



Ediacaran in Uruguay: Facts and controversies



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ABSTRACT

The Ediacaran of Uruguay has been regarded as containing a significant geological and paleontological record, which would make these successions critical to unraveling diverse aspects regarding the assembly of southwestern Gondwana and to understanding the conditions surrounding the rise of animal life in a period punctuated by drastic paleoenvironmental changes. However, a review of currently available data leads to the conclusion that, although variable, the stratigraphy, distribution and age of these units remain ambiguous. The same is true for existing basin models and tectonic evolution, which show different and sometimes contradicting supporting evidence. Here, we propose that the Ediacaran record consists of the Maldonado Group (Playa Hermosa, Las Ventanas and San Carlos formations), and the Tacuarí, Barriga Negra, Rocha and Sierra de Aguirre formations. The Arroyo del Soldado Group (Yerbal, Polanco Limestones and Cerro Espuelitas formations) and the Arroyo de la Pedrera Group (Piedras de Afilas and Cerro Victoria formations) were likely deposited between 700 and 1000 Ma. The best available radiometric age constraints indicate intense magmatic–tectonic activity occurred between 600 and 560 Ma, incompatible with previous models suggesting a stable, Atlantic-type passive margin on this portion of southwestern Gondwana. Further research is needed in order to firmly establish a consistent litho- and chronostratigraphic framework; particularly, before attempting any regional or global correlation, and inferences on global paleoenvironmental and paleobiological events.

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1. Introduction

The Ediacaran Period (635–541 Ma) witnessed significant environmental and biological transformations. Ediacaran sedimentary rocks contain information on atmospheric and oceanic composition (e.g., C- and Sr-isotopic excursions), as well as on the appearance and diversification of metazoans (Narbonne et al., 2012). Besides the well-known Ediacaran successions, such as those located in South Australia, Namibia, Russia, China and the Avalon Peninsula in Canada (e.g., Geyer, 2005; O'Brien and King, 2005; Knoll et al., 2006; Grey and Calver, 2007; Jiang et al., 2011; Johnston et al., 2012), new promising areas have emerged in the last few years (McCall, 2006), including those in Uruguay which

have been suggested to record global climatic, biogeochemical and biotic events (Gaucher et al., 2009; Frei et al., 2011; Pecoits et al., 2012a,b).

According to previous interpretations, the Ediacaran Period in Uruguay is represented by the Arroyo del Soldado and Maldonado groups, the Sierra de Aguirre, Rocha and Tacuarí formations, and part of the Arroyo de la Pedrera Group (Fig. 1). These units have been the focus of numerous sedimentary, stratigraphic, paleontological and geochemical studies. As a result, a range of divergent chrono-stratigraphic, depositional and tectonic interpretations has been proposed to explain the origin and evolution of these volcano-sedimentary units. Unfortunately, most of these models are supported by limited and, in some cases, questionable evidence (see for example Sánchez Bettucci et al., 2010; Zimmermann, 2011). This has resulted in controversial associations with important Ediacaran events and correlations with other successions worldwide.

In this article, we review and summarize tectonostratigraphic schemes of Uruguayan Ediacaran strata focusing on lithostratigraphy, age and geological setting: the purpose of this paper is to

