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The hidden passive margins from the birth of SW Gondwana

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Abstract

The final consolidation of southwestern Gondwana during the Ediacaran–Cambrian resulted in the formation of a large landmass originally surrounded by the newborn Panthalassic Ocean. The Río de la Plata Craton is one of the last pieces that complete the geotectonic puzzle along the austral part of this supercontinent. However, the sedimentary record corresponding to the interval between the consolidation of SW Gondwana until the initial deposition in a large Ordovician cratonic basin is apparently missing. In this context, the Ediacaran–Cambrian epiclastic shallow-marine ramp of the Cerro Negro Formation, the uppermost unit of La Providencia Group, Tandilia System, is envisaged as the first known stratigraphic record of the hidden pericratonic basins of Gondwana. Geochronological and provenance data, coupled with robust stratigraphic and sedimentologic background, support that this unit keeps more tectono-sedimentary affinity with the Ordovician Balcarce Formation than the Neoproterozoic Sierras Bayas Group. The presence of similar Neoproterozoic source areas for both units, the absence of any metamorphism and deformation related to the Brasiliano cycle, and shallow marine deposition strongly suggest that the paleogeography and physiography of the original southernmost continental platform of Gondwana were similar to the Ordovician ones. Thus, the Cerro Negro Formation appears as the missing link between the ultimate stages of the Brasiliano Orogenic Cycle and the final stabilization of the continental platform from the SW part of Gondwana.

KEYWORDS: Gondwana supercontinent; geochronology; sedimentary provenance; paleogeographic reconstruction; Cerro Negro Formation; Tandilia System.

Supplementary material

Supplementary data associated with this article can be found in the online version: Supplementary Table A1.

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INTRODUCTION

The final amalgamation of the Gondwana supercontinent took place during the Ediacaran–Cambrian transition, synchronously to the most important climatic, geotectonic, and evolutionary novelties in Earth's history (Grotzinger *et al.* 1995, Hoffman *et al.* 1998, Hoffman and Schrag 2002, Li *et al.* 2008). In the South American continent, these striking changes were recorded in interior basins (e.g., Bambuí Group in Brazil; Pedrosa-Soares *et al.* 2011, Ganade *et al.* 2014, Caxito *et al.* 2021), deformed passive margins (e.g., Corumbá and Itapucumi groups in Brazil and Paraguay, respectively; Gaucher *et al.* 2003, McGee *et al.* 2012, Warren *et al.* 2019, Cordani *et al.* 2020, Moreira *et al.* 2020), and slightly tectonized basins (Sierras Bayas and La Providencia groups, Tandilia System in Argentina; Hernández *et al.* 2017), developed between ~660 and ~520 Ma. As recorded in other coeval sedimentary basins worldwide (Bengtson 1994, Wood 2011, Yuan *et al.* 2011, Gehling and Droser 2013, Penny *et al.* 2014, Cui *et al.* 2017), the Ediacaran–Cambrian basins from SW Gondwana documented fluctuations in the carbon cycle dynamics, first presence of complex macroscopic life, changes in trophic chains, and modifications in architecture of carbonate platforms (Gaucher *et al.* 2003, Gómez-Peral *et al.* 2017, 2018, 2019, Paula-Santos *et al.* 2018, Hippertt *et al.* 2019, Uhlein *et al.* 2019, Warren *et al.* 2019, Caxito *et al.* 2018, 2021, 2023). Some of these short-lived basins formed in the borders of the proto-Gondwana supercontinent (Trindade *et al.* 2006, Tohver *et al.* 2006, 2010, 2012) were deformed by tectonism related to the end of the Brasiliano cycle (630 to 500 Ma—Caxito *et al.* 2021).

Despite the relatively large number of stratigraphic, paleontological, geochemical, and structural data from the pre-Gondwana Ediacaran–Cambrian basins, there is no information regarding the time interval between the final consolidation of SW Gondwana and the evoked first depositional cycle represented by the Ordovician sequences of the interior basins (e.g., Paraná, Parnaíba, and Amazon basins—Assine *et al.* 1994, Milani and Ramos 1998, Oliveira and Mohriak 2003). The geological archives from almost the entire Cambrian and part of the Ordovician are apparently absent, implying the assumption of an early Paleozoic continental-scale erosive cycle in this part of the newly formed supercontinent (Brito Neves and Fuck 2014).

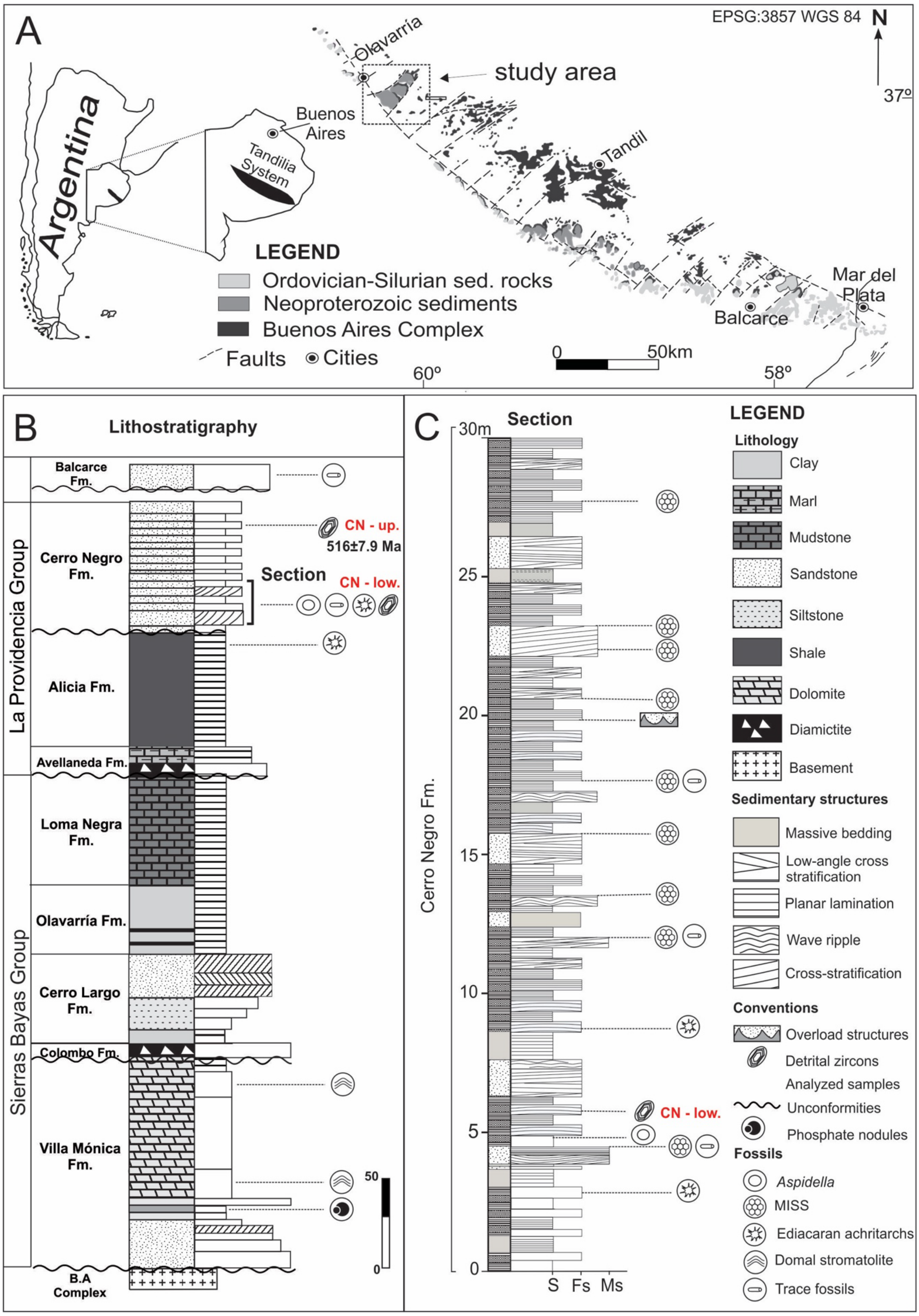
The southernmost part of SW Gondwana was interpreted as formed by the late oblique collision of the Río de la Plata against the Kalahari Craton between 540 and 520 Ma (Rapela *et al.* 2011). This last event was responsible for the deformation of previously deposited Ediacaran–Cambrian basins and also the closure of the Clymene Ocean, west of Río de la Plata Craton (RPC) (Goscombe and Gray 2008, Rapela *et al.* 2011). After this, the sedimentary record is represented by the deposition of siliciclastic sequences indicative of the first subsidence pulse related to the huge Paleozoic intra- and pericratonic basins (Milani and Ramos 1998, Rapela *et al.* 2011). In the austral part of SW Gondwana, the Ordovician Balcarce Formation in Argentina and the coeval Table Mountain Group in the South African counterpart represent these basal successions (Rapela *et al.* 2011). However, some doubts still prevail as to whether these sequences represent the first marine units deposited in Gondwana. In this sense, the lack of reliable geochronological constraints, integrated work on basin evolution, and the absence of sedimentary provenance data make it difficult to falsify this hypothesis.

Grounded in a robust sedimentologic, stratigraphic, and paleontological background and new geochronological data presented in this piece, we support that the Cerro Negro Formation (Iñiguez Rodriguez and Zalba 1974)—the uppermost unit from the La Providencia Group, Tandilia System (Arrouy *et al.* 2015)—corresponds to the first pericratonic basins deposited just after the final consolidation of SW Gondwana in the South American continent. Hence, this study aimed to analyze the sedimentologic and provenance data to assess the original paleogeography from the rare preserved marine platforms that preceded the deposition of the large Paleozoic intracontinental basins. These previously hidden geological archives afford us the opportunity to investigate the origin and geodynamics of Paleozoic basins in Gondwana, allowing us to reconsider the importance of the early Paleozoic erosive cycle in this part of Gondwana. In light of these new data, the dawn of the Panthalassic Ocean opening can now be better constrained offering us the opportunity to explore some key issues, including paleoenvironmental reconstruction, and the Cambrian faunal turnover in this part of the planet.

