting that these crystals represent a re-working product of previous Paleoproterozoic volcanic rocks.

Diamictite levels were recognized at the Sierra del Volcán, Balcarce area (Spalletti and Del Valle 1984) in between the crystalline basement and the Balcarce Formation. This diamictite is 4 m thick and bears polihedrical dropstones, often in vertical position, affecting both ripple bedding and lamination structures. Based on its stratigraphic position, the Sierra del Volcán Diamictite was originally considered to represent an Ediacaran glacial event (Spalletti and del Valle 1984; Pazos et al. 2008). However, Poiré and Spalletti (2005) and Zimmermann and Spalletti (2009) suggested a possible Hirnantian age for these glacial event, as a member of the Balcarce Formation deposits on the basis of Ordovician U–Pb ages (Fig. 8) of detrital zircons reported by van Staden et al. (2010). Therefore, this glacial unit should be referred to the Upper Ordovician, which can be correlated with an important glacial event in southern South America and South Africa.

As a final event. some subalkaline dolerite sills intrude kaolinitic shales assigned to the Balcarce Formation in Los Barrientos area (Rapela et al. 1974) yielded whole-rock K–Ar ages of 450 and 490 Ma. However, at the Cerro del Corral a dolerite sample obtained from the mining exploration borehole (Cingolani et al. 1985) yielded a K–Ar whole-rock age of 396 ± 11 Ma and it is tentatively correlated to the outcrops of Los Barrientos area.

Diagenetic and hydrothermal activity

In the Tandilia System, several evidence of hydrothermal activity (clay deposits, quartz crystals, alunite and iron-rich levels) were recognized (Dristas and Frisicale 1988; Dristas et al. 2003). The latter described in the sedimentary cover (Balcarce Formation), an alteration of original fall-out pyroclastic material at Cerro del Corral area, showing a kaolinite and rutile-anatase assemblage from low-temperature process. Other deposits involving mainly reworked pyroclastic material were located in the west of Barker, Sierra de la Tinta areas (Fig. 9) displaying an advanced argillic alteration, which include pyrophillite, kaolinite, dickite, rutile, alunite, diaspore, hematite and secondary quartz as mineral association. There are also deposits derived from alteration of migmatites from the basement complex rocks, showing advance argilic alteration represented by pyrophyllite, kaolinite, sericite, diaspore, hematite, alunite, tourmaline, and rutile. The interpretation done by Dristas and Frisicale (1984) was that these deposits occur along faults, fractures and breccias through which the hydrothermal fluids could be mobilized. The consequent mixing hydrothermal solutions with meteoric water gave rise to more oxidizing conditions and to the formation of alunite veins. The iron-rich deposits of the Barker region were studied by Dristas and Martínez (2007) that concluded they were formed under low temperature conditions and are related to an unconformity with a large-scale hydrothermal activity. The source of iron may be assigned to the alteration of mafic minerals of the migmatitic Paleoproterozoic basement during a Late Precambrian age (616 ± 17 Ma, K–Ar data). As was mentioned earlier, Gómez Peral et al. (2007) have studied the diagenetic processes, divided into several stages that affected the dolostones from the lower part of the sedimentary cover (Villa Mónica Formation) and the carbonaceous Loma Negra Formation.

Stratigraphic correlations and tectonic setting

The Neoproterozoic-Early Paleozoic marine deposits, initially known as *'La Tinta Sandsteine', as a* Formation (or as Group) now composed of the Sierras Bayas Group, Cerro Negro and Balcarce Formations, were correlated with the Nama Group in southwest Africa (Germs 1972; Dalla Salda 1979, 1980, 1982, Dalla Salda et al. 1988), that records the assembly of southwestern Gondwana during the Neoproterozoic. On the other hand, Aceñolaza (1978) mentioned this correlation and described the common Neoproterozoic-Lower Paleozoic sequences as the "Nama-La Tinta basin".

More recently, Gaucher et al. (2005a) based on litho, bio and chemostratigraphy have compared the Tandilia Neoproterozoic sedimentary successions with the lower section of the Arroyo del Soldado Group (Nico Pérez terrane, Uruguay). Both are characterized by alternation of carbonatic and siliciclastic members deposited in a passive margin tectonic setting. Despite the Arroyo del Soldado is up to 5 km thick, the Neoproterozoic of Tandilia records a shallower epicontinental condensed section showing erosive surfaces in a 350–400 m thick profile.