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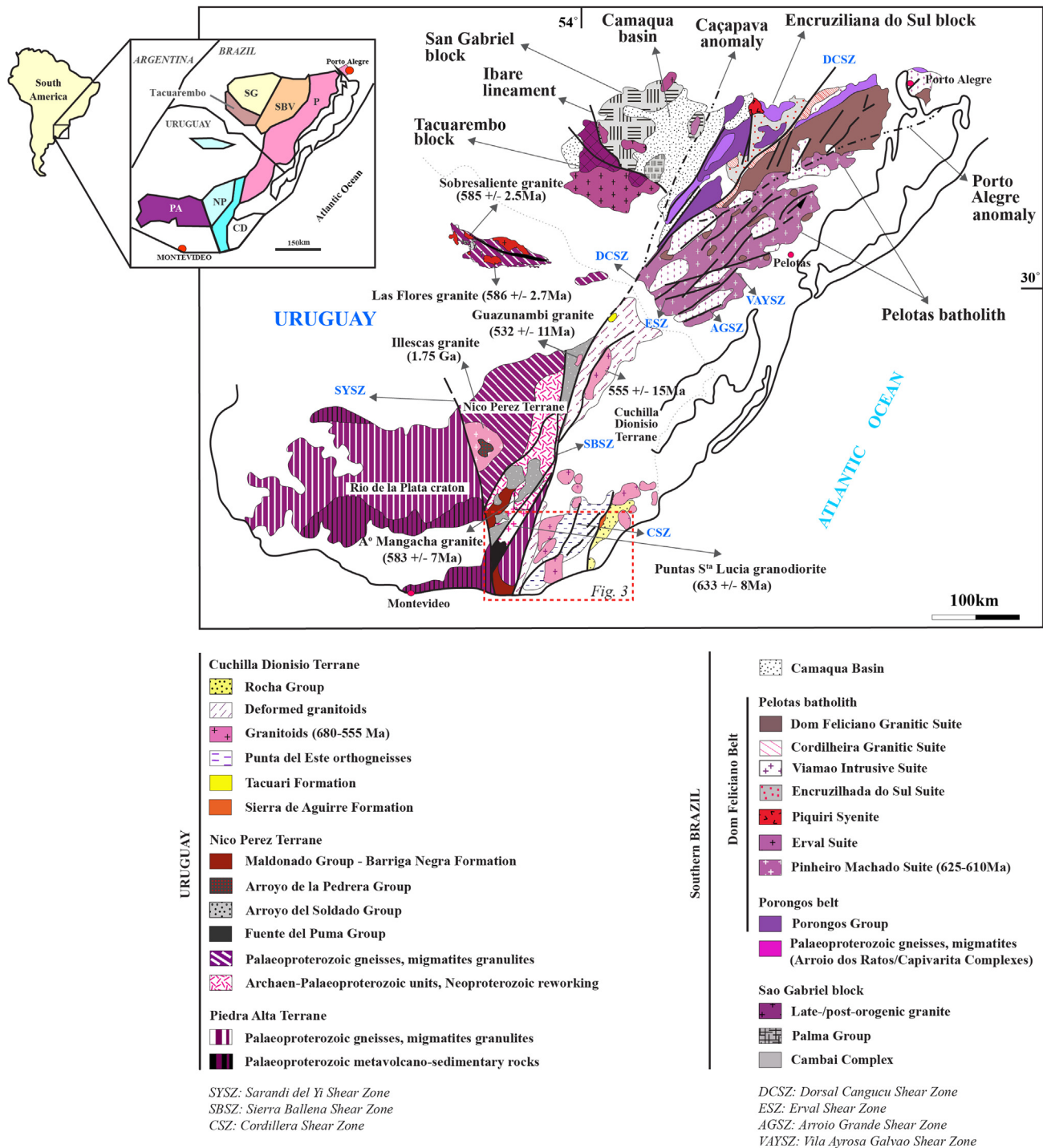


Fig. 1. Simplified geologic map of Uruguay and southern Brazil (modified from Saalman et al., 2011 and references therein). Inset: PA-Piedra Alta, NP-Nico Pérez, and CD-Cuchilla Dionisio Terranes of Uruguay; SG-São Gabriel, SBV-Santa da Boa Vista, P-Pelotas and Tacuarembó Blocks of southern Brazil.

identify and analyze the strengths, limitations and misconceptions pertaining to the nature and age of units. Of particular interest are the Arroyo del Soldado and Maldonado groups because of their potential relevance to unravel several aspects of the Ediacaran Period. Therefore, the ultimate goal of this article is to present a constructive but critical review of key issues regarding the Ediacaran of Uruguay, with the aim of promoting further research that allows a better understanding of the local geology and its implications for the Precambrian processes and events.