GEOLOGICAL SETTING

The Tandilia System consists of a 350-km-long NW-SE trending low cordillera located in the southern part of the Buenos Aires Province, Argentina (Fig. 1A). Neoproterozoic to early Paleozoic sedimentary units resting directly on a regional unconformity with the igneous and metamorphic rocks of the Buenos Aires Complex constitute these successions. The basement unit (Buenos Aires Complex) is one of the several terrains that form the RPC and its Paleoproterozoic age (Rhyacian, Shields *et al.* 2022) is relatively well-constrained through U-Pb SHRIMP zircon dating, suggesting ages between 2234 and 2065 Ma (Hartmann *et al.* 2002b, Cingolani *et al.* 2002, Pankhurst *et al.* 2003, Rapela *et al.* 2007, Cingolani 2011), and an Sm-Nd T_{DM} model age of ~2600 Ma (Pankhurst *et al.* 2003).

In the Olavarría area that is located at the NW part of the Tandilia System, the mainly Neoproterozoic-early Cambrian cover corresponds to the ~455-m-thick succession (Iñiguez Rodriguez *et al.* 1989), which is composed of the Sierras Bayas (Poiré and Spalletti 2005, Gaucher *et al.* 2006, Poiré and Gaucher 2009) and La Providencia groups (Arrouy *et al.* 2015) (Fig. 1B). From the base to the top, the Sierras Bayas Group includes the Villa Mónica (sandstone and dolostone), Colombo (iron-rich shale, chert breccia, and diamictite), Cerro Largo (heterolithic rocks and quartz sandstone), Olavarría (siltstone and mudstone), and Loma Negra (limestone) formations. In general terms, this unit corresponds to a mixed siliciclastic-carbonate succession deposited between 1160 to 560 Ma (Gómez-Peral *et al.* 2018, 2023), directly on the rocks of the Buenos Aires Complex. The Sierras Bayas and La Providencia groups are separated by a regional disconformity (Barker Surface, Poiré and Gaucher 2009), characterized by a karstic surface developed on the carbonate rocks of the Loma Negra Formation. Above this, a siliciclastic succession composed of Avellaneda (mudstone and marl), Alicia (dark fissile mudstone), and Cerro Negro (heterolithic rocks and sandstone) formations (Arrouy *et al.* 2015) comprises the La Providencia Group. The Alicia Formation is a fine-grained succession restricted in the subsurface to small depocenters bounded by normal faults (Arrouy *et al.* 2015). The Cerro Negro Formation rests upon the Alicia Formation and represents an abrupt change from a dark- to gray-colored succession deposited in anoxic offshore transition settings to red-colored facies deposited in shoreface conditions (Arrouy *et al.* 2016, Arrouy and Gómez-Peral 2021). Despite the presence of diverse forms of stromatolites in the Villa Mónica Formation (Poiré 1993), the fossil content in other units of the Sierras Bayas Group is meager and doubtful (e.g., putative presence of *Cloudina* fragments in Loma Negra Formation, Gaucher *et al.* 2006). On the contrary, there is a notable presence of distinct types of late Ediacaran non-acanthomorphic organic-walled microfossils in the Alicia and Cerro Negro formations (Figs. 1B and 1C, Arrouy *et al.* 2019), in addition to rare simple trace fossils, microbially-induced sedimentary structures and discoidal forms assigned to *Intrites*-like structures, sand-volcano-like pseudofossils, and *Aspidella* plexus (Arrouy *et al.* 2016, Inglez *et al.* 2021). This fossil assemblage indicates a late Ediacaran depositional age (DA) at least for the lower part of the Cerro Negro Formation (Arrouy *et al.* 2016, 2019), which is consistent with the C and O isotope data and $^{87}Sr/^{86}Sr$ ratios of the Villa Mónica and Loma Negra formations (see Gómez-Peral *et al.* 2017, 2018 for further information)



Fm.: Formation; S: shale; Fs: fine sand; Ms: medium sand.

Figure 1. (A) Geological map of the Tandilia System in the southern Buenos Aires Province, Argentina. (B) Lithostratigraphic column of the Sierras Bayas and La Providencia Groups in the Olavarría area. (C) Detailed columnar section from the base to the middle part of the Cerro Negro Formation, showing the position of body fossils (*Aspidella*), MISS, and putative trace fossils.

and with the middle Ediacaran Oceanic Oxygenation Event represented by the Loma Negra Formation (OOE: ca. 580 Ma; Gómez-Peral *et al.* 2019).

At the top, coastal marine deposits of the Early Paleozoic Balcarce Formation disconformably overlie the Neoproterozoic succession of the Sierras Bayas and La Providencia groups. The basal part of this siliciclastic unit encompasses diamictite deposits assigned to the late Ordovician Hirnantian glaciation (Van Staden *et al.* 2010), which is in agreement with the trace fossil assemblage described in the Balcarce Formation (Poiré *et al.* 2003), and U-Pb SHRIMP ages between 475 and 480 Ma performed in detrital zircons (DZs) (Rapela *et al.* 2007, 2011). Based on these data, it is plausible that the upper part of the Balcarce Formation is younger than 475 Ma, perhaps reaching the Silurian period.

Cerro Negro Formation

The Cerro Negro Formation is an ~80-m-thick succession comprising centimeter to metric-thick tabular and lenticular beds of fine sandstone interbedded with red- and green-colored siltstone (Figs. 1C and 2A). The succession is organized in meter-scale fining upward cycles characterized by fine to very fine sandstone (Fig. 2B) grading to fine-grained facies. Tabular to lenticular beds of trough cross-bedded fine sandstone, which locally have reddish mudstone intraclast and features of fluidization, are present (Fig. 2C, Inglez *et al.* 2021). Scour marks are common in the lower part of the sandstone beds, indicating the erosion of the substrate by currents (Fig. 2D). To the top, this facies transition to decimeter- to centimeter-scale tabular beds of swaley and hummocky cross-laminated fine sandstone (Figs. 2E and 2F) interbedded with heterolithic beds. Most of these cycles frequently end in red-colored siltstone and mudstone (Fig. 2B) and are suggestive of deposition in lower shoreface conditions by storm events. In the studied context, massive or through-cross bedded sandstone facies from the basal part of the Cerro Negro Formation is interpreted as subtidal deposits followed by heterolithic intertidal facies deposited in permanent oxidizing conditions. These cycles culminate in fine-grained facies deposited in supratidal settings marked by rare subaerial exposure (Arrouy *et al.* 2015).

Microbially induced sedimentary structures (MISS) such as *Kinneyia*, Elephant Skin, and *Arumberia* are very common throughout the unit (Arrouy et al. 2023; Figs. 2F, 2G, and 3A). The MISS commonly occur on fine-grained sandstone substrates and are intrinsically related to pavements containing putative bilobed and simple trace fossils (Arrouy *et al.* 2016, Fig. 3B) and vertical tubes assigned to the ichnogenus *Skolithos* (Poiré and Spalletti 2005, Gaucher and Poiré 2009, Poiré *et al.* 2018). Thousands of discoidal structures (Figs. 3C–3E; also see Arrouy *et al.* 2016) occur as low positive epirelief forms of distinct sizes having a central rounded projection with radial grooves. The size variations, internal structures, and external morphology allow assigning only part of these structures to the plexus *Aspidella* (Arrouy *et al.* 2016), which is considered a discoidal holdfast of Ediacaran frondose organisms (Gehling *et al.* 2000). The other part of these discoidal structures may have been formed by alternative processes, such as fluidization and expulsion of fluids under microbial mats (Inglez *et al.* 2021).

The first evidence of a Neoproterozoic age for the Cerro Negro Formation was achieved through whole rock Rb-Sr ages obtained in shale from the base of this unit, indicating deposition ~730 Ma (Bonhomme and Cingolani 1980). However, these data are not completely reliable due to the input of older detrital material. Recently, the description of body fossils, trace fossils, and a non-acanthomorphic microfossil (Fig. 3F) assemblage assigned to the Late Ediacaran Leiosphere Palynoflora (LELP; Gaucher and Sprechmann 2009) suggested a Later Ediacaran age for the basal part of the Cerro Negro Formation (560–541 Ma; Gaucher and Sprechmann 2009, Arrouy *et al.* 2019). Thus, the upper part of the topmost unit from the La Providencia Group can be younger, possibly Cambrian in age. The absence of internal discontinuities in the Cerro Negro Formation also suggests that this unit was not deposited synchronously to the final stages of the Brasiliano Orogenic Cycle and was not affected by tectonic efforts related to the Pampean Orogeny, between 545 and 520 Ma (Rapela *et al.* 2007).

MATERIALS AND METHODS

Stratigraphic analysis was carried out by the description of outcrops and tens of well cores that intercepted the upper part of the La Providencia Group located in the operational area of the Cementos Avellaneda (cement factory) and surroundings.

A total of 38 uncovered polished thin sections were analyzed under a polarized Zeiss microscope of the Centro de Investigaciones Geológicas, La Plata, Argentina (CIG). Petrographic analysis was conducted on siltstone and sandstone samples to determine the distribution of detrital, authigenic, and diagenetic components. A total of 50 siltstone to fine-grained sandstone samples from Cerro Negro Formation were analyzed by X-ray diffraction (XRD) and subjected to soft grinding with a rubber mortar and repeatedly washed on distilled water to avoid deflocculation. The XRD analyses were performed in an X PANalytical model X´Pert PRO diffractometer housed at the Centro de Investigaciones Geológicas, La Plata, Argentina (CIG), using Cu radiation, 40 kV at 40 mA. Powder mounts were analyzed between 2 and 36 °2θ at a scan speed of 2 °2θ/min. The diffractograms were digitally processed with the Origin® software, to convert the values from angles 2θ into Å. The whole rock semi-quantification analysis was performed using the intensity of the main peak for each mineral, and the abundance of mineralogical components was determined by the following percentages: traces (Tr: < 1%); very scarce (VS: 1–5%); scarce (S: 5–15%); moderate (M: 15–35%); abundant (A: 35–50%); and very abundant (VA: > 50%) (Arrouy and Gómez-Peral 2021).

