19

The Glaciations in South America

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Abstract

Neoproterozoic successions in South America are recorded in many areas of Brazil, Paraguay, Bolivia, Uruguay and Argentina. Some of these units show glaciogenic formations like those represented in the Puga and Serra Azul formations in the Northern Paraguay Belt (Brazil) in agreement with their accumulation in a Snowball Earth context. However, in other cases, tillites or other glacio-marine deposits are absent, which may indicate a distant position (tropical) regarding the ice cap, as occurs in the Tandilia System (Argentina) related to a "Phantom glacial" context. In this contribution we show the comparison between direct and indirect evidence of glaciations in the Neoproterozoic successions of South America. The Puga and Serra Azul formations in the Paraguay Belt and Sierras Bayas Group in the Río de la Plata Craton have been chosen to describe the "Snowball Earth" and "Phantom glacial" models, respectively. By means of multiproxy analysis it is also possible to indicate changes in paleoclimate conditions in both cases. The presence of tillites is considered to be direct evidence of the extreme climatic conditions during deposition during a glaciation. Meanwhile, more subtle evidence such as regional unconformities related to drastic sea level changes, trends in $\delta^{13}C$, events of phosphogenesis, constitute, among others, the tools to indicate the influence of Neoproterozoic global glaciations during the deposition of the sedimentary units.

Keywords

Paleoclimatic proxies • Neoproterozoic • Tillite records
Phantom glacial deposits

19.1 Introduction

Neoproterozoic diamictite rocks such as tillites or glacio-marine deposits have been recorded as the product of regional glaciations around the world, in accordance with the Snowball Earth hypothesis (Hoffman et al. 1998). However, in some parts of the planet, contemporaneous non-glaciogenic sedimentary rocks have also been observed related to sedimentation in non-glacial environments but influenced by planetary glaciation, which was termed "Phantom glacial" (Cozzi et al. 2002; Poiré 2004) in a "slushball Earth" scenario. In the first model, the glacial mass covers the whole planet during glaciations, whereas in the slushball hypothesis the Earth was not completely frozen during periods of extreme glaciation (Hyde et al. 2000; Lewis et al. 2007; Micheel and Montenari 2008). Floating ice would have covered up to 60% of the ocean, but this left a lot of the ocean open, and littoral and low continental environments in the tropics without any ice cover. In this case, the total glacial mass was increasing while the sea level was falling, producing diamictites in the frozen areas around the world and falling sea-level deposits in tropical and equatorial regions. Phantom glacial deposits are those that are not glacial diamictites but show glacial sea level dropping sedimentation, such as deltas progradation, fluvial erosional unconformities and karstic surfaces on limestone shelves.

As synthesized by Sohl and Chandler (2007), of these two end-member climate conditions, the Snowball Earth glaciations have attracted most attention in recent years, in large part because of the discussion about the possible climatic influence on the evolution of macroscopic life. Previous iterations of the Snowball Earth hypothesis (Hoffman et al. 1998; Hoffman and Schrag 2002) have taken the geological evidence for widespread cold climates and extrapolated a vision of the world practically entombed in ice, with the oceans totally frozen. Proponents of the "hard" Snowball Earth have suggested that total or near-total sea-ice cover is

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necessary to explain both an interpreted rapid transition from the glacial to the non-glacial state, and unusual δ^{13}C signatures, as low as –5‰, in carbonate rocks ("cap carbonates") directly overlying the glacial deposits (Hoffman et al. 1998; Hoffman and Schrag 2002). Those in favor of a slightly less extreme scenario, the slushball Earth, point to sedimentary deposits (ice-rafted debris in deep marine settings) that can be used to argue in favor of more open ocean rather than less (e.g., McMechan 2000; Condon et al. 2002; Kellerhals and Matter 2003). Furthermore, some authors have suggested that icebergs have never reached equatorial positions, but the strong polar glaciations have led to falling sea levels with karstic surfaces in tropical and equatorial latitudes over carbonate platforms (Poiré 2004; Gómez Peral et al. 2014a, b, 2017).

The South American geological record shows both types of occurring given by successions with the presence of tillites ("Snowball Earth") and others without these diamictite deposits ("Phantom glacial"). The aim of this contribution is to make a comparison between evidence of the direct and indirect influence of glaciations in the Neoproterozoic successions of the Tandilia System and Northern Paraguay Belt (Fig. 19.1) as end-members of the climate conditions in South America. Thus the Puga Formation in Northern Paraguay Belt, Amazonia Craton in Brazil, and the Sierras Bayas Group in the Rio de la Plata Craton of Argentina have been chosen to describe both models. By means of multiproxy analysis it is also possible to indicate changes in paleoclimatic conditions in both cases.

The Paraguay Belt shows the occurrence of tillite deposits associated with glacial events and is in agreement with the Snowball Earth hypothesis.

In particular, the example of Phantom glacial is postulated on the basis of the development of regional karstic unconformities related to drastic sea level changes, trends in δ^{13}C and phosphogenesis events, which among others constitute indirect evidence that can be used to indicate the influence of Neoproterozoic global glaciations during the deposition of the sedimentary units of the Tandilia System.

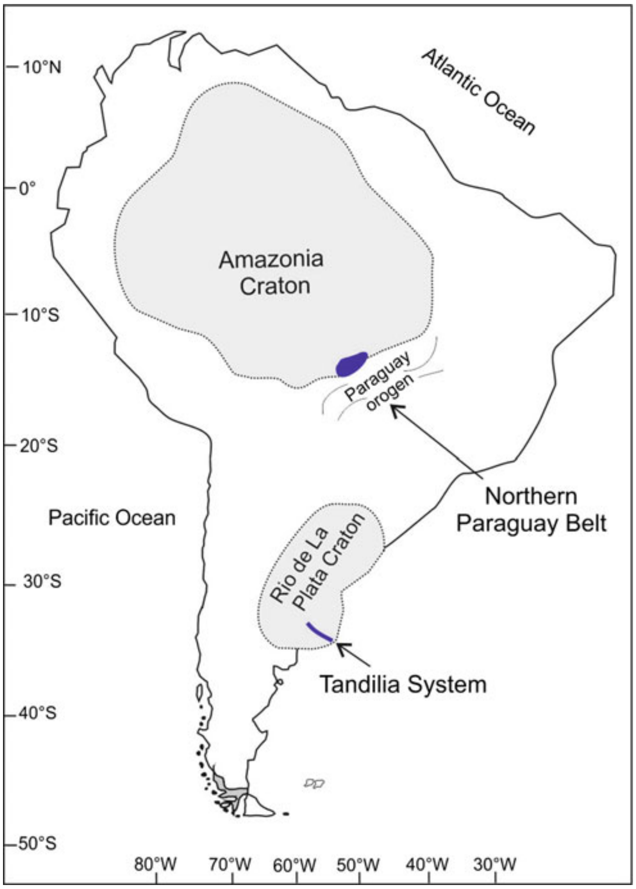


Fig. 19.1 General map of the Rio de la Plata craton and Amazonia craton of southern South America (modified from Rapela et al. 2016 and references therein)

19.2 Glacial Deposits in South America

19.2.1 Northern Paraguay Belt in the Amazonia Paleocontinent

The Paraguay Belt is an extended region located on the southeastern edge of the Amazon Craton (Fig. 19.1), also defined as Amazonia Paleocontinent by Alvarenga et al. (2009). In the Northern Paraguay Belt, two indubitable Neoproterozoic tillite units have been recognized (Fig. 19.2): the Marinoan-aged Puga Formation and the Gaskiers-aged Serra Azul Formation (Alvarenga and Trompette 1992; Alvarenga et al. 2004, 2007, 2009).