2. Previous work

2.1. Arroyo del Soldado Group

The conceptual stratigraphic framework of lithologies now included in the Arroyo del Soldado Group was first made by Preciozzi et al. (1988 and references therein; see also Preciozzi et al., 1993). However, this lithostratigraphic unit was formally defined by Gaucher et al. (1996) to include a marine shallowing-

upward succession (~1500 m) comprising, from base to top, the Polanco Limestones Formation (Goñi and Hoffstetter, 1964), Cerro Espuelitas, Cerros San Francisco and Cerro Victoria formations (Montaña and Sprechmann, 1993). Later, Gaucher et al. (1998) included the basal Yerbal Formation and the Barriga Negra Formation (Midot, 1984) resulting in more than 5000 m in thickness for the entire group (Fig. 2). Subsequently, Pecoits et al. (2008) proposed a new lithostratigraphic scheme for the Arroyo del Soldado Group excluding the Cerros San Francisco and Cerro Victoria formations into the Arroyo de la Pedrera Group. This exclusion was based on the lack of continuity between the Cerro Espuelitas and the Cerros San Francisco formations.

The age of the Arroyo del Soldado Group is also controversial. Gaucher et al. (2009) concluded that the age of the group is geochronologically constrained by dates obtained from basement and intrusive granites with a maximum U–Pb SIMS zircon age of 583 ± 7 Ma for the Arroyo Mangacha Granite in the basement, and a minimum Rb–Sr isochron age of 532 ± 11 Ma for the intrusive De Los Guazunambí Granite ($R_i = 0.70624$) (Fig. 1). The youngest detrital zircon populations from the Yerbal and Barriga Negra formations show ages between 664 Ma and 566 ± 8 Ma (Blanco et al., 2009), respectively, and further supports an Ediacaran age for the whole group. According to Gaucher et al. (2009), biostratigraphic data also point to an upper Ediacaran age for the lower and middle Arroyo del Soldado Group, and a lowermost Cambrian age for the Cerro Victoria Formation. In this regard, the organic-walled microfossils identified and the occurrence of the upper Ediacaran index fossil *Cloudina* would appear to support an Ediacaran age (<550 Ma). The same authors also proposed that the presence of a low-diversity stromatolite community and a low-diversity trace fossil association (*Thalassinoides* – *Gyrolithes* – *Palaeophycus* assemblage) suggests a lowermost Cambrian age (541–535 Ma) for the Cerro Victoria Formation. Therefore, the Precambrian–Cambrian boundary would be within the Cerro Victoria Formation or, alternatively, in the Cerros San Francisco Formation; both units still being part of the Arroyo del Soldado Group according to Gaucher et al. (2009). Recently, Aubet et al. (2012, 2013) provided new K–Ar ages from diagenetic illite and proposed a minimum age of 600–580 Ma for the uppermost Yerbal Formation. These authors also challenged some of the geochronological constraints presented by Gaucher et al. (2009) and suggested that the *Cloudina* material

was so poorly preserved that their identification as fossil material remains uncertain.

2.2. Maldonado Group

The Maldonado Group was formally erected by Pecoits et al. (2004) to include the Playa Hermosa Formation (Elizalde, 1979; Preciozzi et al., 1989; Masquelin and Sánchez Bettucci, 1993) and Las Ventanas Formation (Midot, 1984). Given its structural, chronostratigraphic and lithologic attributes, the San Carlos Formation was informally included in the group (Pecoits et al., 2004, 2008). Masquelin and Sánchez Bettucci (1993) described the main sedimentological features of the Playa Hermosa Formation. Pazos et al. (2003) characterized in detail the lower part of this unit and recognized two distinct facies associations: (i) medium- to coarse-grained facies (consisting of interbedded breccias, conglomerates, sandstones and minor mudstones), and (ii) fine-grained facies (composed mostly of mudstones but also diamictites, rhythmites and sandstones). The authors concluded that both facies associations accumulated in a sub-aqueous glacially influenced marine environment and represent a proximal to distal depositional trend. Pazos et al. (2003) further suggested that this glacially-influenced succession constitutes a record of the Varanger glaciation.