The two samples sent for geochronological analysis were collected in the Cementos Avellaneda main quarry in the town of Olavarría (Fig. 1A), southern Buenos Aires Province, Argentina. About 8 kg of fine sandstone was sampled in cores from the entire succession of Cerro Negro Formation (base—Sample CN-low. and top—Sample CN-up., Figs. 1B and 1C), precisely in centimeter-thick beds containing discoidal structures and putative traces fossils (basal sample CN-low., 4 kg) described in detail by Arrouy *et al.* (2016) and fine sandstone bed (uppermost sample CN-up., 4 kg). The rock samples were processed by standard methods for zircon grain separation and concentration of heavy minerals including heavy liquids (bromoform, $CHBr_3$; only grains smaller than 300 μm), density table, and Frantz magnetic separators (Carver 1971). After these steps, a total of 108 zircon grains were obtained from the concentrate fraction and mounted in a polished epoxy disk with a diameter of 2.5. DZ grains for U-Pb age determination were imaged using a scanning electron microscope (SEM) equipped with

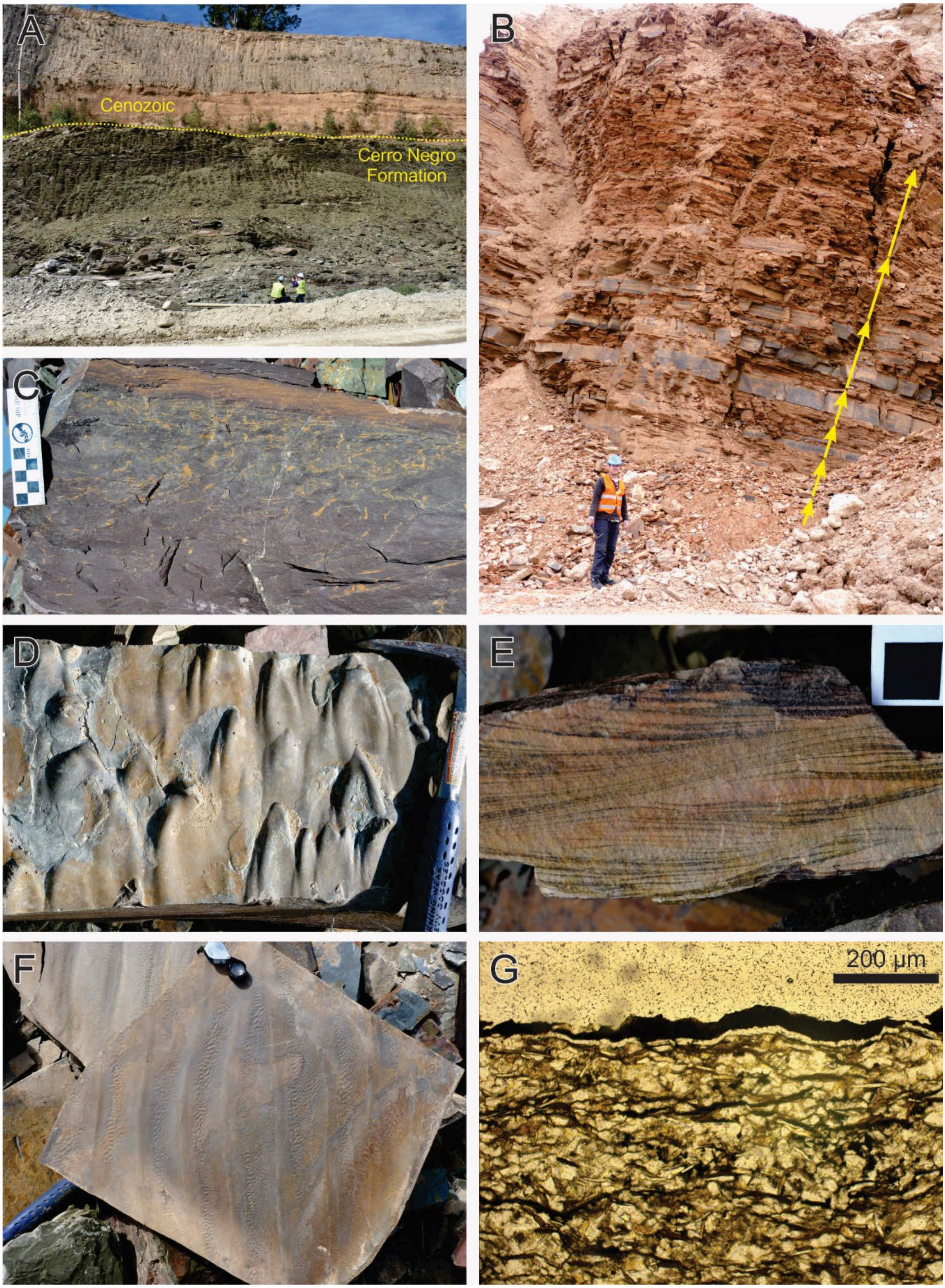


Figure 2. Outcrop and detail photographs of the sedimentary facies from the Cerro Negro Formation. (A) Exposition of the lower part of the Cerro Negro Formation stratigraphic positioned a few meters above the *Aspidella*-bearing bed. (B) Sedimentary succession of the Cerro Negro Formation organized in shallowing-upward tidal cycles. Note that the cycle sets tend to increase in thickness toward the top also indicating an increase in the water depth. (C) Fine-grained massive sandstone facies showing small-scale structures indicative of fluidization. (D) Flute marks at the base of the sandstone bed represented in C. (E) Cross-laminated fine sandstone bed from the basal part of the Cerro Negro Formation. (F) Detail of ripple marks with *Kinneya*-type MISS. (G) Petrographic detail of fossil-rich bed showing grains of muscovite and biotite trapped between organic layers (in black) interpreted as rests of microbial mats (MISS), 50×, parallel polarizers. The hammer is 18 cm long in D and F.

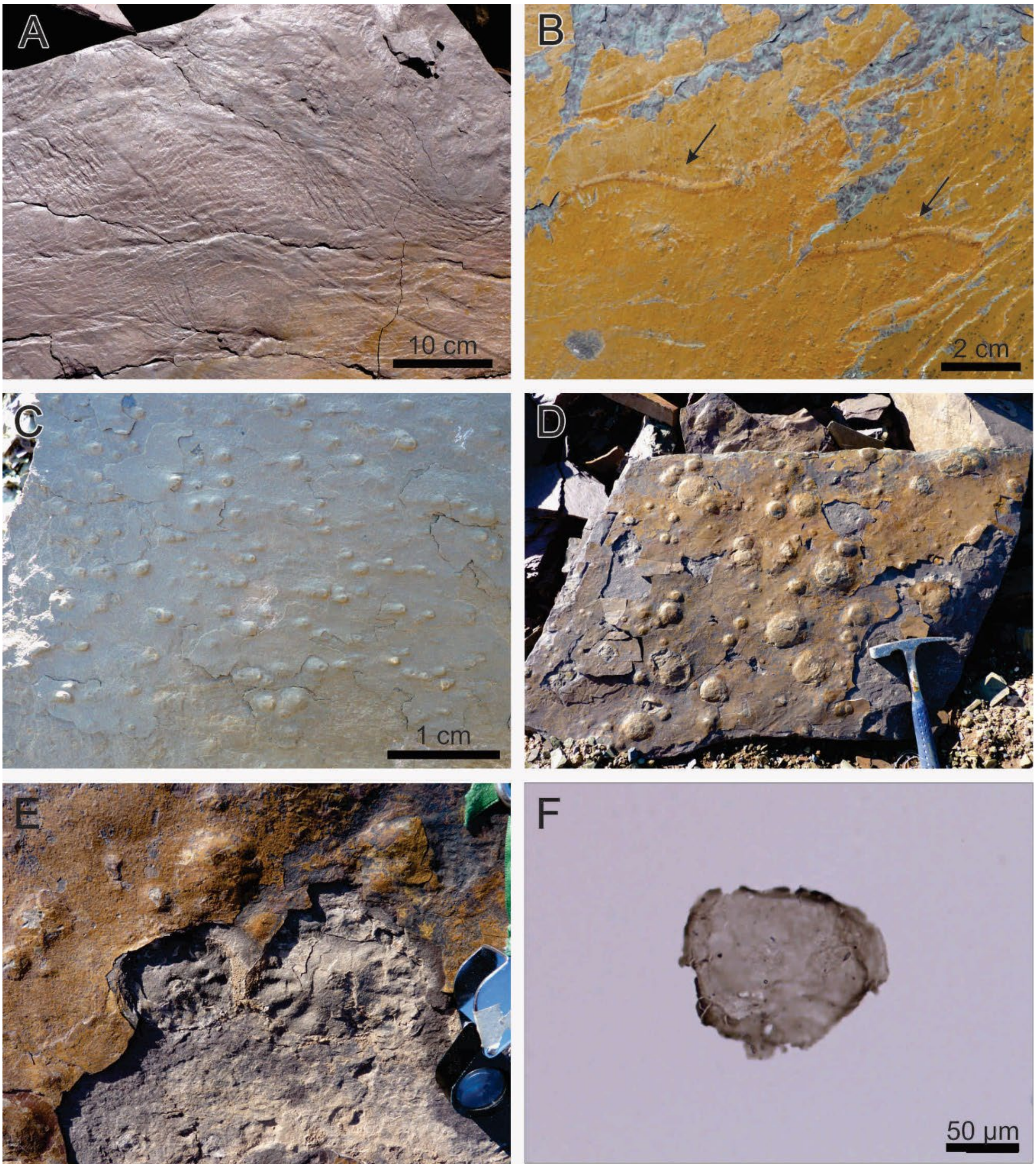


Figure 3. Ediacaran fossil assemblage from the Cerro Negro Formation. (A) Wrinkle marks developed on the surface of a fine sandstone bed. (B) Horizontal tubular traces assigned to the ichnogenus *Palaeophycus*. These traces occur immediately above the beds containing the discoidal fossils (see Figs. 1B and 1C). (C) Several small disks with a central opening interpreted as *Intrites*-like structures. (D) Several *Aspidella* disks with different sizes preserved in positive epirelief. (E) Detail of two *Aspidella* specimens preserved in negative epirelief showing radial groves and a small central hollow. (F) Specimen of *Bavlinella faveolata* preserved in gray siltstone from the upper part of the Alicia Formation (Arrouy *et al.* 2019). The hammer in D and the lens in E are 25 and 8 cm long, respectively.

secondary electron and cathodoluminescence (CL) detectors housed in the Isotope Laboratory at Universidade Federal de Ouro Preto (UFOP, Brazil). These images were used to observe the external and internal morphologies of the DZ to identify locations for analysis that avoided fractures, inclusions, and zones of recrystallization.