Marinoan glacial deposits have also been identified in the Southern Paraguay Belt with carbonate rocks overlying the glaciogenic deposits. The Santa Cruz (Fig. 19.3a) and Puga formations in the Corumbá area have been correlated with this glacial event (635 Ma) based on cap-dolomite lithofacies, paleomagnetic data, and associated δ^{13}C and ^{87}Sr/^{86}Sr isotope trends (Boggiani 1998; Trompette et al. 1998; Nogueira et al. 2003; Trindade et al. 2003; Alvarenga et al. 2004, 2009, 2011; Boggiani et al. 2004; Sial et al. 2016). However, tillites of the Puga Formation are better represented in the Northern Paraguay Belt (Figs. 19.2 and 19.3b). According to Alvarenga et al. (2011) and Sial et al. (2016), the Puga Formation was originally described from the Southern Paraguay Belt (Maciel 1959) but is not necessarily coeval with the homonymous unit in the Northern Paraguay Belt. Besides, the deposition of these Puga Formation terrigenous sediments in the south is probably associated with the development of a rift basin (Boggiani 1998; Gaucher et al. 2003).

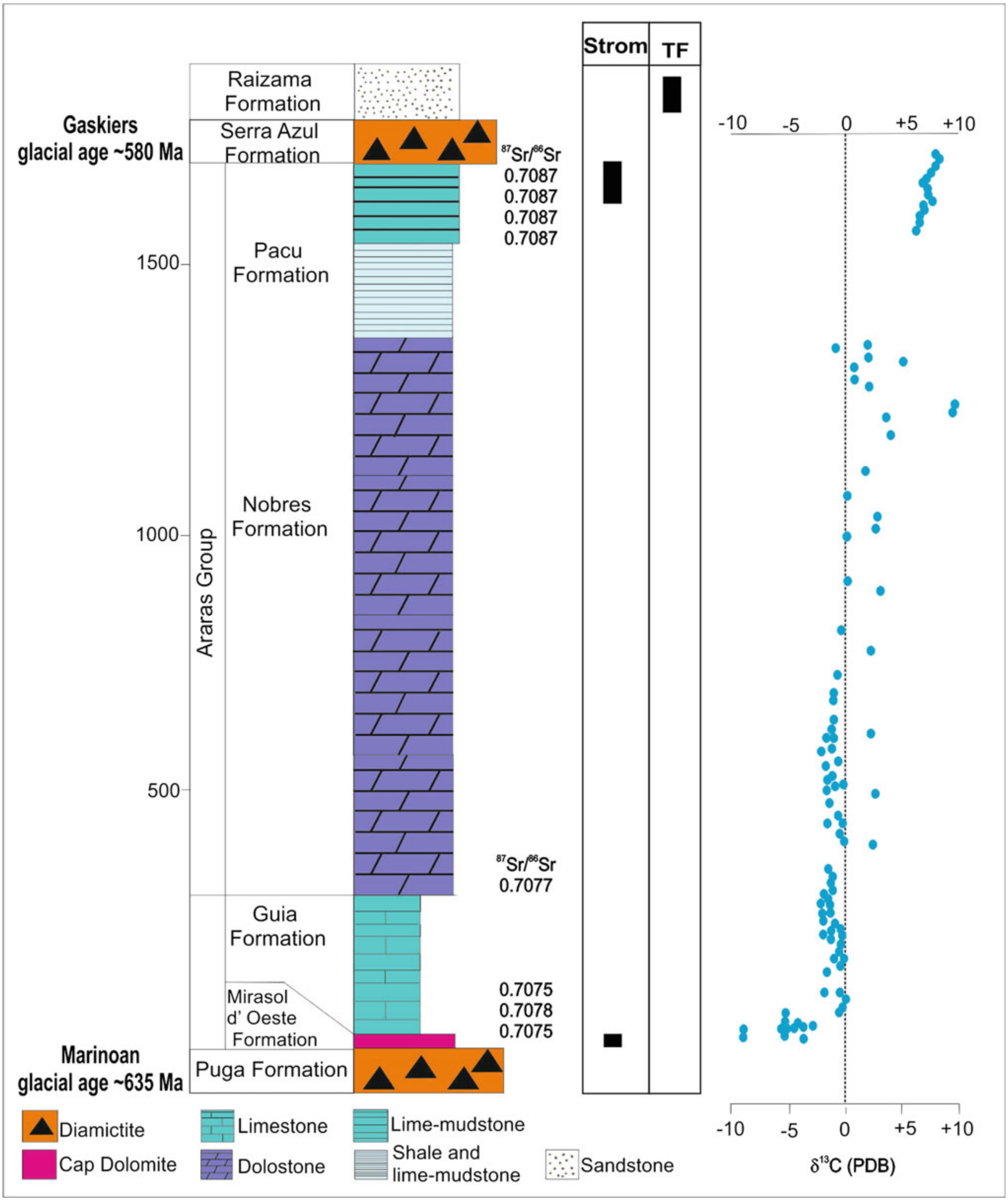


Fig. 19.2 Stratigraphic and bioestratigraphic section and variations in δ13C and 87Sr/86Sr for the Araras Group (modified from Sial et al. 2016)

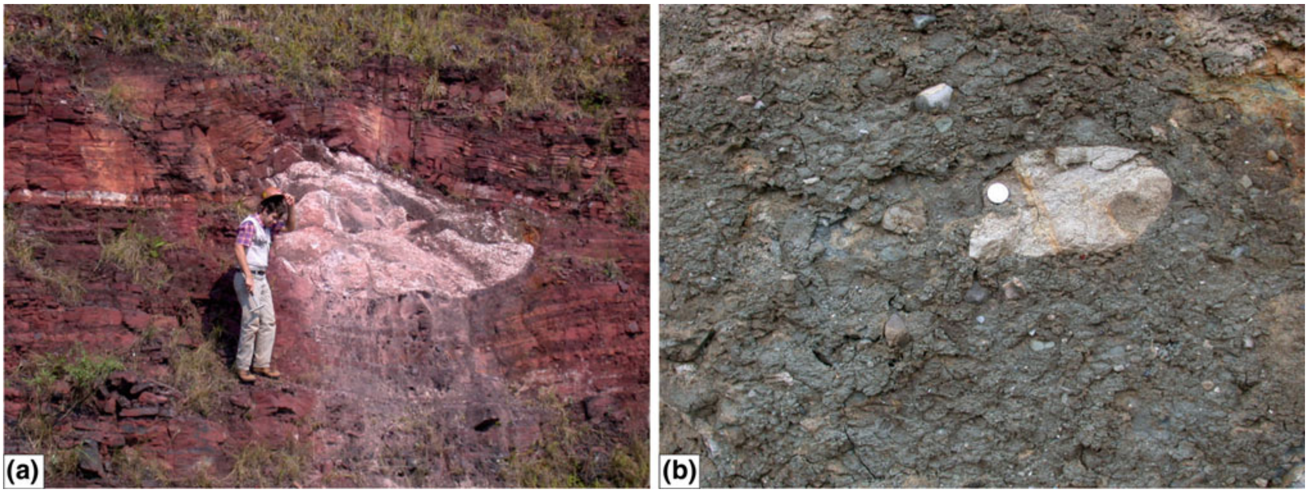


Fig. 19.3 Field photographs. **a** Granite megaclast dropstone in Santa Cruz Formation, Southern Paraguay Belt, Brazil. **b** Tillite of Puga Formation, Northern Paraguay Belt, Brazil