Midot (1984) erected the Las Ventanas Formation to include conglomerates, sandstones and pelites cropping out at Las Ventanas Hill and in the surrounding areas. This unit was considered to be an Ordovician sedimentary sequence (e.g., Midot, 1984; Masquelin and Sánchez Bettucci, 1993). Pecoits (2003a,b) redefined the unit as a Neoproterozoic (ca. 580 Ma) volcano-sedimentary succession. These deposits were interpreted as a product of sheetflood-dominated fan deltas, which were intercalated with minor marine deposits. Pecoits (2003a,b) and Pecoits et al. (2004) reported the presence of organic-walled microfossils and evidence for glacial influence in the lower part of the unit, respectively. Subsequent work showed that the unit continues to the north in the vicinity of Minas (Pecoits et al., 2004, 2008; Gaucher et al., 2008). Blanco and Gaucher (2005) proposed a different lithostratigraphic scheme from that proposed by Pecoits (2003a,b) and reported seven additional species of organic-walled microfossils (acritarchs).

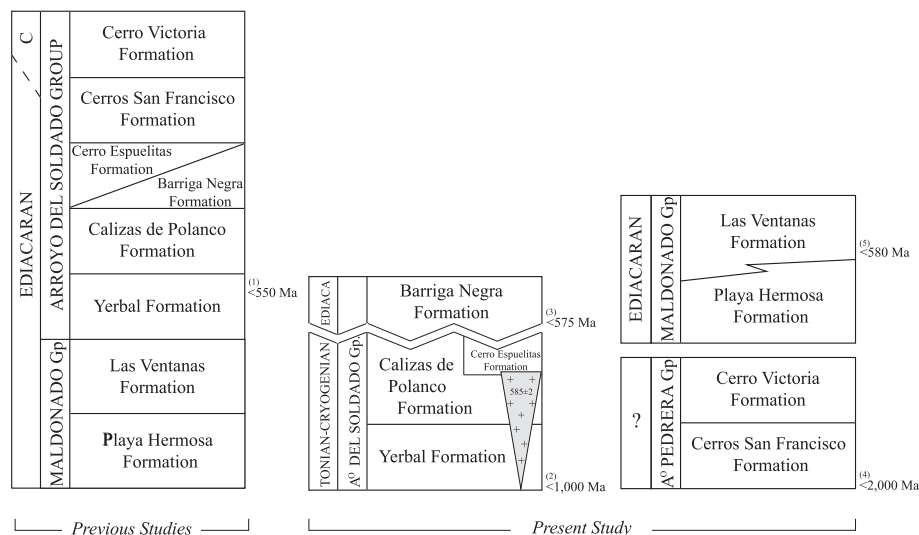


Fig. 2. Lithostratigraphic columns of the Arroyo del Soldado, Arroyo de la Pedrera and Maldonado groups, showing a comparison between the stratigraphy reported in previous studies and in this work (see text for explanation). Chronostratigraphic constraints: (1) *Cloudina*; (2–4) Oldest detrital zircon populations (U–Pb LA–ICP–MS); (5) Volcaniclastic rocks (U–Pb SHRIMP).

The San Carlos Formation (Masquelin, 1990) occurs to the east of the Sierra Ballena Shear Zone but shows characteristics similar to the Las Ventanas Formation. Field relationships suggest a similar geological setting and age for both units (Pecoits et al., 2008). At the stratotype, the succession consists of interbedded conglomerates, sandstones and pelites, with the latter dominating up-section. Palynological macerations carried out for the pelites (Pecoits et al., 2004) revealed the occurrence of microfossils similar to those described for the Las Ventanas Formation Pecoits (2003a,b). Pecoits et al. (2004, 2008) indicated that further research was needed to resolve whether both units are the same or were deposited in the same basin that was subsequently dismantled by the displacement of the Sierra Ballena Shear Zone (Fig. 3).

2.3. Rocha formation

This unit was originally defined as the Rocha Group by Hasui et al. (1975), but Sánchez Bettucci and Mezzano (1993) proposed a formation rank. The succession comprises a lower unit dominated by chlorite phyllite and minor graphitic phyllite, and an upper unit

of bedded meta-sandstones with minor meta-siltstones. It has been inferred that the group formed in a platformal marine-shelf environment, with the basin deepening eastwards (Sánchez Bettucci and Mezzano, 1993).