The Pb/U and Pb isotope ratios in zircon grains were measured in an Element II laser ablation sector-field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS) coupled to an LSX-213 G2+ CETAC laser also hosted in the Isotope Laboratory at Ouro Preto Federal University (DEGEO-UFOP, Brazil). The analyses were based on Gerdes and Zeh (2006, 2009) and Frei and Gerdes (2009) protocols using a laser energy density of ca. 6–8 J/cm^2 at a repetition rate of 10 Hz and a spot diameter of 20–30 µm. The data were obtained with single-spot analyses on individual zircon grains, and the ablations were performed on both grain rims and cores. The isotope ratios and respective U-Pb and Pb-Pb ages of the unknown zircons were calculated using GJ-1 (608 ± 0.4 Ma; Jackson *et al*. 2004) as the primary reference material and Plesovice zircons (337.1 ± 0.4 Ma; Sláma *et al*. 2008) were analyzed as secondary reference materials to test the accuracy of the obtained results. The background data were obtained for 20 s followed by 40 s of laser signal. The LA-SF-ICP-MS data were reduced using the SATURN software (Silva *et al*. 2023), while age calculations, concordia diagrams, and probability density plots (PDP) were done using the Isoplot-Ex application software (Ludwig 2003) and the Java-based Density Plotter program (Vermeesch 2012), respectively. All ages considered are described as $^{207}Pb/^{206}Pb$ ages for grains older than 1.4 Ga (correlated discordance of $^{206}Pb/^{238}U$ to $^{207}Pb/^{206}Pb$) or $^{206}Pb/^{238}U$ ages for grains younger than 1.4 Ga (correlated discordance of $^{206}Pb/^{238}U$ to $^{207}Pb/^{235}U$). To determine a robust maximum depositional U-Pb age (MDA; see Zhang *et al*. 2016, Ross *et al*. 2017, Coutts *et al*. 2019 for detailed review) for the stratigraphic level of the fossil assemblage, we considered only DZs that were < 3% discordant. The age of the youngest zircons assemblage is also derived from different grains overlapping in age at 2σ (standard deviation; Dickinson and Gehrels 2009).

The age distribution of DZ ages is mainly controlled by the volume of magma generated in each tectonic setting, their associated fertility, and preservation potential (Cawood *et al*. 2012, Spencer *et al*. 2018). Cumulative age distribution curves were made by the subtraction of the crystallization age (CA) of the DZ by the DA of a given sedimentary unit (CA–DA gap curve; Cawood *et al*. 2012). This method allows us to interpret and compare DZ U-Pb age distribution and helps to identify the tectonic setting of deposition.

Multidimensional scaling (MDS) analysis was used to determine the similarity/dissimilarity for distinct source areas from Cerro Negro (this work) and Balcarce formations (Rapela *et al*. 2007, 2011) and Sierras Bayas Group (Cerro Largo and Villa Monica formations; Rapela *et al*. 2007, Gaucher *et al*. 2008). The MDS is based on a Kolmogorov-Smirnov (KS) dissimilarity matrix considering U-Pb ages from 619 DZ grains (Sierras Bayas Group, Cerro Negro and Balcarce formations). These data were represented in a diagram in which similar U-Pb ages are plotted together forming clusters; dissimilar ages plot distant from each other (Vermeesch 2013). In provenance studies, these analyses are particularly useful for establishing similarities or differences in distinct source areas (Vermeesch 2013). For MDS analysis, we use the provenance R package from Vermeesch (2012). Synthetic age end members (Spencer and Kirkland 2016) were also plotted in the MDS to better understand potential source areas.

RESULTS

XRD analyses and petrography of detrital and authigenic components

Whole-rock XRD and petrographic analysis were performed on 50 samples of siltstone and fine-grained sandstone from the entire succession of the Cerro Negro Formation (Fig. 4A). XRD analysis revealed a marked presence of quartz with subordinate presence of plagioclase and alkaline feldspars. Scattered phyllosilicate (muscovite, biotite, illite, chlorite, and chlorite-smectite interlayer) and clay minerals also occur (Fig. 4A).

Unweathered samples of fine-grained quartz sandstone are mainly constituted by subangular to subrounded, mono and subordinately, polycrystalline, quartz grains showing embedded edges (Figs. 4C and 4D). Subrounded to subangular grains of plagioclase (oligoclase and andesine) also occur scattered and are commonly substituted by sericite (Figs. 4B and 4C), giving a cloudy aspect to the grains. Elongated very fine detrital grains of illite, chlorite, biotite, and muscovite and rounded to subrounded lithic grains occur as scarce grains (Fig. 4D). Rare detrital lithic grains with diffuse extinction and presenting inclusions immersed in a massive, aphanitic matrix (poikilitic texture) correspond to volcanic glass, locally substituted by glauconite (Fig. 4E).

Microspar calcite occurs as cement. Cubic to pseudocubic pyrites commonly have an oxidation halo and were interpreted as authigenic in origin (Fig. 4E) and occur exclusively filing intergranular space between detrital grains.

Distribution of U-Pb ages and definition of maximum depositional age of the Cerro Negro Formation

A total of 108 DZ grains of very fine sandstone from the base basal (sample CN-low.) and top (sample CN-up.) of the Cerro Negro Formation (Figs. 1B and 1C) were analyzed considering only data with discordance better than 3%. In general, the grains are anhedral and smaller than 50 μm long (very fine to coarse silt), marked by dominant well-rounded shapes with preserved magmatic zonation (Fig. 5). Well-formed subhedral prismatic (probably volcanic) zircons are rare, and even these grains show some degree of rounding (Fig. 5).

As observed in Figs. 6A and 6B, the most prominent population of zircon grains records Paleoproterozoic ages, with two well-marked peaks around 1914 and 2103 Ma. The Ediacaran population is also important and shows a high concentration of DZ grains around 563 and 603 Ma peaks. Considering all samples analyzed (Table 1), the majority of the DZ grains present Paleoproterozoic age (~57.4% of the total), followed by the Neoproterozoic (~25% of the total), Mesoproterozoic (~10.2% of the total), Archean (~6.5% of the total), and Cambrian ages (0.9% of the total).

The Paleoproterozoic population (Fig. 6B) varies from the Statherian (two grains yielded ages from 1676 ± 19 to 1785 ± 19 Ma; 1.9% of the total), Orosirian (1806 ± 18 to 2047 ± 19 Ma; 18.5% of the total), Rhyacian (yielding ages between 2054 ± 18 and 2283 ± 17 Ma; 34.3% of the total), and Siderian (yielding ages from 2386 ± 17 to 2484 ± 17 Ma; 2.8% of the total). Mesoproterozoic zircon grains reveal ages varying from Stenian (yielding ages between 1155 ± 15 and 1174 ± 16 Ma; 2.8% of the total), Ectasian (yielding ages from 1240 ± 16 to 1298 ± 17 Ma; 2.8% of the total), and Calymmian periods (yielding ages from 1398 ± 21 to 1570 ± 18 Ma; 4.6% of the total). The population of Neoproterozoic DZ grains is mainly Ediacaran (yielding ages from 553 ± 8 to

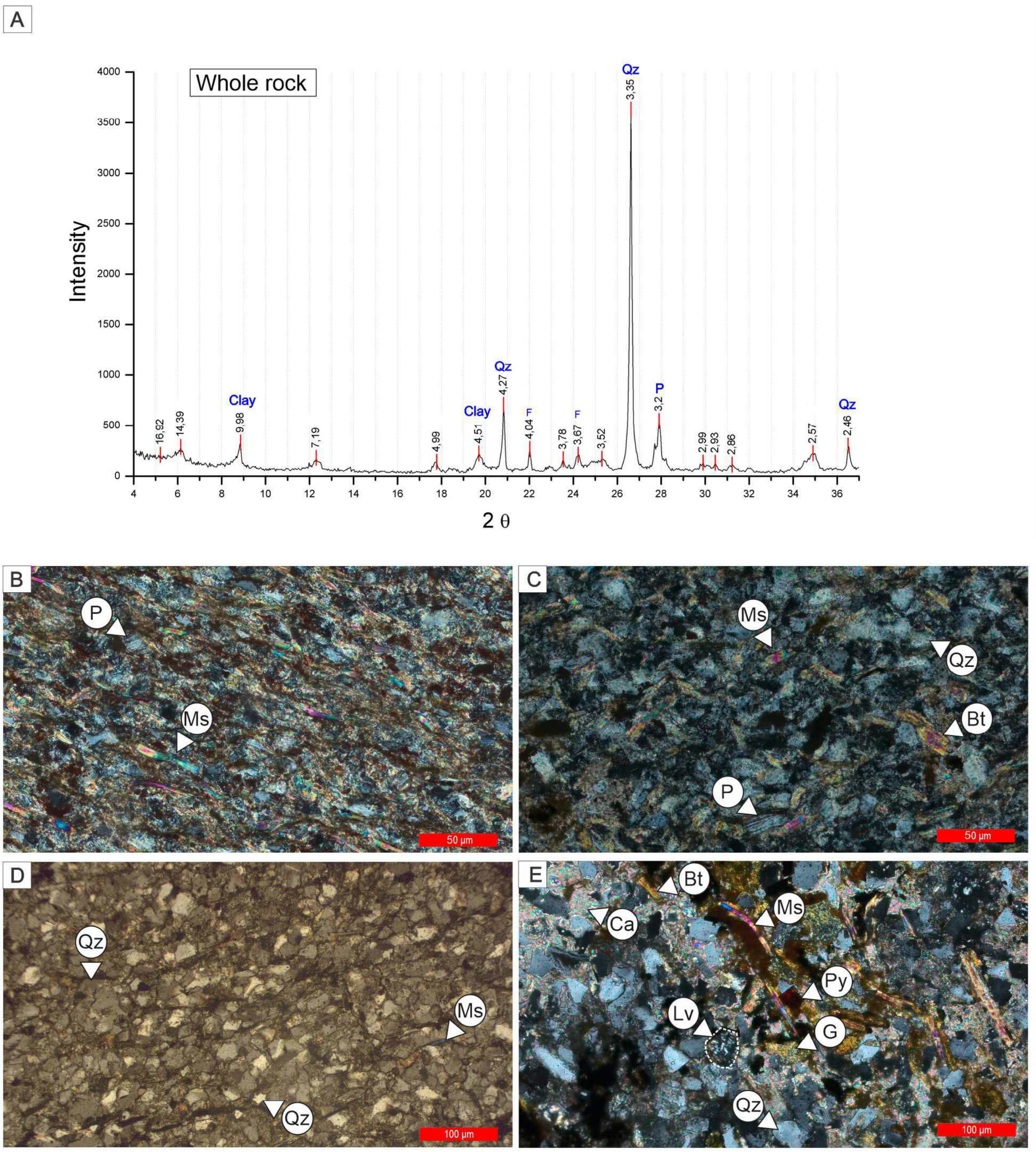


Figure 4. Detrital and authigenic components from the Cerro Negro Formation lithotypes. (A) Whole-rock XRD compositional data of the Cerro Negro Formation showing the presence of abundant quartz, scarce feldspars, and phyllosilicate/clays. (B–E) Microphotographs from Cerro Negro Formation rocks. (B) Laminated siltstone, highlighting muscovite (Ms) and plagioclase (P) grains. (C) Siltstone showing subangular to subrounded quartz grains (Qz), plagioclase with polysynthetic twinning (P), muscovite (Ms), and biotite grains (Bt). (D) Siltstone with abundant quartz (Qz) sometimes with embedded edges and scarce micas (Ms). (E) Siltstone showing subangular to subrounded quartz (Qz), muscovite (Ms), and biotite grains (Bt). Note the presence of glauconite (G), rounded to subrounded volcanic lithic grains (Lv), and cubic to pseudocubic authigenic pyrite (Py). Calcite occurs as rock cement. C, D, and F images were taken with cross-polarized.