19.2.1.1 Lithostratigraphy

Lithostratigraphically, this region comprise a crystalline basement complex (gneisses, schists, granites, metaquartzites) overlain by a Neoproterozoic sedimentary succession that from bottom to top is composed of the Puga Formation, Araras Group (Mirassol d´Oeste, Guia, Nobres and Pacu formations) and Serra Azul Formation, all covered by the Ediacaran/Cambrian Razaima Formation (Fig. 19.2).

The Puga Formation (Maciel 1959) is the oldest depositional unit (100 m thick) and comprises purple, reddish, brownish or dark-greenish gray, pebbly tillite with striated clasts of granite and sandstone (Fig. 19.3b), also accompanied by conglomerates, sandstones, and shales. It has been interpreted as a glacial-marine deposit (Maciel 1959; Alvarenga and Trompette 1992). Based on detrital zircon ages (Babinski et al. 2013), paleomagnetic data (Trindade et al. 2003) and chemostratigraphy of the overlying limestones (Nogueira et al. 2003), this unit is considered Cryogenian in age.

The basal unit of the Araras Group is the Mirassol d´ Oeste Formation (up to 30 m thick), which is composed of pinkish dolostones bearing stromatolites, tube-like structures, breccia, giant wave ripples, deformed microbialites dislocated by synsedimentary faults, red iron-oxide-rich mudstones in the top level (Nogueira et al. 2003; Alvarenga et al. 2004, 2008; Nogueira and Riccomini, 2006) and fan-like crystals interpreted as aragonite pseudomorphs (Alvarenga et al. 2008). The unit is interpreted as a moderately deep euphotic platform (Nogueira et al. 2003).

The middle one, the Guia Formation (up to 250 m thick), consists of dark-gray laminated limestones and shales, with slumps and other deformational sedimentary structures, interpreted as deposited in a deep platform environment (Nogueira et al. 2003).

The Nobres Formation (up to 1100 m thick) is composed mainly of light-gray grainstone, packstone dolostones, with some interlayered breccias. This unit was interpreted as a carbonate platform deposited under shallow-water sedimentation.

The uppermost unit of the Araras Group is the Pacu Formation (∼300 m thick), described as carbonate mudstones and stromatolitic limestones (Souza et al. 2012), in a coarsening upward succession, which was interpreted as deposited by a marine transgression followed by a regression with the development of a carbonate shallow marine platform during the Ediacaran (Souza 2015).

Above the Araras Group through an erosional surface, the Serra Azul Formation (up to 270 m thick) is recorded, composed of a very thick basal diamictite unit (70 m) of massive reddish diamictite with an abundant clay-silty matrix. Well-rounded to highly angular clasts (from millimeters to centimeters in diameter) are dispersed throughout the matrix, some of them reaching up to 30 cm in diameter. The composition of the clasts is sandstones, quartz, quartzites, arkoses, carbonates, cherts, basalts, rhyolites, diabases and weathered granitic rocks. Some faceted, polished and striated clasts have also been preserved in the diamictite (Alvarenga et al. 2007, 2009). These tillites are overlain by a succession of reddish laminated siltstone (25 m thick), which is overlaid by a rhythmite unit (175 m thick) interbedded with episodic sandstones (Alvarenga et al. 2009).

The Razaima Formation (up to 700 m thick) covers the Neoproterozoic sedimentary cover of the Northern Paraguay Belt, which consists of a siliciclastic succession. The lower part of this unit consists of whitish parallel-laminated and small-scale hummocky cross-stratified sandstone and pebbly sandstone, interbedded with parallel-laminated mudstone that grades upwards into swaley cross-stratified sandstone, forming a shallowing upward succession (Santos et al. 2017). The ichnogenera *Skolithos*, *Arenicolites* and *Diplocraterion* have been reported by Santos et al. (2017). According to these authors, (1) these trace fossils are therefore consistent with sedimentologic data which indicates a wave-dominated nearshore environment, and (2) the ichnofauna are suggesting an early Cambrian age or younger for the Raizama Formation in contrast to the previously held view of an Ediacaran age for this unit.

19.2.1.2 Glacial Deposits of Puga Formation

The Puga Formation tillites were correlated with the Marinoan glaciation related to Araras Group cap-carbonate lithofacies, paleomagnetic data, and associated δ^{13}C and ^{87}Sr/^{86}Sr isotope trends (Nogueira et al. 2003; Pinho et al. 2003; Trindade et al. 2003; Alvarenga et al. 2004). Over the diamictites of the Puga Formation, the cap dolostone of the Mirassol d'Oeste Formation is succeeded by transgressive, deep-platform deposits of dark-gray laminated lime-mudstone and shales of the Guia Formation, reaching up to 250 m thick in the middle shelf domain (Alvarenga et al. 2004, 2008, 2011; Nogueira et al. 2007; Riccomini et al. 2007).

Ca isotopic compositions of post-glacial carbonate successions in central Brazil (Mirassol d'Oeste-Cáceres and Tangará) have been reported by Silva-Tamayo et al. (2010a, b). These authors indicate that the Ca-isotope secular variation trend is similar to those of Marinoan post-glacial carbonate successions in Namibia, suggesting that the perturbation of the marine Ca cycle was, perhaps, global. Carbon isotope data for rocks of the Guia Formation revealed predominantly negative δ^{13}C values, from –3.5 to 0.1‰, and δ^{18}O values from –13.5‰ to –6.3‰ (Nogueira et al. 2003, 2007; Alvarenga et al. 2004, 2008; Figueiredo 2006). ^{87}Sr/^{86}Sr ratios for limestones with a higher Sr content (>750 ppm) and low Mn/Sr ratios (<0.2) range from 0.7076 to 0.7078 (Alvarenga et al. 2008, 2011).

19.2.1.3 Glacial Deposits of Serra Azul Formation

Dropstones and striated clasts provide evidence of a glacial setting for the Serra Azul diamictite (Fig. 19.2). This unit is composed of massive diamictite with an abundant clay-silty matrix (70 m thick), followed by a thick succession of laminated siltstone (200 m). This unit is not overlaid by a cap carbonate, as was reported for the Puga Formation. The Serra Azul Formation was described as discontinuous outcrops of diamictites and siltstones above post-Marinoan carbonates of the Araras Group (Fig. 19.2), and it represents a record of the Gaskiers glaciation (Alvarenga et al. 2007) with an age of *c*. 580 Ma (Knoll et al. 2004).