Granites from the basement yielded a maximum age of 762 ± 8 Ma (SHRIMP, U–Pb; Hartmann et al., 2002), while the minimum age was given by post-tectonic alkaline granite bodies in the region (e.g., Santa Teresa Granite; Fig. 3). According to Basei et al. (2005), sedimentation took place between ca. 600 Ma, as indicated by the youngest detrital zircon grains, and ca. 550 Ma, the onset of post-tectonic alkaline magmatism. Based on their similar lithologies, comparable tectonic setting and the detrital zircon age patterns, Basei et al. (2005) further suggested that the Oranjemund Group (Namibia) and the Rocha Formation are time equivalents, and probably represent sediment fill of the same basin.

2.4. Sierra de Aguirre Formation

Bossi (1966) first described this sedimentary succession dominated by sandstones and pelites. Masquelin and Tabó

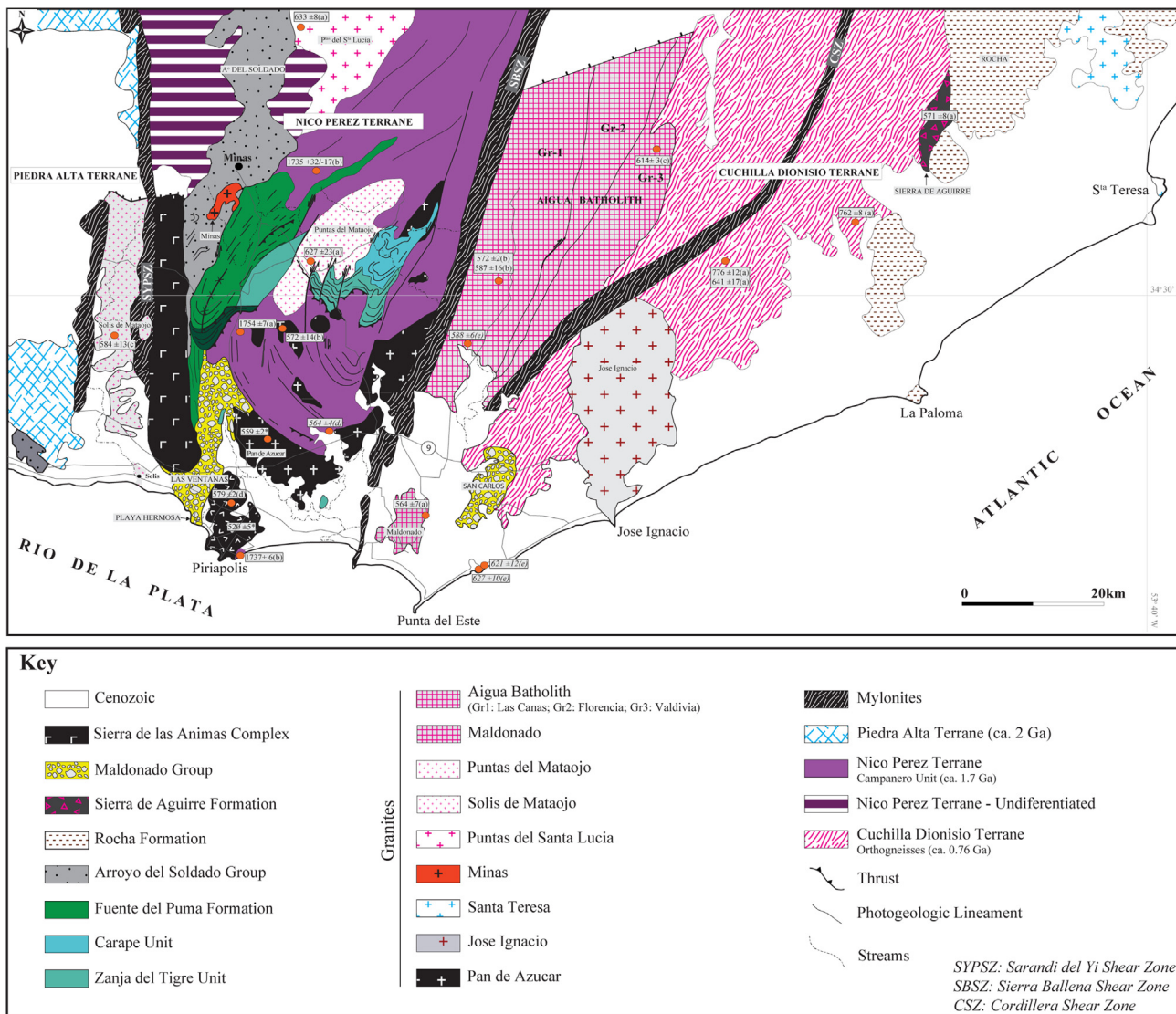


Fig. 3. Geologic map of southeastern Uruguay showing published geochronological data and distribution of Ediacaran volcano-sedimentary units: Arroyo del Soldado and Maldonado groups, and San Carlos, Sierra de Aguirre and Rocha formations. Modified from Oyhançabal (2005), Oyhançabal et al. (2009) and Pecoits et al. (2011).

(1988) later defined it as the Sierra de Aguirre Formation and interpreted this unit as a marine sedimentary succession consisting of pelites, sandstones and pyroclastic rocks intruded by rhyolite dykes. By contrast, [Campal and Schipilov \(2005\)](#) described the unit as composed of volcanic and pyroclastic rocks, including rhyolite, trachyte, ignimbrite of rhyodacitic composition, and laminated tuff. [Fantin \(2003\)](#) reported 110 m thickness for the unit in the southern part of the type area and recognized volcanic, sub-volcanic and epiclastic rocks. In its lower part, the succession is dominated by volcanic deposits, whereas, in the upper part, sedimentary deposits are more common. Depositional environments correspond to shallow-marine and deltaic settings ([Fantin, 2003](#)) of a pull-apart basin ([Campal and Schipilov, 2005](#)). The contact with the basement (to the west) is