634 ± 9 Ma; 24.1% of the total), with just one occurrence of Tonian zircon grain (951 ± 12 Ma; 0.9% of the total). A subordinated population of Archean DZ grains also occurs and presents few Neoarchean (varying from 2624 ± 18 to 2746 ± 17 Ma, 5.6% of the total) and one individual Mesoarchean zircon grain (2979 ± 15 Ma, 0.9% of the total). One single grain with Cambrian age was also identified in the upper part of the Cerro Negro Formation (Series 2, Stage 3, 516 ± 8 Ma, 0.9% of the total). From the geotectonic point of view, 57.4% of the obtained ages (Paleoproterozoic population) can be related to the Orosian-Rhyacian cycle in the Rio de La Plata Craton, while 25.9% are related to the Brasiliano Cycle (Neoproterozoic and Cambrian populations).

From all data analyzed, it is possible to note that the three youngest DZ grains yielded ages of 517 ± 8 Ma (102% concordant; Cambrian, Series 2), 553 ± 7 Ma (100% concordant;

Neoproterozoic, Ediacaran), and 558 ± 8 Ma (102% concordant; Neoproterozoic, Ediacaran). Thus, the Youngest Three Zircons method defines a 542 ± 8 Ma (Late Ediacaran) MDA for the lower to intermediate part of the Cerro Negro Formation. Other MDA methods (see Coutts *et al.* 2019 for a detailed review) reached MDA ages of 516 ± 8 Ma (Youngest Single Grain), 516 Ma (Youngest Graphical Peak), 545 ± 9 Ma (Youngest Four Zircons), and 564 ± 2 Ma (Weighted Mean; MSWD = 0.85).

DISCUSSION

Sedimentary provenance through detrital zircon U-Pb geochronology

The DZ age distribution (Fig. 6B) reveals a clear predominance of grains with Ediacaran and Paleoproterozoic (especially Rhyacian) ages, indicating that the main source areas for the Cerro Negro Formation come from Neoproterozoic plutonic and volcanic units and older igneous and metamorphic units of the regional basement, respectively. Subordinated sources are related to Mesoproterozoic and Archean units (less than 15% of the total). From the provenance perspective, the heterogeneity of the Precambrian terrains that surround the Tandilia System allows us to suggest distinct units from the RPC as potential candidates for source areas. Archaean rocks are extremely rare in RPC and are exclusively recorded in the Nico Pérez Terrane in Uruguay, yielding ages between 3.1 and 2.7 Ga (e.g., La China Complex, Hartmann *et al.* 2001, Gaucher *et al.* 2008). The lack of other coeval units indicates that this terrain is the most likely source area for Archaean zircons in the Cerro Negro Formation. However, Archaean DZs are also reported in some metasedimentary units of the Rio de La Plata Craton which could also provide recycled detrital grains. It is important to note that recycling of DZs from non-original sources is quite common and occurs in other terranes of W Gondwana such as in the Gariep Belt (Andersen *et al.* 2016). The most plausible Paleoproterozoic zircons must be related to granitic to tonalitic gneiss, migmatite, and amphibolite rocks from the Buenos Aires Complex having well-defined Rhyacian ages between ~2.2 and ~2.1 Ga (Oyhantçabal *et al.* 2011). Rhyacian/Orosirian granitic and tonalitic intrusions with ages between ~2.05 and ~2.04 Ga could also have contributed as proximal sources (Cingolani *et al.* 2002, Oyhantçabal *et al.* 2011, Angeletti *et al.* 2023), as well as the La Tuna granite (Pamoukaghlian *et al.* 2017). Alternatively, the Rhyacian/Orosirian Piedra Alta Terrane (~2.2 to ~2.05 Ga) and Siderian/Statherian Nico Pérez Terrane (2.4–1.7 Ga) in Uruguay and more distant source areas for Proterozoic DZs could be considered (Hartmann *et al.* 2000, 2008, Santos *et al.* 2003, Peel and Preciozzi 2006, Mallmann *et al.* 2007, Oyhantçabal *et al.* 2011). Rare Statherian zircon grains can also be sourced from the Piedra Alta Terrane, especially from the Florida dike swarm, with an estimated CA of ~1.790 Ma (Halls *et al.* 2001, Oyhantçabal *et al.* 2011). Mesoproterozoic rocks from the Nico Pérez Terrane, represented by the metavolcanoclastic and gabbro from the Zanja del Cerro Grande Group (Oyhantçabal *et al.* 2005, 2011), are the most probable source area for Stenian, Ectasian, and Calymmian detrital grains of the Cerro Negro Formation.

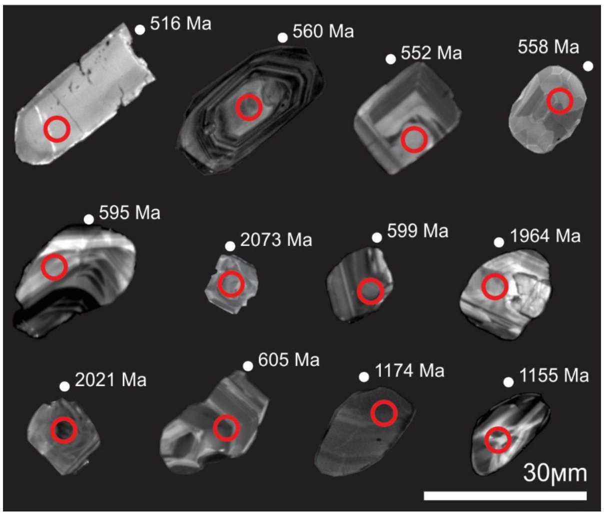


Figure 5. Cathodoluminescence images of detrital zircons from the *Aspidella* bearing bed stratigraphically located in the base of the Cerro Negro Formation. The circles on zircons are the spots where the laser ablation was performed (20 μm spot diameter).

The Neoproterozoic DZ grains, especially those with Ediacaran age, represent the second most significant population in the Cerro Negro Formation (see Fig. 6B) and can be derived from igneous and metamorphic units located in Uruguay, Brazil, and Argentina. The most probable plutonic sources were the post-orogenic and rift-related granitic plutons associated with the final stages of the Brasiliano Cycle that intrude Nico Pérez and Cuchilla Dionísio terranes between ~762 and ~571 Ma (Hartmann *et al.* 2002a) and the La Paz anorogenic granite in Uruguay with 585 ± 4 Ma (U-Pb ages in zircon, Abre *et al.* 2014). Other likely sources were the metamorphosed sequences from Cerro Olivo Complex with

Table 1. Detrital age distribution (total percentages) from Neoproterozoic to Ordovician–Silurian units of the Tandilia System (Sierras Bayas Group—Villa Mónica and Cerro Largo formations, Cerro Negro Formation and Balcarce Formation).

Lithostratigraphic units	Detrital zircon sources (%)					
	Ordov.	Cambr.	Neop.	Mesop.	Paleop.	Arch.
Balcarce Formation	2.7	13.7	36.4	19.5	25	2.7
Cerro Negro Formation	—	0.9	25	10.2	57.4	6.5
Sierras Bayas Group	—	—	0.4	9.2	83.2	7.2

The percentages in light gray indicate source similarities between the lithostratigraphic units. Ordov.: Ordovician; Cambr.: Cambrian; Neop.: Neoproterozoic; Mesop.: Mesoproterozoic; Paleop.: Paleoproterozoic; Arch.: Archaean.