19.3 Phantom Glacial Deposits in South America

19.3.1 Tandilia System in the Río de La Plata Craton

The Neoproterozoic sedimentary cover of the Tandilia System in the Sierras Bayas- Olavarría area comprises a ~455 m-thick succession, which overlays a crystalline basement. The Sierras Bayas Group (Villa Mónica, Colombo, Cerro Largo, Olavarría and Loma Negra formations) and La Providencia Group (Avellaneda, Alicia and Cerro Negro formations) are compound this sedimentary cover (Fig. 19.4a), which are composed of different carbonate and siliciclastic units separated by regional unconformities (Poiré 1987; Iñiguez et al. 1989; Poiré and Spalletti 2005; Poiré and Gaucher 2007, 2009; Arrouy et al. 2015).

19.3.1.1 Lithostratigraphy

Crystalline Basement

The Buenos Aires Complex (Marchese and Di Paola 1975) is composed of granitoids, migmatites, mylonites, amphibolites and basic dykes (Cingolani and Dalla Salda 2000), yielding U-Pb SHRIMP ages of between 2234 and 2065 Ma (Cingolani et al. 2002; Hartmann et al. 2002a, b; Cingolani 2011) and Sm-Nd model ages averaging around 2620 ± 80 Ma (Pankhurst et al. 2003).

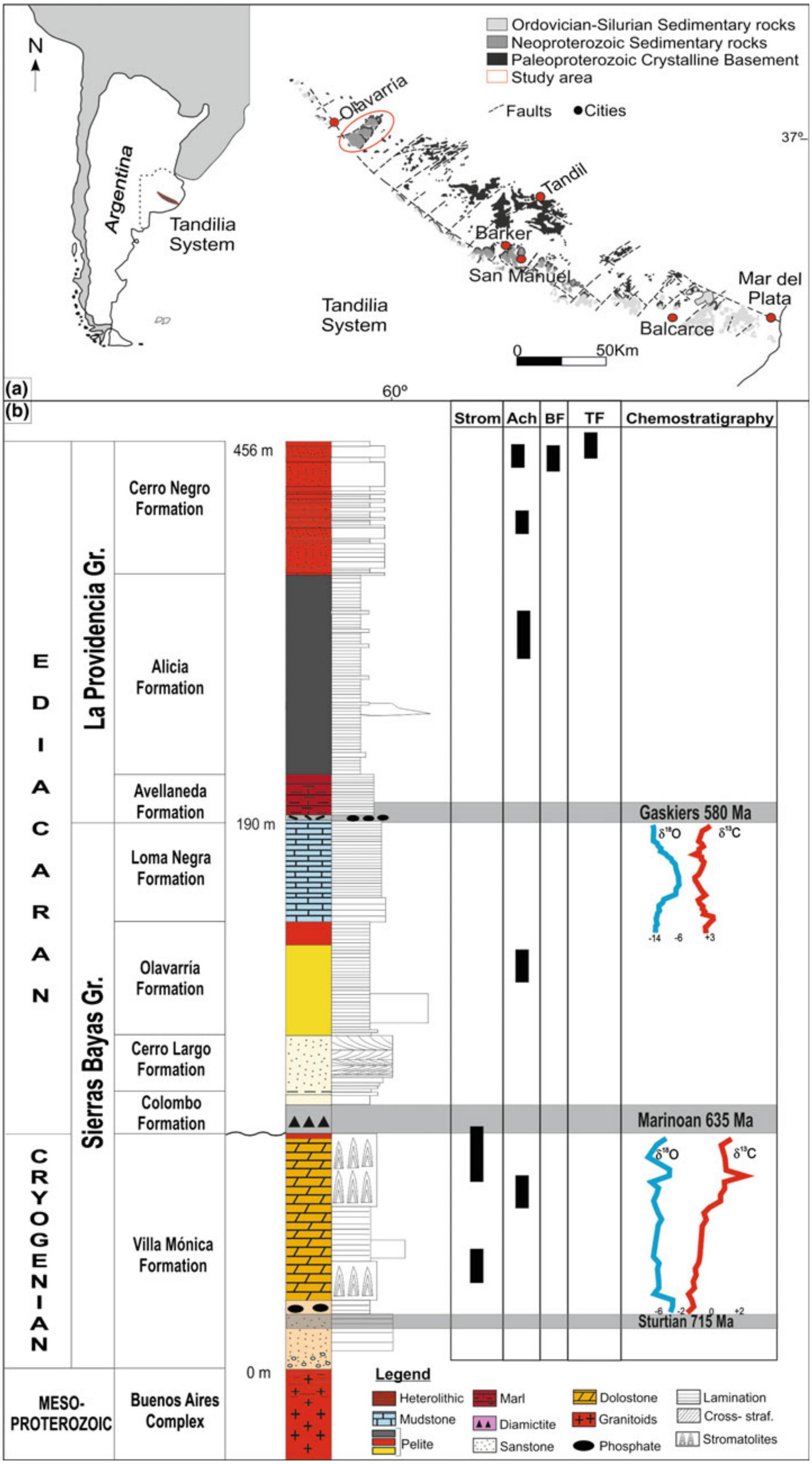
Sierras Bayas Group

In the Olavarría-Barker area (Fig. 19.4a) the overlying Neoproterozoic lithostratigraphic units are grouped into five depositional intervals (Fig. 19.4b) (Poiré et al. 2003; Poiré and Spalletti 2005; Poiré and Gaucher 2009). Detrital zircon U-Pb ages indicate a Paleoproterozoic to Mesoproterozoic source of clastic material in the Neoproterozoic succession (Rapela et al. 2007, 2011; Gaucher et al. 2008; Cingolani 2011). Gaucher et al. (2008) and Cingolani (2011) observe an obvious change in detrital provenance from the basal to the upper formations (see also Zimmerman et al. 2011, who provide geochemical evidence for a change in provenance).

The basal unit, the Villa Mónica Formation (52–70 m thick), exhibits two sedimentary facies associations: quartz-arenite and arkosic sandstone at the base, and dolostone including shallow marine stromatolites and shale-marls at the top (Poiré 1993; Gaucher and Poiré 2009a).

The erosional surface above the Villa Mónica Formation, the Piedra Amarilla Surface, is followed by breccias and diamictites of the Colombo Formation (Poiré and Gaucher

Fig. 19.4 **a** Location map of Argentina in South America and study area in the Tandilia System, Buenos Aires Province, Argentina (modified from Iñiguez 1989). **b** Schematic representation of the lithostratigraphic, biostratigraphic and quimiostratigraphic successions of Sierras Bayas and La Providencia Groups (Poiré and Gaucher 2009; Arrouy et al. 2015; Gómez Peral et al. 2017)



2009; Gómez-Peral et al. 2011). The diamictites (Gaucher and Poiré 2009b) contain blocks up to 3 m in diameter (i.e., sandstone, shale, dolostone and chert breccia), synsedimentary deformation structures, and a sandy-muddy matrix (Gómez-Peral et al. 2011). Rapalini et al. (2013) assigned a tentative age for the Piedra Amarilla Surface of 590 Ma on the basis of paleomagnetic data. Above the diamictite, finely laminated glauconitic shales and fine-grained sandstones appear in the basal part of the Cerro Largo Formation. The upper part of this unit consists of cross-bedded quartz sandstones with sigmoidal, herringbone and hummocky cross-stratification (Gómez-Peral et al. 2011). This succession represents a shallowing-upward succession, ranging from subtidal nearshore to tidal-flat deposits (Poiré 1987; Poiré and Gaucher 2009).