unconformable and with the Rocha Formation (to the east) is tectonic ([Fig. 3](#)). A dacite yielded a SHRIMP U–Pb concordia age of 571 ± 8 Ma ([Hartman et al., 2002](#)). This age is similar to that obtained further to the north for acidic volcanic rocks of the Sierra de Ríos Formation at 575 ± 14 Ma ([Bossi et al., 1993](#)), which indicates an extensive volcanic activity at that time.

2.5. Tacuarí Formation

The Tacuarí Formation was erected by [Veroslavsky et al. \(2006\)](#). It comprises basal diamictites, sandstones and minor pelites that grade upwards into fine-grained rhythmites which contain abundant out-sized clasts. The latter, interpreted as dropstones, along with diamictites hosting faceted and striated clasts and associated varved sediments, provide definitive evidence for the glacial origin of these deposits. Although the Tacuarí Formation was long considered Carboniferous–Permian in age (formerly San Gregorio Formation), U–Pb zircon ages (LA-MC-ICP-MS and SHRIMP) obtained for a cross-cutting granitic dyke places a minimum age of the unit to 585 ± 3 Ma ([Pecoits et al., 2012a,b](#)). A maximum depositional age for the Tacuarí Formation is 600 ± 9 Ma, based on the youngest detrital zircon age cluster reported ([Pecoits et al., 2012a,b](#)). Significantly, metazoan trace fossils occur within the uppermost fine-grained rhythmites. This new discovery provides evidence for bilateral burrows from shallow-water sediments that are at least 30 million years older than previously reported trace fossils ([Pecoits et al., 2012a,b](#)). Although [Gaucher et al. \(2013\)](#) questioned the age of these trace fossils, [Pecoits et al. \(2013\)](#) presented new evidence further supporting an age between 585 ± 3 and 600 ± 9 Ma.

3. Stratigraphy of the Ediacaran in Uruguay

For the units briefly described above, the following discussion will focus on the Arroyo del Soldado and Maldonado groups. Both are regarded as important for unraveling critical aspects of the Ediacaran Period and are the subject of controversy in terms of their lithostratigraphy, age and geological setting.