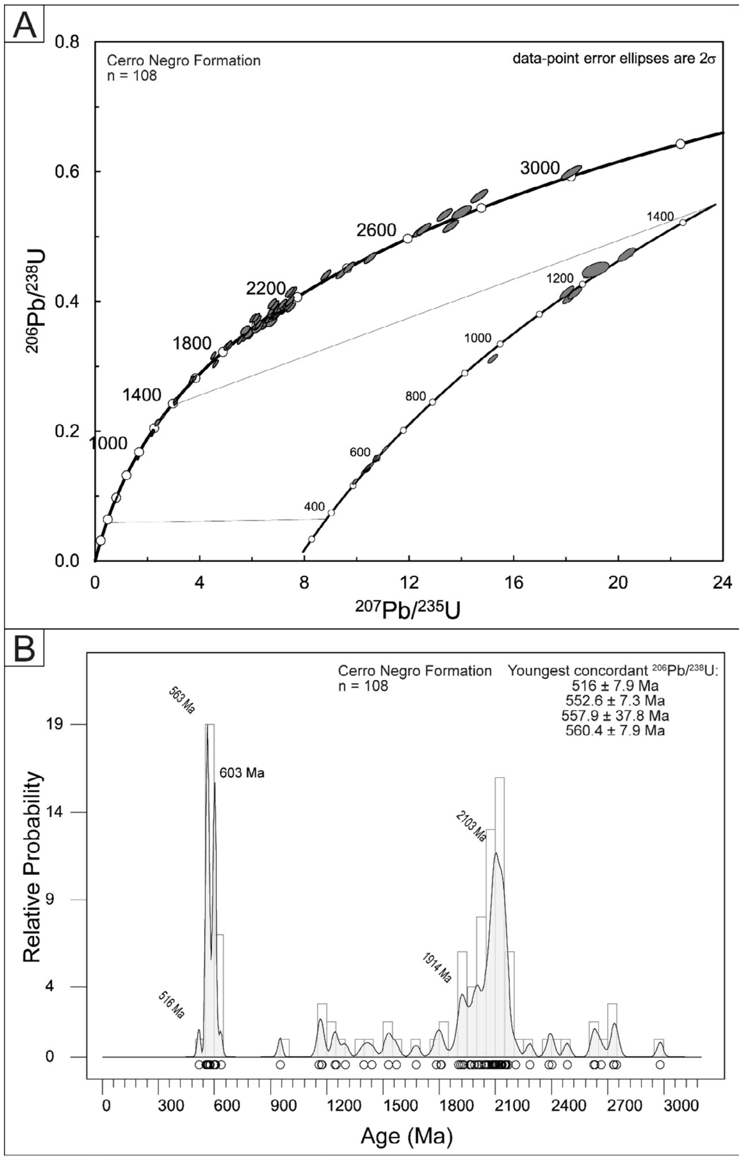


Figure 6. Detrital zircon ages distribution from the base of Cerro Negro Formation, La Providencia Group. (A) Concordia diagram for the analyzed detrital zircons showing the obtained $^{206}Pb/^{238}U$ youngest concordant ages. n is the total number of analyzed grains. (B) Probability plot highlighting two prominent detrital zircon populations with Paleoproterozoic and Neoproterozoic ages, respectively. All ages were according to the International Chronostratigraphic Chart 2023/01. Histograms and KDEs were built using the Density Plotter Java application (Vermeesch 2012).

crystallization and metamorphism ages between 850–750 and 650–600 Ma, respectively (Oyhantçabal *et al.* 2011) and volcano-sedimentary successions from the Ediacaran Porongos (Pertille *et al.* 2015) and Brusque (~843 Ma) groups of southern Brazil (Basei *et al.* 2008, Oyhantçabal *et al.* 2011). Although more distant, the DZs with ~800–700 Ma ages could be alternatively sourced from rift-related alkaline magmatic rocks from the Damara belt in the western Kalahari Craton (Rapela *et al.* 2011).

The Cambrian DZs from the top of Cerro Negro Formation were most probably sourced by the Early Cambrian metaigneous rocks from the El Carancho Igneous Complex (Pampean magmatic arc and backarc), with U-Pb SHRIMP CAs between 528 ± 5 and 520 ± 1.4 Ma, which was the result of the 545–510 Ma Pampean Orogeny (Verdecchia *et al.* 2011).

Recently, igneous zircons from the Santa Teresa Granite in Brazil also revealed an Early Cambrian age of 532 ± 6 Ma (Will *et al.* 2023), suggesting that collision-related plutons of the Dom Feliciano Belt (or the coeval Cape Granite Suite in South Africa) can also be a potential source for DZs. Alternatively, the Early Cambrian Cerro Colorado Granite (531.1 ± 4.1 Ma, Rapela *et al.* 2003) in Sierra de La Ventana could also be considered a possible source of zircons for the upper part of the Cerro Negro Formation.

Tectono-sedimentary evolution and paleogeography of the Cerro Negro Formation

Encompassing a progradational marine siliciclastic succession deposited over fine-grained rocks of the Alicia Formation (Arrouy *et al.* 2015, Arrouy and Gómez-Peral 2021), the Cerro Negro Formation constitutes the upper unit of the last transgressive-regressive cycle of the Neoproterozoic sequences of the Tandilia System (Poiré and Spalletti 2005). The marine influence in the sedimentation of the Cerro Negro Formation is based on robust evidence, such as the presence of (1) storm and tidally-influenced sedimentary facies at the upper part of the unit (Arrouy *et al.* 2015); (2) putative soft-bodied multicellular organisms and trace fossils (Arrouy *et al.* 2016); and (3) marine acritarchs species and filamentous microfossils (Arrouy *et al.* 2019). It is important to note that the analysis of several well cores and outcrops reveals that the Cerro Negro Formation occurs as a widespread sedimentary cover over the Alicia Formation (Arrouy *et al.* 2015). In other words, the Alicia Formation is apparently confined by regional scale faults, while the Cerro Negro Formation covers the entire underlying sedimentary succession, including parts of the uplifted basement block of the Buenos Aires Complex, possibly representing the passage of a mechanical to thermal subsidence regime (Arrouy *et al.* 2015). The intense erosion of the basement, which is indicated by the massive presence of Paleoproterozoic zircons, reinforces the hypothesis of reworking and recycling of DZs from older units.

Despite the presence of slightly post-depositional brittle deformation (Hernández *et al.* 2017), the Cerro Negro Formation does not show significant variation in thickness in its occurrence area. This suggests that the unit was originally deposited in an almost flat basin not substantially affected by synsedimentary tectonism. The present-day geographical position of the Cerro Negro Formation in the southeastern part of the RPC (Rapela *et al.* 2011, and references therein) also allows us to assume that this shallow marine succession was probably deposited in a platform with a gentle slope probably opened to the S-SW. In this way, the Zimmermann *et al.* (2010) proposition that the Cerro Negro Formation was deposited in a basin developed in a context of active margin deserves some careful consideration. First, this model is exclusively grounded in the presence of volcanoclastics and the alleged proximity with the speculative Terra Australis Orogen (Cawood 2005). However, it is important to note that volcanoclastic rocks have never been formally described in the Cerro Negro Formation and Neoproterozoic sedimentary units of the Tandilia System (Arrouy *et al.* 2015). Indeed, volcanoclastic grains are very rare and are only recorded scattered in some sandstone beds at the base of the unit (Zimmermann *et al.* 2010). Second, despite the presence of Early Cambrian magmatism in SW Gondwana (e.g., Sauce Chico Complex, Rapela *et al.* 2003), the existence of an active orogen in this sector of SW Gondwana is not supported by the complete absence of any Ediacaran-Early Cambrian arc-related sedimentary succession in the RPC (Basei *et al.* 2008, Gaucher *et al.* 2008, Oyhantçabal *et al.* 2009) and even in all Argentinian territory (Zimmermann *et al.* 2010). Hence, the presence of rare arc-derived Ediacaran volcanic zircons in the Cerro Negro Formation (Zimmermann *et al.* 2010) is much more easily explained by the proximity with volcano-sedimentary Ediacaran–Cambrian sources, such as those of the Porongos and Brusque groups in the present-day Brazilian territory, or even in the La Paz anorogenic granite in Uruguay (Abre *et al.* 2014) and El Carancho Igneous Complex and Cerro Colorado Granite in central Argentina (Chernicoff *et al.* 2012). In this context, the presence of Early Cambrian DZs in the Cerro Negro Formation that are possibly related to the Santa Teresa Granite in Brazil (or alternatively its African counterpart, the Cape Granite Suite or the Cerro Colorado Granite in Argentina) reinforces that collision-related granites acted as sources of sediment just after the closure of Gondwana (Will *et al.* 2023).

Based on the above-exposed issues, the hypothesis that the Cerro Negro Formation was originally deposited in a foreland basin can be refuted given: (1) the geometry (e.g., unit tabular shape and uniform thickness, Arrouy *et al.* 2015) and architecture of the Cerro Negro Formation that do not indicate significant variations in thickness, a condition that could be expected in foreland basins (from foredeep to back-bulge areas); (2) the absence of any synsedimentary or tectonic deformation and internal discontinuities related to the Brasiliano Cycle or other Early Cambrian tectonic event in the La Providencia Group (Hernández *et al.* 2017, Christiansen *et al.* 2021); and finally (3) the scarce fine volcanoclastic grains (< 50 μm), just indicative of proximity with non-active magmatic arcs. However, it must be highlighted that the presence of incipient hydrothermalism in the Sierras Bayas succession indicates some influence of a proximal thermal source (Gómez-Peral *et al.* 2011, 2023), although this does not necessarily imply the presence of a magmatic arc close to the original basin site. In this case, the most probable cause for the hydrothermalism is the emplacement of anorogenic alkaline and calc-alkaline granite and rhyolite between 533 and 505 Ma (Agua Blanca and Sauce Chico Complex, Ventania System, Argentina; Christiansen *et al.* 2021).

Unlike the majority of South American Ediacaran sedimentary successions (e.g., Itapucumi Group in Paraguay, and Corumbá, Araras, and Bambuí groups in Brazil, see Dardenne 1978, Boggiani 1998, Nogueira *et al.* 2007, Sial *et al.* 2016, Warren *et al.* 2019, Caxito *et al.* 2021), the Cerro Negro Formation was unexpectedly not deformed by the compressive tectonism related to the final stages of the Brasiliano Cycle around 500 Ma (Hernández *et al.* 2017, Christiansen *et al.* 2021, Caxito *et al.* 2021). This implies that this unit was deposited after the active compressional tectonism during the final Gondwana amalgamation between 540 and 520 Ma (Rapela *et al.* 2011). Considering the maximum (DA) of 542.3 ± 7.7 Ma obtained through DZ analysis and the maximum age limit for the compressive events, it is plausible that at least the uppermost part of the Cerro Negro Formation is younger than 520 Ma (maximum age of deformation). This is reinforced by the presence of the ichnogenus *Skolithos* in the upper part of this unit which range from Early Cambrian to the Present (Jensen 2003, Mángano and Buatois 2019, Buatois *et al.* 2020). The slight deformation observed in all Neoproterozoic sedimentary covers of the RPC seems to be related to the Permian compressional event produced by the collision of Patagonian Massif against Gondwana or even the Mesozoic opening of the Salado Basin (Christiansen *et al.* 2021).