The overlying Olavarría Formation is approximately 35 m thick and includes a transitional basal contact represented by quartzite to mudstone heterolithic facies. Mudstone and heterolithic facies contain 8–20 cm concretionary iron-rich beds (Gómez-Peral et al. 2011).

The youngest depositional unit of the Sierras Bayas Group is the Loma Negra Formation (Figs. 19.2b), which is represented by 40 m exclusively composed of micritic limestones originating from suspension fall-out in open marine platform environment. The age of the Loma Negra Formation was debated. It was suggested first as ~540–550 Ma, based on the presence of *Cloudina* (Gaucher et al. 2005), but it could be older (~580–590 Ma) considering $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ combined trends (Gómez Peral et al. 2007). Moreover, in the overlying Cerro Negro Formation, Arrouy et al. (2016) described typical morphs of *Aspidella* (related to the 560–550 Ma White Sea assemblage; Wagooner 2003).

La Providencia Group

The Sierras Bayas Group is overlain discordantly by La Providencia Group. The basal Avellaneda Formation is the filling of a channelized paleosurface (Barker surface, Fig. 19.4b) composed on common chert breccias (Barrio et al. 1991) with phosphate concretions first recognized by Leanza and Hugo (1987). The Avellaneda Formation (up to 25 m thick) is composed mostly of red to purple laminated and massive marls at the base, which grade vertically into red massive mudstones (Fig. 19.2b). This formation was interpreted as deposited under supratidal conditions in a tidal-flat depositional environment, probably in well-oxygenated conditions (Arrouy 2015; Arrouy et al. 2015).

The Alicia Formation (up to 150 m thick) conformably overlies the previous one and is composed of dark fissile mudstones and massive gray siltstones, as well as gray heterolithics with lenticular and wavy bedding (Fig. 19.2b). This facies succession was interpreted to represent low-energy subtidal settings, likely with suboxic to anoxic bottom conditions (Arrouy 2015; Arrouy et al. 2015).

The Cerro Negro Formation (~100 m) unconformably rests on the previous, and represents an abrupt change to red heterolithics with wavy and flaser bedding, together with cross-laminated and massive, fine- to medium-grained sandstones (Fig. 19.4b). Mudcracks, scour marks and flutes are common in this succession, which was interpreted to represent subtidal to intertidal settings, probably with well-oxygenated substrates. The top of this succession has been removed by erosion in both the subsurface and outcrops (Arrouy 2015; Arrouy et al. 2015).

19.3.1.2 Geobiology

The Neproterozoic sedimentary cover of the Tandilia System is very rich in signs of primitive life. These include stromatolites, Ediacaran Biota, trace fossils, microbial induced sedimentary structures (MISS) and acritarchs.

Stromatolites of the Villa Monica Formation of the Sierras Bayas Group include *Colonnella* fm., *Conophyton* fm., *Conophyton ressoti*, *Cryptozoon* fm., *Gongylina* fm., *Gymnosolen* fm., *Inzeria* fm., *Jacutophyton* fm., *Jurusania* cf. *nisvensis*, *Katavia* fm., *Kotuikania* fm., *Kussiella* fm., *Minjaria* fm., *Parmites* fm., *Parmites* cf. *concrescens* and *Stratifera* fm (Poiré 1987, 1989, 2002; Poiré and Spalletti 2005). Megascale studies show that the lower and upper parts of this dolostone unit are composed of 0.5–1.4 m-thick domal biostromes and 0.1–0.5 m-thick interbiostromal green shales. A few bioherms are present at the top of this unit. In contrast, in the middle part the stromatolites are completely absent. Domal biostromes are very conspicuous and they reflect the strong influence of paleocurrents in their morphogenesis. The direction of elongation was perpendicular to the shoreline. Two types of elongated bioconstruction are distinguished: symmetrical and asymmetrical. The latter suggests their acute end-points out to sea. The measured paleocurrents suggest a north–south local shoreline direction with open sea towards the east (Poiré 1987, 1989).

Very abundant and diverse discoidal structures in fine-grained micaceous sandstones, associated with abundant MISS, in the Cerro Negro Formation of the La Providencia Group, were assigned to the genera *Aspidella* sp. as the oldest record of Ediacaran macrobiota in South America (Arrouy et al. 2016). In this unit, *Skolithos* isp., *Helminthopsis* isp. and bilobate trace fossils are also reported (Poiré and Spalletti 2005; Arrouy et al. 2016).

In terms of microfossils, the Sierras Bayas Group contains acritarchs assigned to *Chuaria circularis*, *Leiosphaeridia minutissima, L. tenuissima* and *Synsphaeridium* sp. In addition, *Leiosphaeridiajacutica*, *L. tenuissima* and *Synsphaeridium* sp. from Sierras Bayas and La Providencia groups were also recognized in the shales (Gaucher et al. 2005; Gaucher and Poiré 2009a).

19.3.1.3 Synglacial Sea Level Falls

Two major stratigraphic discontinuities are recorded in the Sierras Bayas Group, including the lower surface at the contact between the Villa Mónica and Cerro Largo formations, "Piedra Amarilla Surface" (Fig. 19.5a), and the upper surface on top of the Loma Negra Formation, "Barker Surface" (Fig. 19.5b). The latter may have been expressed worldwide and related to glacial eustacy insofar as it has been correlated with other Neoproterozoic omission surfaces in Uruguay, Brazil, South Africa and Namibia (Poiré et al. 2007; Praekelt et al. 2008; Germs and Gaucher 2012). Both of the Sierras Bayas unconformities are associated with the development of karst on carbonate lithologies filled with diamictite, chert and phosphate concretions, and intraformational breccia (Fig. 19.5). On the other hand, the transitional or planar contacts between the Cerro Largo and Olavarría formations, and the Olavarría and Loma Negra formations, reflect variations in paloenvironmental conditions, recognized primarily by pronounced lithological changes (Fig. 19.5b).

The Piedra Amarilla Surface was defined as a karstic surface (Gómez Peral et al. 2011), which is located at the contact between the Villa Mónica and Colombo formations (Fig. 19.5a) dividing the Sierras Bayas Group in two sections with very different depositional and diagenetic stories. Some iron-rich levels related to the basal Colombo Formation were placed by paleomagnetic studies in ~595 Ma (Rapallini et al. 2013). On the other hand, some iron concentrations were related to hydrothermal activity (Gómez Peral et al. 2012), as well as in the Barker area (Martínez et al. 2010) related to hydrothermal activity between 620 and 590 Ma based on K/Ar ages (Martínez et al. 2013).

Siliceous cementation and replacement were assumed for subaerial exposure when the pH dropped. This subaerial exposure is associated with an important sea-level fall whose relation to glaciation can be assumed, probably as a response to the Marinoan global event.