3.1. Arroyo del Soldado Group

3.1.1. Lithostratigraphy

The Arroyo del Soldado Group (*sensu* [Gaucher et al., 1998](#)) includes, from base to top, Yerbal, Polanco Limestones, Cerro Espuelitas, Barriga Negra, Cerros San Francisco and Cerro Victoria formations ([Fig. 2](#)). In other lithostratigraphic schemes, the group would include all those units with the exception of the Cerros San Francisco and Cerro Victoria formations ([Pecoits et al., 2008](#); [Aubet et al., 2012](#)). This redefinition is based on the absence of a

conformable contact between the Cerro Espuelitas and the Cerros San Francisco formations (see discussion on the Arroyo Mangacha granite below). Therefore, following the original name proposed by [Montaña and Sprechmann \(1993\)](#), the Arroyo de la Pedrera Formation (composed of the Cerros San Francisco and the Cerro Victoria units) was elevated to group status and separated from the Arroyo del Soldado Group ([Pecoits et al., 2008](#)).

3.1.1.1. The Barriga Negra Formation. Recently, [Frei et al. \(2013\)](#) suggested that the Barriga Negra Formation represents the base of the Arroyo del Soldado Group and not its middle part as was previously accepted. This change was challenged by [Aubet et al. \(2013\)](#) who questioned the rationale of relocating strata previously bracketed between two distinct units ([Fig. 2](#)), the Polanco Limestones and Cerro Espuelitas formations with their respective upper and lower contacts exposed and described ([Gaucher, 2000](#); [Gaucher et al., 1998, 2004, 2008](#); [Gaucher and Poiré, 2009b](#); [Blanco et al., 2009](#); [Frei et al., 2011](#)), to a lower stratigraphic position. The only argument presented by [Frei et al. \(2013\)](#) to justify this change in the lithostratigraphy is the apparent resetting (values were not shown) of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Isotopic ratios, however, are not considered as a basis for lithostratigraphic subdivision ([Murphy and Salvador, 1999](#); [NACSN, 2005](#)). Furthermore, the alteration of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in this unit is not rare. As shown by [Aubet et al. \(2012\)](#), even the stratotype of the Polanco Limestones Formation displays Sr isotopic values that have been heavily overprinted.

There is a number of compelling arguments that support that the Barriga Negra Formation overlies the Polanco Limestones Formation, namely: (i) clasts of the Polanco Limestones Formation have been described and illustrated within the Barriga Negra Formation ([Preciozzi, 1988](#); [Preciozzi et al., 1988](#); [Fambrini et al., 2005](#)); (ii) there are incised valleys in the Polanco Limestones Formation that are infilled with Barriga Negra breccias and conglomerates ([Gaucher et al., 2004](#)), and (iii) the contact between units is traceable and observable for several kilometers in the field, mainly in the type area of the Polanco Limestones Formation ([Fragoso-Cesar et al., 1987](#); [Preciozzi, 1988](#); [Preciozzi et al., 1988](#); [Gaucher, 2000](#); [Fambrini et al., 2005](#)).

Recent geological mapping in the area support these observations and, more importantly, revealed an angular unconformity between these units (see [Fig. 4](#)). Although this observation is not new (see references below), it has largely been ignored and inevitably led to a reevaluation of the lithostratigraphy of the Arroyo del Soldado Group. [Fragoso-Cesar et al. \(1987\)](#) originally suggested that the Barriga Negra Formation rests unconformably on marbles of the Polanco Limestones Formation and on the Polanco Granite. [Preciozzi \(1988\)](#) later indicated an angular discordance between these units while mapping the area, confirming previous observations by [Fragoso-Cesar et al. \(1987\)](#). It is worth noting that the lithological attributes and diagnostic features of the Polanco Limestones Formation are unique, which has permitted its separation since the original definition by [Goñi and Hoffstetter \(1964\)](#). This stratigraphic relationship has been accepted by all the researchers working in the area (e.g., [Fragoso-Cesar et al., 1987](#); [Preciozzi et al., 1988](#); [Preciozzi, 1988](#); [Bossi et al., 1998](#); [Gaucher, 2000](#); [Fambrini et al., 2005](#); [Pecoits et al., 2008](#)). Therefore, it is clear that the Polanco Limestones Formation underlies the Barriga Negra Formation. The existence of an unconformity is not only supported by field relationships ([Fig. 4](#)), but also by detrital zircon geochronology for the Barriga Negra Formation (see below).