Despite the presence of Paleoproterozoic and Mesoproterozoic zircons in older Neoproterozoic units from the Tandilia System (Cingolani 2011), it is remarkable that Ediacaran zircons are only described in the Cerro Negro Formation (Fig. 7, Supplementary data, Table 1). On the contrary, Cambrian and Neoproterozoic detrital grains with ages between 552.6 ± 7.9 and 634.2 ± 8.9 Ma are also recorded in coarse sandstone from the base of the Ordovician–Silurian Balcarce Formation (see Fig. 7, Zimmermann and Spalletti 2009), suggesting an affinity between the source areas of both successions (Supplementary data, Table 1). Based on these data, it is plausible that older units of the Buenos Aires Complex and Piedra Alta and Nico Pérez terranes act as continuous source areas during the whole Neoproterozoic. Note that a significant provenance shift probably occurred at the Upper Ediacaran with the maintenance of Cambrian and Ediacaran sources areas until the Ordovician, such as the Porongos Granite in Brazil and West Sierras Pampeanas and Sierra de La Ventana terranes, in Argentina (Figs. 6 and 7, Supplementary data, Table 1). The analysis of the DZ ages reveals a subordinated influence of Archean source areas for the entire Sierras Bayas Group, Cerro Negro, and Balcarce formations. While Mesoproterozoic sources are also recorded in the three units, there is a notable decrease in Paleoproterozoic sources in the Balcarce Formation. Figure 8A shows an MDS plot constructed using U-Pb ages from the Cerro Negro and Balcarce formations and the Sierras Bayas Group (Villa Mónica and Cerro Largo formations) and reveals differences and similarities between their source areas. The proximity of Balcarce and Cerro Negro Formation (solid lines in Fig. 8A) is due to the presence of a significant population of Neoproterozoic zircons in both units, whereas the presence of Paleoproterozoic zircons in Cerro Negro and Sierras Bayas Group results in contiguity. On the contrary, the distance between the Balcarce and Sierras Bayas Group is directly related to the absence of Neoproterozoic sources in the last unit and a very significant contribution of Paleoproterozoic sources. The synthetic age end members (Fig. 8A)

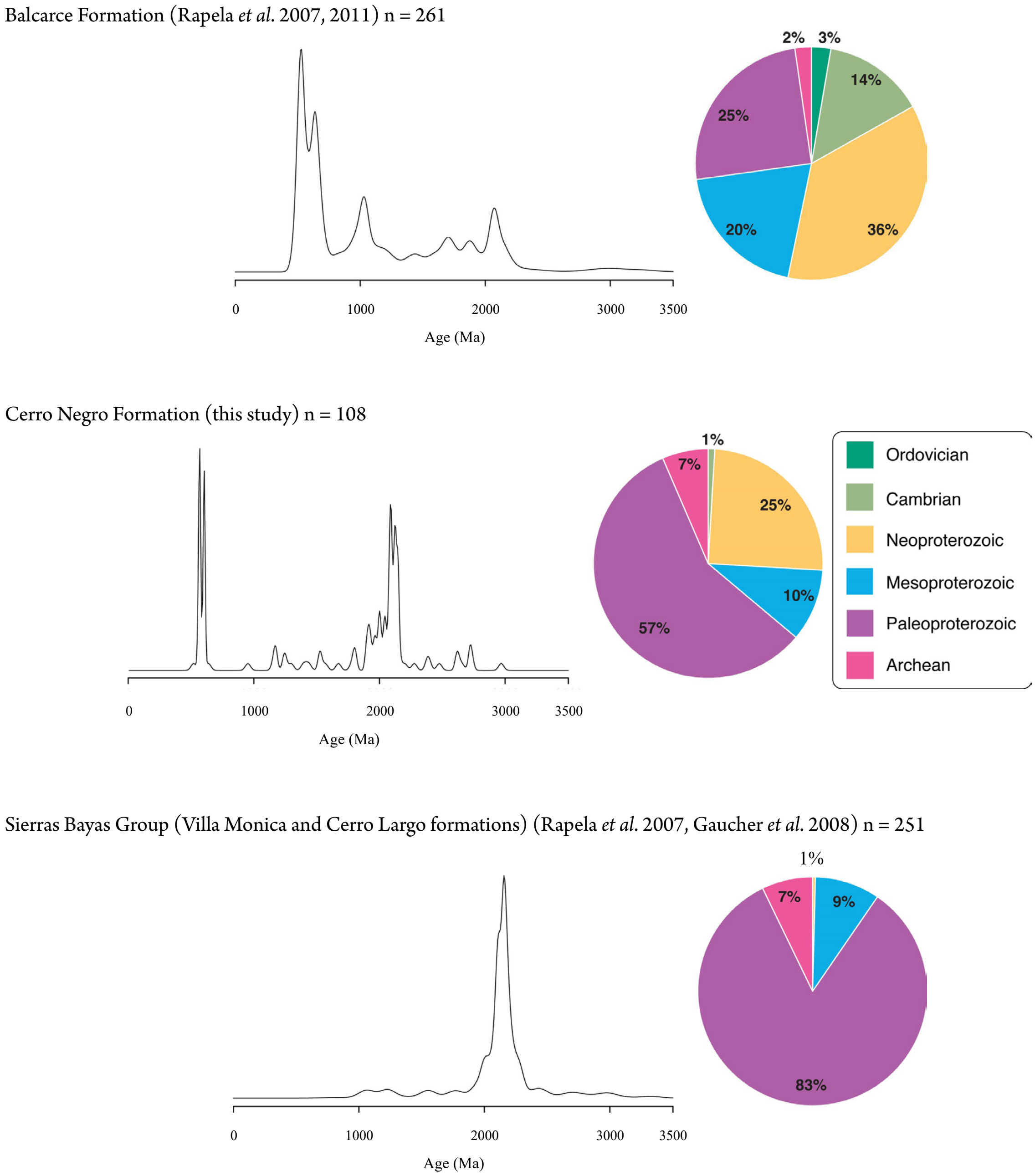


Figure 7. Pie charts and age probability plot (right) for the analyzed detrital zircons of the Balcarce and Cerro Negro formations and Sierras Bayas Group. Based on new data presented in this work and from Rapela *et al.* (2007, 2011) and Gaucher *et al.* (2008).

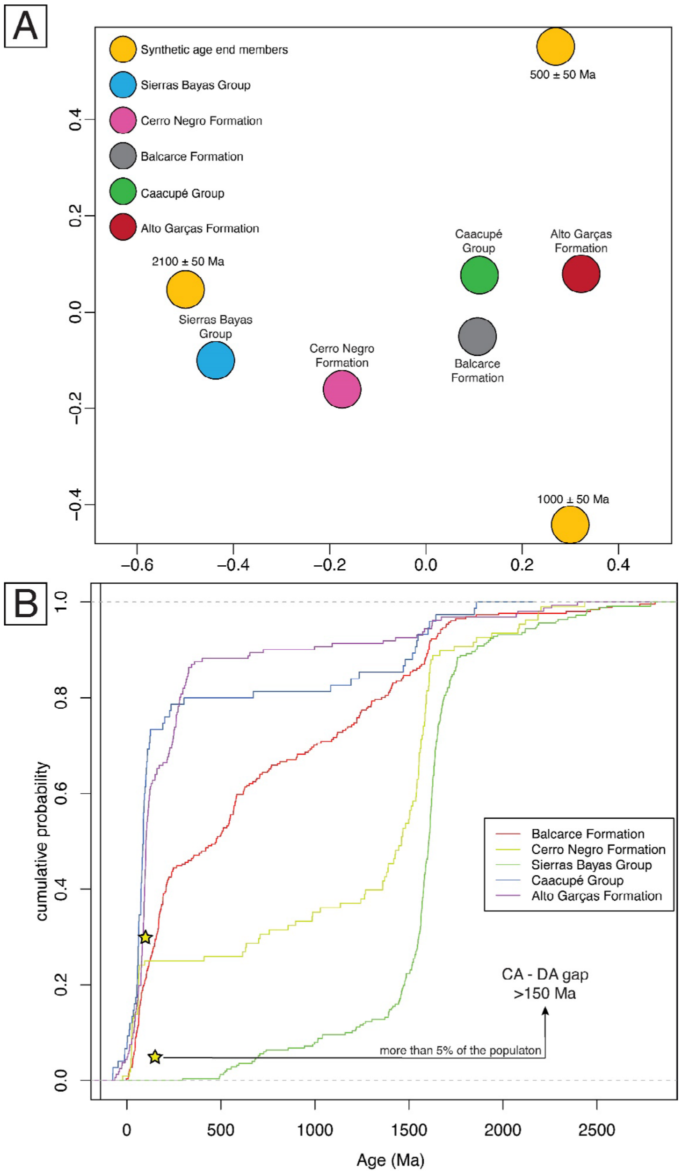
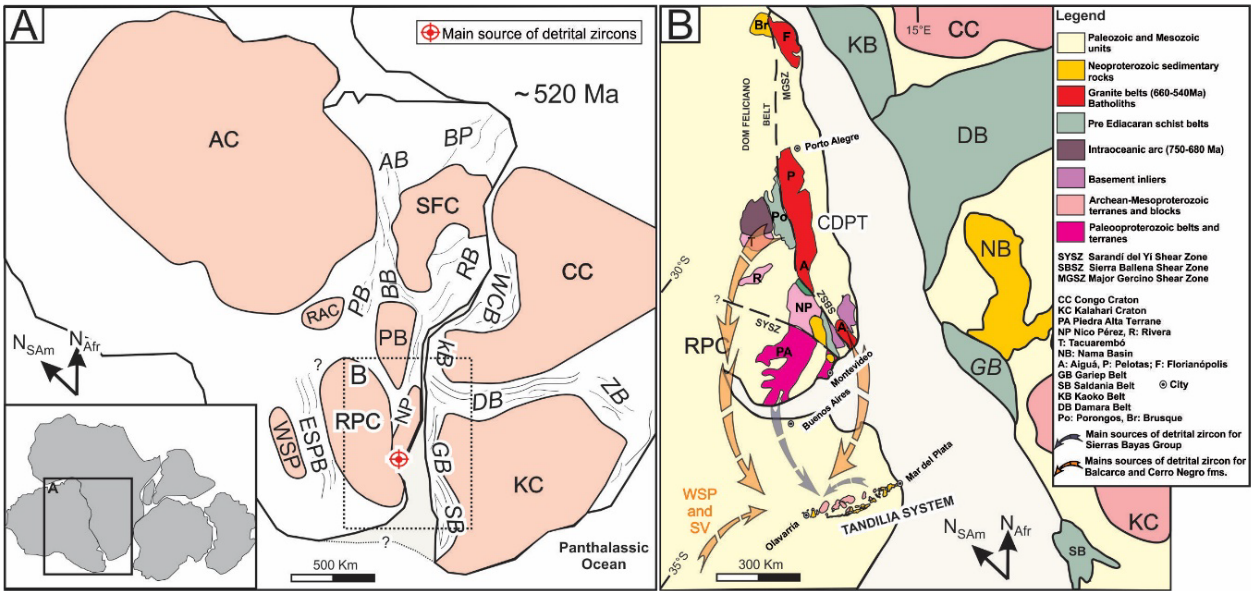


Figure 8. (A) MDS plot evidencing the dissimilarity degree between U-Pb ages from the Sierras Bayas (Cerro Largo and Villa Mónica formations) and Cacacupé groups (Chaco-Paraná Basin), Alto Garças (Paraná Basin), Balcarce, and Cerro Negro formations. Solid lines represent the closest detrital zircon cluster ages, and dashed lines represent more distant clusters. (B) CA–DA gap curves (Cawood *et al.* 2012), evidencing that Cerro Negro and Balcarce formations were deposited in extensional settings. Additional data from Rapela *et al.* (2007, 2011), Gaucher *et al.* (2008), and Henrique-Pinto *et al.* (2021).

demonstrate this relationship, whereas the Sierras Bayas Group was plotted near the 2100 ± 50 Ma end member, and Cerro Negro and Balcarce formations were plotted near the Neo- to Mesoproterozoic end members. It is possible to quantitatively assert that the Cerro Negro and Balcarce formations have the highest degree of similarity, differing drastically from the pattern of source areas observed for the Sierras Bayas Group. This suggests the maintenance of source areas between the Upper Ediacaran–Cambrian and Ordovician and could indicate that the configuration of catchment areas remained similar after the final consolidation of Gondwana (Fig. 9).