The Barker surface (Fig. 19.5b) is on top of the Sierras Bayas Group and has been correlated with other Neoproterozoic surfaces in SW Gondwana in Uruguay, Brazil, South Africa and Namibia, and related tentatively to the Gaskiers glaciation (Poiré et al. 2007; Gaucher and Poiré 2009b; Gaucher et al. 2009). This surface is associated with a drastic regional sea-level fall that exposed the Loma Negra shelf carbonates (Barrio et al. 1991; Gómez Peral 2008).

Telodiagenetic processes were defined in detail by Gómez Peral (2008), where besides the intense silicification also hematite constitutes a frequent type of cementation related to meteoric fluids during kastification. This is strong evidence of subaerial exposure.

19.3.1.4 Paleoclimate-Controlled Chemostratigraphy

Trends in δ^{13}C curves from the dolostones of Villa Mónica Formation showed consistent values from –2 to 2.6‰ (Gómez Peral et al. 2017) and δ^{18}O values vary from –2 to –6‰. Dolostones immediately above a subtle diamictite level show the lowest δ^{13}C value. ^{87}Sr/^{86}Sr values are ~0.7069. The clear positive trend of δ^{13}C was considered to suggest this unit as a cap dolostone (Fig. 19.4b; Gómez Peral et al. 2017). In addition, low Sr content in was associated with precipitation influenced by fresh water (Brand and Veizer 1981; Veizer 1983), Mn/Sr ratios <6 and Rb/Sr <0.002 (Gómez Peral et al. 2017).

The Loma Negra Formation, composed almost exclusively of micritic limestones, shows constant positive values of δ^{13}C ranging between 2.2 and 4.5‰ (Fig. 19.4b), δ^{18}O values varying from –8 to –14‰, and ^{87}Sr/^{86}Sr values from 0.7070 to 0.7082. The later uplift of the succession in relation to the implantation of the karstic surface on top of the sequence was related to a regional sea level fall, later linked to the Gaskiers glacial event (~580 Ma), but no negative δ^{13}C anomalies have been mentioned to date. The Sr content is ~400 ppm on average and Mn/Sr <1.4 (Gómez Peral et al. 2007) are in agreement with carbonate platforms developed in warmer conditions. In addition, the paleogeographic position of the Río de La Plata Craton suggested by Merdith et al. (2017) between 600 and 560 Ma coincides with a tropical latitude.

19.3.1.5 Post-glacial Events of Phosphogenesis

Two phosphogenic events were recorded in the Neoproterozoic successions of the Tandilia System. The older one occurring just below the cap-dolostone (Upper Villa Mónica Formation) was considered to be Cryogenian based on stromatolite assemblages, carbon isotope trends and strontium isotope abundances of <0.7071 (Gómez Peral et al. 2014a, b). This level (Fig. 19.6a) occurs in the contact between the lower and upper sections of the Villa Mónica Formation, where phosphate concretions are interbedded with iron-rich shales (Gómez Peral et al. 2014a, b).

The later event of phosphogenesis was over the karstic Barker surface and was Ediacaran in age (Gómez Peral et al. 2014a, b). This phosphate horizon is at the base of the Avellaneda Formation and is composed of phosphate and chert concretions in either a laminated shale or mudstone matrix (Fig. 19.6b; Gómez Peral et al. 2014a, b). This level was first recognized by Leanza and Hugo (1987), who interpreted it as the filling of a channelized paleosurface resulting from sea-level regression.

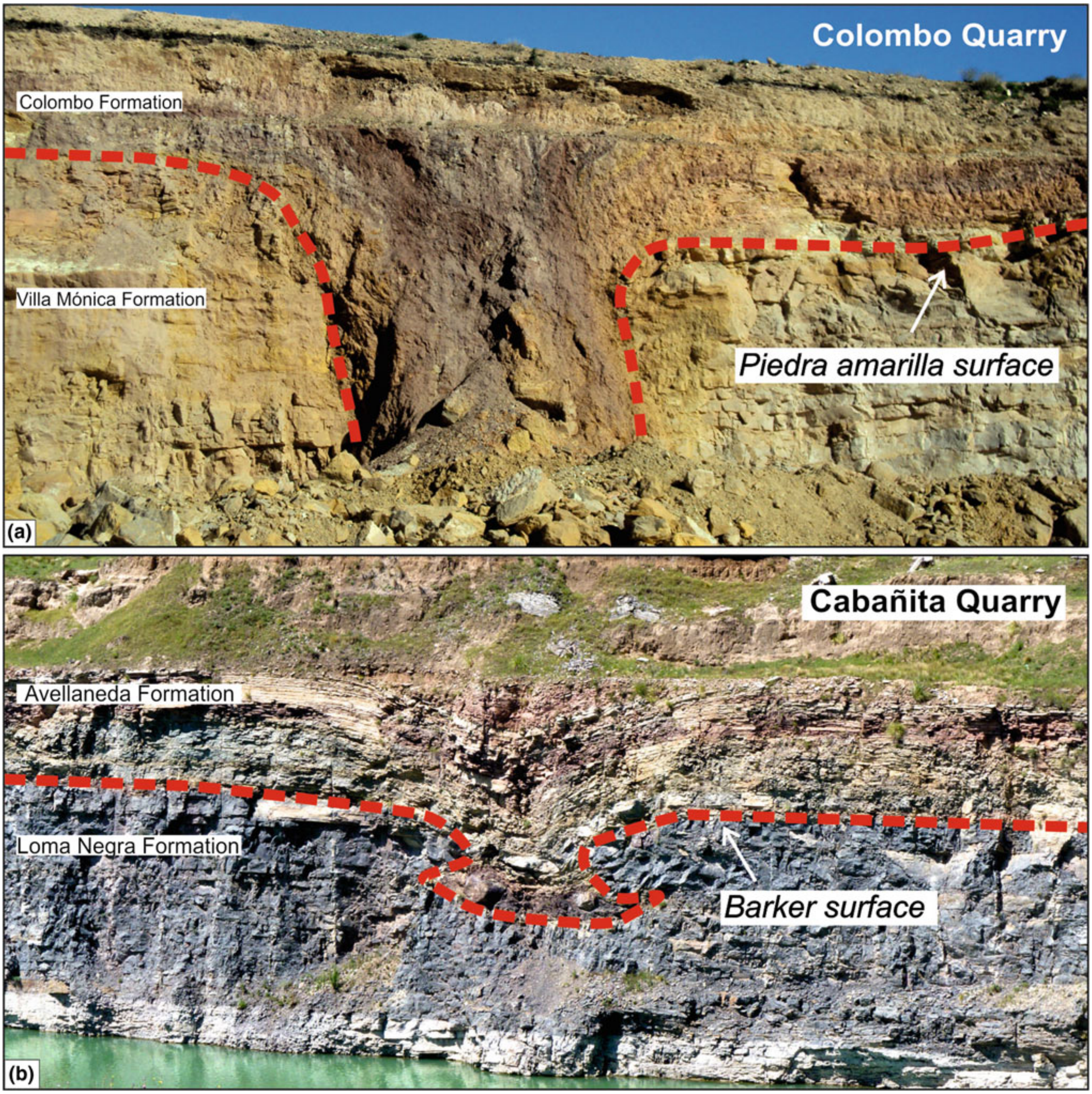


Fig. 19.5 Field photographs. **a** Piedra Amarilla karstic surface in the Colombo Quarry, Olavarría, Argentina. **b** Barker karstic surface in the Polcecal Quarry (Olavarría)

These two levels have been suggested as the result of events of generalized phosphogenesis related to relative sea-level fall and exposure in response to glacial eustacy. The reported oxic seawater conditions where phosphate was concentrated in the Neoproterozoic Tandilia System were markedly different for both levels. The Villa Mónica phosphates was related to stratified ocean under reducer conditions, while the Avellaneda level reveals well oxygenated conditions regarding Ce anomalies (Fig. 19.6; Gómez Peral et al. 2014a, b).