The isotopic signatures of Loma Negra limestones, the possible occurrence of shelly fauna elements (*Cloudina*) and a karstic surface developed on the top of the carbonates, indicate main SW Gondwanan sea-level drop and platform exposure (Poiré and Gaucher 2007; Poiré 2008). The low diversity acritarchs assemblages in siliciclastic units were also used for stratigraphic correlations, making a direct connection with similar time intervals in Uruguay and Brazil (Corumbá Group). The correlations suggested by Gaucher et al. (2005a, b) imply that an extensive marine shelf opened toward the East was developed on a large area of the 'Río de la Plata paleocontinent' during the Neoproterozoic. Tropical paleoclimate conditions in a tectonic quiescence and far from Brasiliano/Pan-African orogenic belts (Gaucher 2000, 2007; Gaucher et al. 2003, 2005a) have been recognized.

Finally, the last transgression of the Balcarce Formation could be correlated after Zimmermann and Spalletti (2009) with similar rocks in the Cape Fold Belt of South Africa, the Peninsula Formation, and the upper Table Mountain Group (Windhoek and Nardouw Subgroups) and partially with the lower sedimentary Sierra de la Ventana sequences.

Tectonic evolution

The evolution model could be represented by time stages (Figs. 10, 11) using the IUGS Precambrian subdivisions as suggested by Brito Neves (2009), as follow.

Neoarchean-Siderian (Fig. 10, stage 1)

In a first stage (c. 2.2 Ga), a juvenile evolution of separated continental blocks as suggested by petrological, geochemical and isotopic data was developed. Based on isotopic evidence, the protolith of the rock crust could be Neoarchean (c. 2.5–2.6 Ga). Subduction-related magmatic arcs were developed (Teruggi et al. 1988). After Ramos (1999) were interpreted the interaction with Buenos Aires, El Cortijo and Tandilia continental blocks related in a subduction tectonic setting. This tectonic scenario was mentioned by Hartmann et al. (2002b) as the 'Encantadas Orogeny' based on U–Pb SHRIMP zircon data.

Early-Late Rhyacian (Fig. 10, stage 2)

At this stage was interpreted a continent–continent collisional event, as suggested by the thick mylonites belts, the presence of ocean floor rocks, and the presumed thickening of the crust (c. 2.2–2.0 Ga). The collision caused thrusting and transcurrent faulting favoring the anatexis of the crustal rocks. Furthermore, the emplacement of the granitoid plutons in the thick gneissic sequence in the Tandil area could have been coeval with the regional high-temperature metamorphism, mylonitization, and calc-alkaline dykes during a transtensional event and as a consequence anatexis processes occurred. After Hartmann et al. (2002b), this event corresponds to the collisional 'Camboriú Orogeny'.

Orosirian-Statherian (Fig. 10, stage 3)

At this stage, it took place the generation of heterogeneous, highly radiogenic and typically post-collision leucogranitoids (c. 1.8 Ga). The dolerite dykes (c. 1.6 Ga) constrain the time of crustal extension associated with the last stages of Tandilia basement evolution.

Early Mesoproterozoic to Late Neoproterozoic (Fig. 10, stages 4 and 5; Fig. 11 stage 6)

The igneous-metamorphic basement suffered a long period of peneplanization, paleoweathering and generation of an arkosic saprolite (c. 1.6–0.9 Ga). The Tandilia basement was variably affected by hydrothermal overprints. During Late Neoproterozoic developed a first marine transgression with siliciclastic and stromatolite-rich dolostones over a highly weathered Paleoproterozoic basement. Separated with an unconformity, a second sedimentary transgression was developed with siliciclastic and limestone units. After that a karstic surface and an iron-phosphoric level record the regression and sea-level drop event (Leanza and Hugo 1987; Poiré and Gaucher 2007; Gómez Peral et al. 2007). A new marine transgression was described as a final Neoproterozoic siliciclastic sedimentary event.