The CA of the DZ by the DA gap curve for the Sierras Bayas Group (Fig. 8B) evidence that more than 5% of the zircon grains record an age gap greater than 150 Ma (between CA and DA ages), that are a typical signature of extensional settings (Cawood *et al.* 2012). On the contrary, the Balcarce and Cerro Negro formations (Fig. 8B) record a CA–DA gap of less than 150 Ma (more than 30% of the DZ population present a CA–DA gap greater than 100 Ma), which could tentatively indicate deposition in a collisional setting (Cawood *et al.* 2012). However, it is important to note that this effect is also observed for other pre-Carboniferous sedimentary units deposited in an intracontinental setting. For example, the marine Caacupé, Alto Garças, Iapó (Late Ordovician), Furnas (Early Devonian), and Ponta Grossa (Late Devonian) formations of the Paraná Basin also have a CA–DA gap curve similar to that obtained for collisional environments (see Fig 8B, Henrique-Pinto *et al.* 2021). In the case of Cerro Negro and Balcarce formations, this apparently conflicting pattern just reflects the proximity of the depositional site with Neoproterozoic orogenic terrains related to the final collision of Gondwana between 540 and 520 Ma (Rapela *et al.* 2011).



AC: Amazon Craton; RAC: Rio Apa Craton; WSP: West Sierras Pampeanas; SFC: São Francisco Craton; PB: Paranaiba Block; BP: Borborema Province; RPC: Río de la Plata Craton; NP: Nico Perez Terrain; KC: Kalahari Craton; CC: Congo Craton; PB: Paraguay Belt; SV: Sierra de La Ventana; ESPB: Eastern Sierras Pampeanas Belt; AB: Araguaia Belt; BB: Brasília Belt; RB: Ribeira Belt; WCB: Western Congo Belt; DB: Damara Belt; KB: Kaoko Belt; SB: Saldania Belt; GB: Gariep Belt; ZB: Zambia Belt.

Figure 9. (A) Paleogeographic reconstruction for the southernmost part of the newly formed SW Gondwana supercontinent between 540 and 520 Ma. (B) Detail of A showing the main sources of the Sierras Bayas Group, Cerro Negro, and Balcarce formations. Paleogeographic reconstruction in A based on Trindade *et al.* (2006), Tohver *et al.* (2006, 2010), and Merdith *et al.* (2017). Geotectonic units and architecture in B based on Cingolani *et al.* (2002), Pankhurst *et al.* (2003), Rapela *et al.* (2007, 2011), Basei *et al.* (2008), Goscombe and Gray (2008), Hartmann *et al.* (2002b, 2008), Bossi and Cingolani (2009), Oyhantçabal *et al.* (2009, 2011), Poiré and Gaucher (2009), Zimmermann and Spalletti (2009), and Pamoukaghlian *et al.* (2017).

FROM THE FIRST PERICRATONIC BASINS OF GONDWANA TO THE ADVENT OF THE PALEOZOIC INTERIOR CRATONIC BASINS

Evidence indicates that the La Providencia Group corresponds to a new sedimentary cycle different from that of the Sierras Bayas Group. The La Providencia Group is separated from the older Neoproterozoiic units of the Tandilia System by a regional unconformity (Barker Surface, Poiré and Gaucher 2009) and onlaps this surface. Their continuous thickness, absence of metamorphism, and tectonic deformation indicate that this unit was deposited after the last tectonic stresses related to the Brasiliano Cycle responsible for the final consolidation of western Gondwana and deformation of the older units (e.g., Sierras Bayas Group). Despite the previously pointed differences in the source areas of the Cerro Negro Formation and the underlying Sierras Bayas Group, the analysis of DZs reveals some remarkable similarities with the overlying unit, the Ordovician/Silurian Balcarce Formation. The presence of Paleoproterozoic and Ediacaran zircons in both Cerro Negro and Balcarce formations indicates that these units had similar source areas, although Cambrian sources are particularly common in the latter unit (Fig. 7). This correspondence (Fig. 8) indicates similar erosional terrains during the Upper Ediacaran–Cambrian and Ordovician (Fig. 9), suggesting regional readjustment and maintenance of the drainage pattern and catchment areas after the final consolidation of Gondwana (see similar interpretation in Cerri *et al.* 2021).

Considering the maximum DAs of ~554 and ~475 Ma for Cerro Negro and Balcarce formations, respectively (see discussion above), we must cogitate an erosive gap of, at least, ~80 Ma between these two units. However, it should be noted that this time interval is surely overrated, and if we assume that the Cerro Negro Formation is younger than the last deformational event in the RPC at ~520 Ma (Rapela *et al.* 2011), this age span decreases. In other words, the time between the deposition of the first marine succession after the formation of Gondwana and the beginning of the Ordovician cycle of deposition is less than 45 Ma.

Recently, efforts based on a multi-proxy approach (Cerri *et al.* 2020, 2021) in accordance with the integrated model (Klein 1995, Allen and Armitage 2012) have found evidence that the first basins of Gondwana initiated as flooded ramps opened to adjacent oceanic areas tens of millions of years after the formation of the initial Ediacaran–Cambrian rift basins. Thus, contrary to the notion that the intracontinental basins from SW Gondwana evolved from an NW-SE-oriented Neoproterozoic rift system (Fulfaro 1982, Tankard *et al.* 1995), the updated models postulate that the continental lithosphere stretching and cooling occurred long after the final consolidation of Gondwana supercontinent (Cerri *et al.* 2020). The analysis of the SW Gondwana geodynamics from its final consolidation around 500–490 Ma (Tohver *et al.* 2010) to the first regional subsidence cycle in the Meso to Late Ordovician reveals that the Meso to Late Cambrian and Early Ordovician period was marked by pronounced uplift, erosion, and no deposition (Poiré and Spalletti 2005, Brito Neves and Fuck 2014). This is evidenced by the scarcity of sedimentary units dated in this interval and the presence of significant regional unconformities in almost all basins in South America (Iñiguez Rodriguez *et al.* 1989, Assine *et al.* 1994, 1998, Milani and Ramos 1998, Oliveira and Mohriak 2003, Cerri *et al.* 2020).

In this context, the pericratonic basin of the Cerro Negro Formation figures as the first example of these hidden primeval basins unexpectedly absent in the geological record. This initial subsidence cycle probably took place taking advantage of fragile parts of the marginal part of the Gondwana lithosphere (Allen and Armitage 2012, Armitage *et al.* 2013), that is, weakened continental lithosphere areas stabilized just after the final stages of the Brasiliano Cycle (Milani and Ramos 1998, Oliveira and Mohriak 2003, Cerri *et al.* 2020, 2021). In other words, these initial efforts probably started due to the stretching of this weakened lithosphere followed by its subsequent cooling generating regional tilting towards the Gondwana margins (Allen and Armitage 2012). This primeval tilted ramp was probably opened to the newly formed Panthalassic Ocean toward the south, as observed in the African counterpart of Gondwana (Zimmermann *et al.* 2011, after Van Staden *et al.* 2006 and Zimmermann *et al.* 2009). According to this model, these first short-lived basins were succeeded millions of years later by the basal marine successions from the Early Paleozoic basins of Gondwana mostly deposited during the Ordovician–Silurian interval (Assine *et al.* 1998, Milani and Ramos 1998). This new cycle of widespread intracratonic subsidence was attested by the physical connection between extensive subsiding areas from the newly formed Paraná-Chaco-Cape basins and the presence of subsurface Ordovician–Silurian strata in the north of Argentina (Balcarce Formation, Pezzi and Mozetic 1989), west of Paraguay (Caacupé Group, Wiens 1995), Brazil (Río Ivaí Group, Assine *et al.* 1994, 1998), and east of Bolivia (El Carmen Formation, Assine *et al.* 1998).

CONCLUSION

The end of the Neoproterozoic Era is marked by the final consolidation of the SW Gondwana. The scarce sedimentary record of this key period is related to previously deposited sedimentary basins slightly deformed by the final tectonic stages of the Brasiliano orogenic cycle. Thus, between the deposition of these Late Ediacaran basins and the beginning of the subsidence and filling of the huge Paleozoic cratonic basins during the Ordovician, the geological archives are until now lost. In this piece, we argue that the Cerro Negro Formation, La Providencia Group, Tandilia System, is a true representative of the first passive margins from the newly consolidated continental platform from the SW Gondwana in the South American continent. This hypothesis is supported by the marine deposition of this unit (attested by sedimentary facies and the presence of marine acritarchs microfossils), the absence of deformation and metamorphism, and, finally, similar source areas with the Ordovician Balcarce Formation. Additionally, the presence of Paleoproterozoic sources also described in the Neoproterozoic Sierras Bayas Group (Villa Mónica and Cerro Largo formations) reveals that the Cerro Negro Formation represents the transition from a proto-Gondwana configuration to a newly established Gondwana platform. Finally, the unexpected presence of a supposedly missing record forces us to rethink the duration of the entire alleged erosive cycle between the consolidation of Gondwana and the beginning of deposition in the large Paleozoic cratonic basins.

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