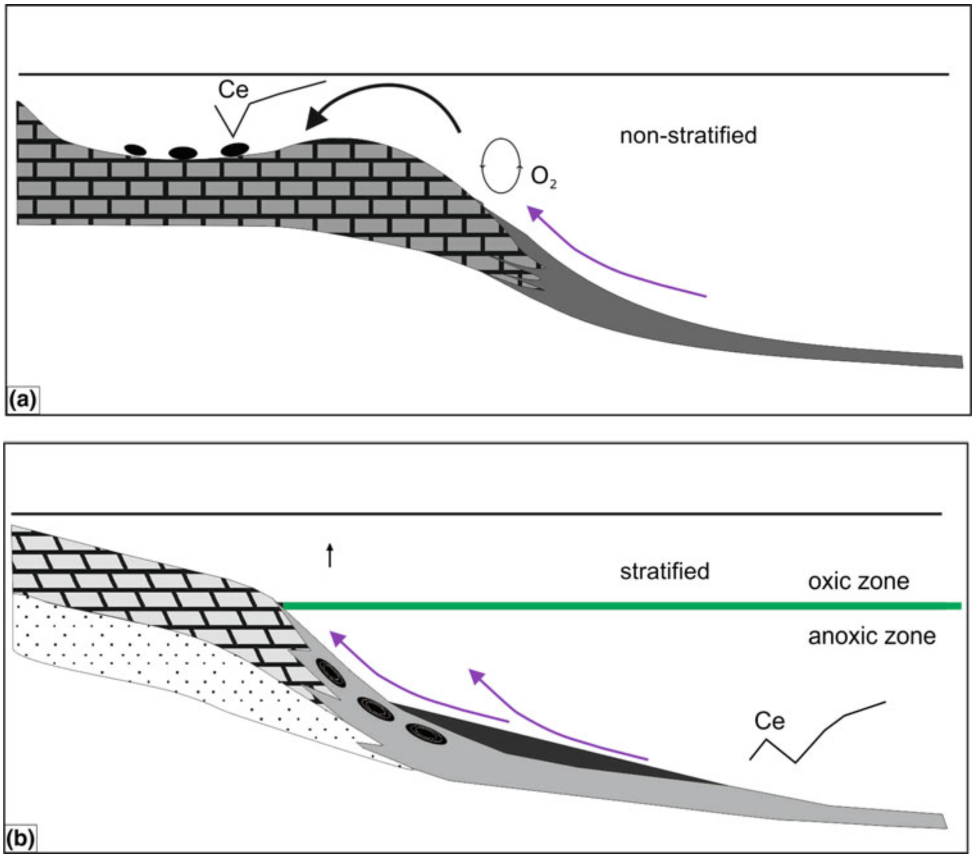


Fig. 19.6 Schematic representation of the two phosphogenesis events in the Tandilia System. **a** Paleoenvironment of the Villa Mónica phosphate level with a stratified basin (positive Ce anomaly). **b** Paleoenvironment scheme of the Avellaneda phosphate level (ex Cerro Negro Formation) with well-mixed ocean and normal circulation of oxygen (negative Ce anomaly) (modified from Gómez Peral et al. 2014a, b)

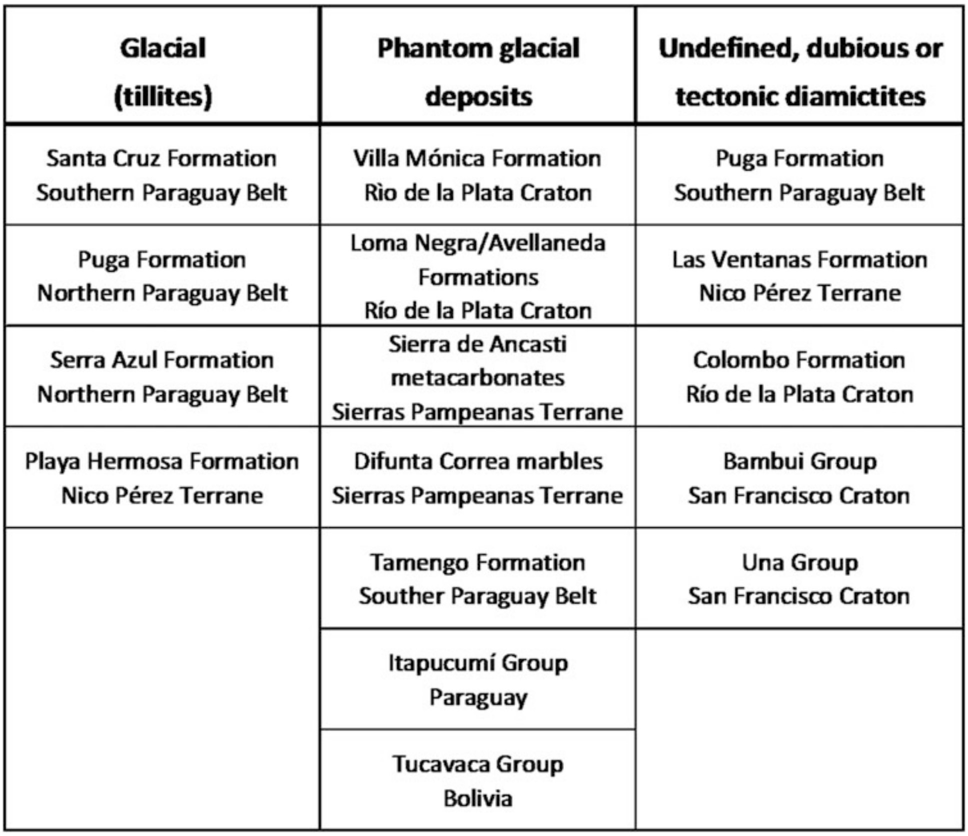
19.4 Other Examples of Tillites, Phantom Glacial Deposits and Indeterminate Diamictites in South America

Besides the above mentioned glacial deposits of the Puga and Serra Azul formations in the Northern Paraguay Belt, and the Santa Cruz Formation in the Southern Paraguay Belt, other Neoproterozoic tillites were referred to in South America (Fig. 19.7). In the Nico Perez Terrane, Uruguay, the diamictites of the Playa Hermosa Formation show the presence of glacial deposits as was suggested by Pazos et al. (2003). Meanwhile the contemporaneous Las Ventanas Formation in the same terrane seems to be associated with rift deposits below the Arroyo del Soldado Group (Blanco and Gaucher 2005, 2014) or above the Mina Verdún Group (Poiré et al. 2005; Poiré 2014) (Fig. 19.7).