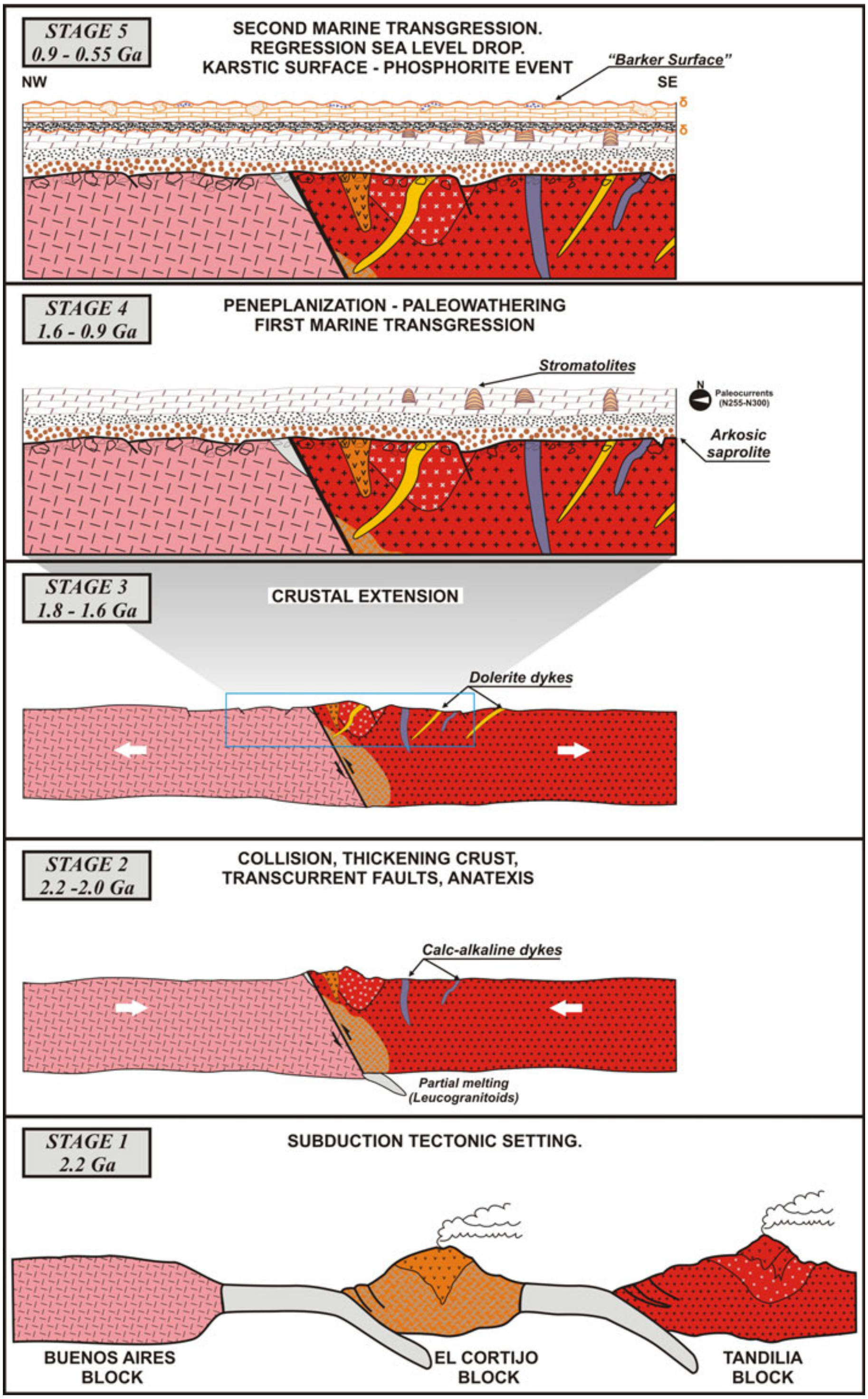


Fig. 10 Diagrams (orientated NW–SE) of the interpreted tectonic evolution by time slices (see stages 1–5) for the Tandilia System showing: subduction arc setting of continental blocks (after Teruggi et al. 1988; Ramos 1999), main collisions, thickening crust, transcurrent faults, anatexis events, final extension with dolerite dykes and cratonization (Dalla Salda et al. 2006). The sedimentary cover starts with an arkosic saprolite and first siliciclastic-dolostone marine transgression occurred (Iñiguez et al. 1989)

Late Neoproterozoic-Cambrian (Fig. 11 stage 7)

A probable tangential tectonic could have developed in relation with the docking of the Cuchilla Dionisio Terrane in Uruguay. Some deformation of the Neoproterozoic sedimentary units already described predates the Early Paleozoic Balcarce Formation. Then an important block faulting occurred as expression of a compressional event in response to south-west stress (Iñiguez et al. 1989). Due to vertical tectonic movements, the Palaeoproterozoic basement was uplifted by normal faulting; the depressed blocks preserved most of the Neoproterozoic

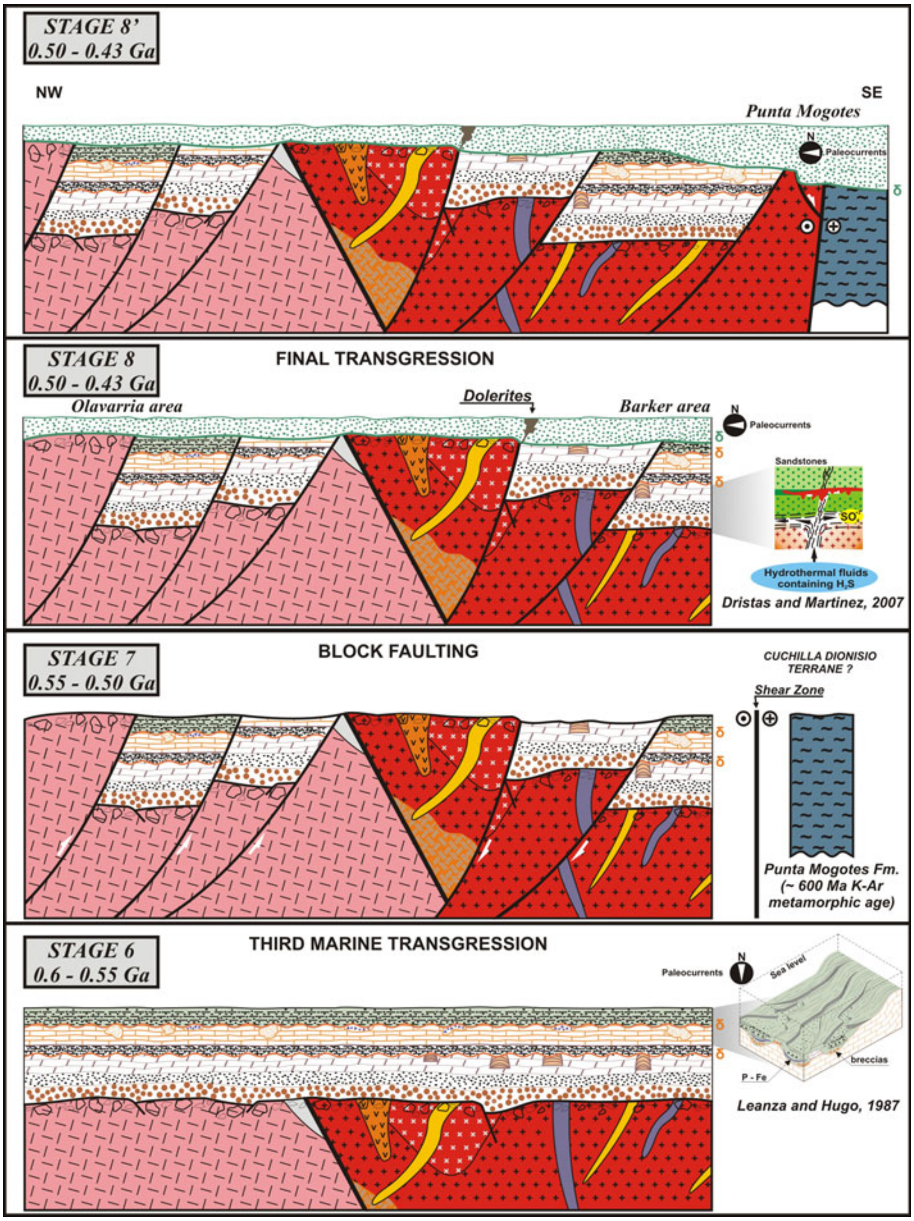


Fig. 11 Second part of the interpreted tectonic evolution diagrams (see stages 6–8′) showing a new marine transgression (siliciclastic and micritic carbonates), regression and sea-level drop with karstic surface developed. Inset detail after Leanza and Hugo (1987). Then another marine transgression occurred (siliciclastics). A probable tangential tectonic could have developed in relation with the docking of the Cuchilla Dionisio terrane (Uruguay). Deformation of the Neoproterozoic sedimentary units predates the Balcarce Formation. Then an important block faulting occurred as expression of a compressional event in response to south-west stress (Iñiguez et al. 1989). The Palaeoproterozoic basement was uplifted by normal faulting but the depressed blocks preserved most of the Neoproterozoic sedimentary cover only in the Sierras Bayas and Barker areas. A final Balcarce transgression occurred over all the mentioned Precambrian units. A diamictite glacial event was described (Zimmermann and Spalletti 2009) and some iron-rich hydrothermal processes were studied by Dristas J and Martínez (2007) as we shown in the detail inset. The last stage shows the thickest section of the Balcarce Formation that was recorded toward the east in the Atlantic Punta Mogotes borehole (see *inset*)

sedimentary cover only in Sierras Bayas and Barker areas.

Ordovician to Silurian (Fig. 11, stage 8–8′)

After the erosive stage, a new transgression developed over the latter tectonic scenario covering all the mentioned blocks. A diamictite member is an evidence of a Hirnantian glacial event. Hydrothermal iron-rich levels occurred as described by Dristas and Martínez (2007). It is important to note that the thickest section of the Balcarce Formation unconformably lying over the Punta Mogotes Formation (c. 600 Ma K–Ar metamorphic ages) was recorded toward the east in the Atlantic borehole.

Upper Paleozoic

Zalba et al. (2007) confirmed that after the uplift and reactivated faulting that occurred during the Middle Permian, the Tandilia System has remained as a positive area. Toward north the rift-related (aulacogene) Salado basin was opened and filled Meso-Cenozoic sequences. To the south, the Claromecó basin (and the Ventania System) was intense deformed during Permian times (see profile of Fig. 1).