Other regions of Brazil show different types of diamictite. For instance, the origin of the Puga Formation conglomerates in its type locality seems to be related to a tectonic event, as previously mentioned (Boggiani 1998; Gaucher et al. 2003) (Fig. 19.7). The Tamengo Formation of the Corumbá Group (Boggiani 1998; Gaucher et al. 2003; Boggiani et al. 2010) bearing *Cloudina* and *Corumbella* fossils associated with volcanic ash levels at the top, which yielded a U-Pb SHRIMP age of 543 ± 2 Ma (Babinski et al. 2008), is another good example of the Phantom glacial model. Over the Tamengo Formation limestones, the shales of the Guaicurus Formation have been correlated with the regional karstic "Barker surface" (Poiré et al. 2007; Poiré and Gaucher 2009b). The Itapucumí Group in Paraguay (Fig. 19.7) also reflects a Phantom glacial model because there are no tillites in the siliciclastic units below the limestones and the upper limestones are perfectly correlated with the Tamengo Formation (Warren 2011; Warren et al. 2011, 2012). The Tucavaca Group in Bolivia near Corumbá suggests the same environmental conditions during its sedimentation (Fig. 19.7).

The Bambuí and Una groups (São Francisco Supergroup) in Brazil are formed by carbonate and siliciclastic successions, with some diamictites overlaid by limestones. However, the glacial origin of these diamictites is still under discussion (Kaufman et al. 2009; Warren et al. 2014; Sial et al. 2016 and references therein).

In Argentina the Colombo Formation in the Río de la Plata Craton constitutes a dubious diamictite deposit considering its origin, but this needs further detailed analysis to understand the depositional processes during its sedimentation (Fig. 19.7). In the Sierras Pampeanas terrane, some limestones and marls are interpreted as Phantom glacial



Glacial (tillites)	Phantom glacial deposits	Undefined, dubious or tectonic diamictites
Santa Cruz Formation Southern Paraguay Belt	Villa Mónica Formation Rìo de la Plata Craton	Puga Formation Southern Paraguay Belt
Puga Formation Northern Paraguay Belt	Loma Negra/Avellaneda Formations Río de la Plata Craton	Las Ventanas Formation Nico Pérez Terrane
Serra Azul Formation Northern Paraguay Belt	Sierra de Ancasti metacarbonates Sierras Pampeanas Terrane	Colombo Formation Río de la Plata Craton
Playa Hermosa Formation Nico Pérez Terrane	Difunta Correa marbles Sierras Pampeanas Terrane	Bambui Group San Francisco Craton
	Tamengo Formation Souther Paraguay Belt	Una Group San Francisco Craton
	Itapucumí Group Paraguay	
	Tucavaca Group Bolivia	

Fig. 19.7 Compilation of glacial, phantom glacial deposits and undefined, dubious or tectonic conglomerates in South America

deposits because there are no diamictites below the carbonate levels ("pseudo-cap carbonate"). The metacarbonates of La Calera Quarry in the Ancasti Range (Murra et al. 2011, 2016) is one example of Phantom glacial deposits, with $^{87}Sr/^{86}Sr$ ratios of 0.70831–0.70860 and 0.70747–0.70781, and values of C and O in three samples of $\delta^{13}C_{PDB} \sim 8.36$ to 9.05‰, $\delta^{18}O_{SMOW} \sim 19.37$ to 22.23‰ (Murra et al. 2011). According to Murra et al., these carbonates are post-Marinoan in age. A similar consideration was proposed by Galindo et al. (2004) for the Difunta Correa marbles in Córdoba Province in the same Sierras Pampeanas terrane (Fig. 19.7).

19.5 Discussion and Conclusions

In this chapter we focus on a comparison between Snowball Earth and Phantom glacial scenarios represented in different successions of South America. Regarding different evidence of glaciations in the Neoproterozoic successions, we choose the Puga and Serra Azul formations in the Paraguay Belt, Amazonia Craton, and the Sierras Bayas Group in the Río de la Plata Craton in order to compare the two models, also related to their different paleolatitudinal position.

The Snowball Earth hypothesis (Hoffman et al. 1998) proposes that Neoproterozoic tillite deposits are recorded as the product of regional glaciations around the world. However, in the Río de La Plata Craton, contemporaneous successions are related to sedimentation in non-glacial environments or Phantom glacial (Cozzi et al. 2002; Poiré 2004).

The Snowball Earth context is well represented by some units of undoubted glaciogenic origin such as the Puga and Serra Azul formations in Northern Paraguay Belt (Brazil) that were related to Marinoan (~635 Ma) and Gaskiers (~580 Ma) glacial events.

On the other hand, the Phantom glacial context is characterized by the successions of the Tandilia System (Argentina) related to a tropical paleogeographic position for this time interval and even older (Cryogenian), in which indirect evidence of those glaciations is also postulated.

Although no tillites were recorded in the Río de La Plata Craton (Argentina), synglacial sea level falls represented by two main karstic discordances over carbonate platforms, the Piedra Amarilla and Barker Surfaces, are considered to be a response of seawater cooling in a distant position with respect to the ice cover.

Conversely, cap-carbonates are defined as deposited over glacial diamictites (Mirasol d´Oeste Fm, Paraguay Belt, Brazil), but a "cap-dolostone" was also referred to (Upper Villa Mónica Formation) by the isotopic trends, Sr content, direct dolomicrite precipitation and tubestone stromatolitic morphologies related to deglacial meltwater environmental conditions (Gómez Peral et al. 2017). A Cryogenian phosphogenic event reported in the Neoproterozoic successions of the Tandilia System, associated with a very discrete level of mudstones with dropstones (Fig. 19.6, Lower Villa Mónica Formation; Gómez Peral et al. 2014a, b) of age ~710 Ma, is postulated as another indirect piece of evidence of the influence of the Sturtian glaciation.

The Barker surface (Fig. 19.5b) on top of the carbonates of the Loma Negra Formation was correlated with others in SW-Gondwana in Uruguay, Brazil, South Africa and Namibia, and related tentatively to the Gaskiers glaciation (Poiré et al. 2007; Gaucher and Poiré 2009b). These micritic limestones show constant positive values of $\delta^{13}C$ ranging between 2.2 and 4.5‰ and $^{87}Sr/^{86}Sr$ from 0.7070 to 0.7082 (Gómez Peral et al. 2007). Later uplift drive in subaerial exposure and meteoric diagenesis in relation to the implantation of the karstic surface on top of the sequence that was also linked to the Gaskiers glacial event (~580 Ma). However, no negative $\delta^{13}C$ anomalies have been mentioned to date. The age of this karst in association with the Ediacaran phosphogenesis event (Fig. 19.6b; Gómez Peral et al. 2014a, b) is supported by the presence of *Aspidella* in the overlying succession (Arrouy et al. 2016).

The two phosphate levels were suggested as being the result of events of generalized phosphogenesis related to relative sea-level fall and exposure in response to glacial eustacy.

Finally, we consider that multiproxy analysis allows the identification of changes in paleoclimate conditions in both cases. In one case, the presence of tillites is considered irrefutable evidence of glaciation particularly when a cap-carbonate is involved, but in the other model the development of regional karstic unconformities related to drastic sea level falls and associated phosphogenesis and trends in $\delta^{13}C$ constitute indirect evidence of the influence of a Phantom glacial during their deposition, under a less extreme climate context.

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