Final remarks

1. The southernmost outcrops of the Río de la Plata cratonic region are well exposed in the Tandilia System also called 'Sierras Septentrionales de Buenos Aires' in eastern Argentina.
2. The igneous-metamorphic Buenos Aires Complex assigned to 'Transamazonian' or Paleoproterozoic age consists mainly of granitic-tonalitic gneisses, migmatites, amphibolites, some ultramafic rocks and granitoid plutons. Subordinate rock-types include schists, marbles, and dykes of acid and mafic composition. Conspicuous features are wide belts of mylonites.
3. The isotopic data coupled with the geochemical characteristics indicate that the igneous-metamorphic basement rocks are associated with intra-oceanic subduction systems or in primitive continental arc settings.
4. After U–Pb data, a lack of recrystallization or new zircon growth in the Neoproterozoic suggests that the Tandilia basement was preserved from younger orogenies such as those of the Brasiliano cycle. This geological evolution can be correlated with the Piedra Alta terrane (Uruguay), where Rb–Sr, Sm–Nd and U–Pb data show a similar signature during Paleoproterozoic times. The average of Hf model-ages (c.2.6 Ga) shows strong evidence supporting the derivation from a Neoarchean crust that indicates a relatively short-lived Paleoproterozoic orogeny.
5. The igneous-metamorphic complex is partially covered by two marine platform sedimentary units: the oldest was described as of Neoproterozoic age, and the youngest was assigned to an Ordovician–Silurian age. In the currently accepted stratigraphic scheme the Sierras Bayas Group (c.185 m thick) is a Neoproterozoic sedimentary cover superposed by Cerro Negro Formation (c. 150 to 400 m thick) and the final sedimentary event at the Lower Paleozoic with c. 100–400 m of the Balcarce Formation.
6. The Tandilia sedimentary cover were slightly deformed and remained flat-lying. However, some deformation was described in the Olavarría (Sierras Bayas) region.
7. Several evidence of hydrothermal activity (clay deposits, quartz crystals, alunite and iron-rich levels) were recognized.
8. The tectonic evolution model could be represented by time stages starting in the Neoarchean-Siderian with subduction arc setting of continental blocks, follow by main collisions, thickening crust and anatexis during Early-Late Rhyacian and continuous during Orosirian-Statherian with the final extensional dykes and cratonization.
9. The basement rocks suffered a long period of peneplanization and paleoweathering during the Mesoproterozoic to Early Neoproterozoic.

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