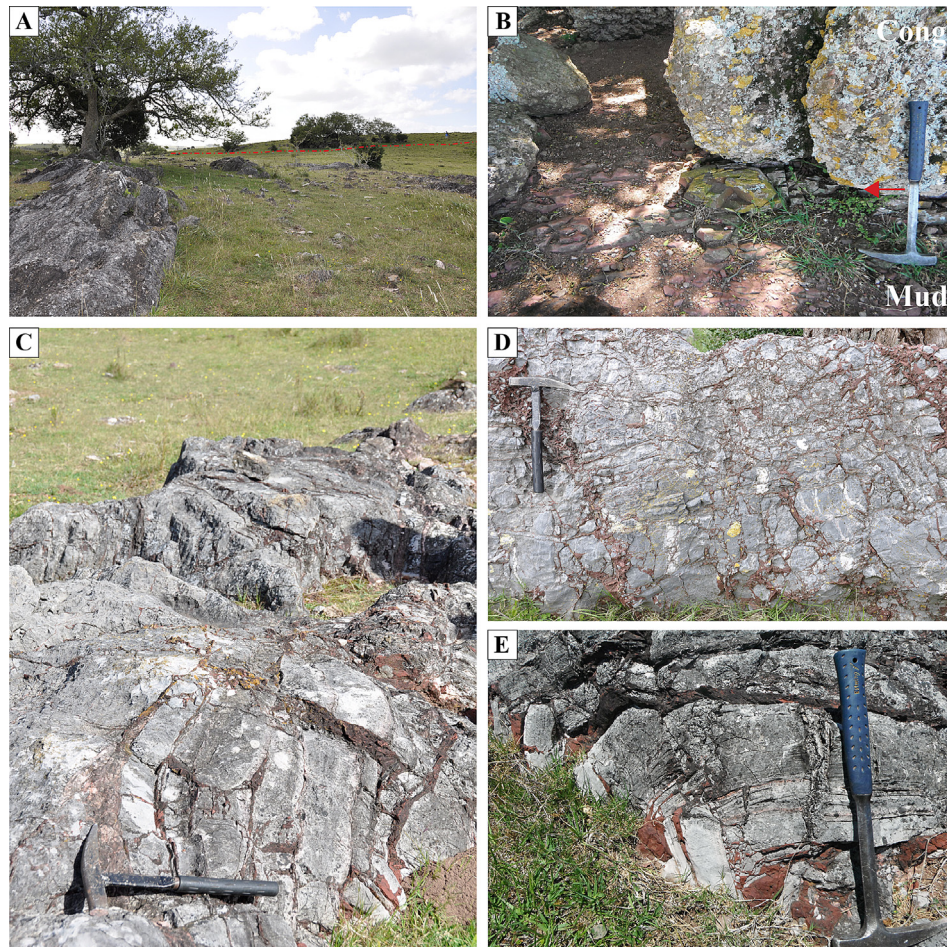


Fig. 4. Field photographs showing some features of the angular, erosional unconformity between the Polanco Limestones Formation and the overlying Barriga Negra Formation (outcrop location: type area of the Polanco Limestones Formation, NE of Polanco village). (A) General view of the outcrop (looking east). The red dashed line indicates location of the unconformity between the underlying and folded (nearly vertical) sedimentary layers of the Polanco Formation and the overlying slightly tilted (nearly horizontal) strata of the Barriga Negra Formation. (B) Lowermost strata of the Barriga Negra Formation. Note the almost horizontal (dip about 5–10° to the east) bedding plane of the basal red mudstone (Mud) and its contact (red arrow) with heterolithic pebble conglomerate (Cong). (C) Upright beds of the Polanco Limestones Formation, dipping ca. 85° to the south, showing evidence of paleo-karst features near the unconformity surface. Paleo-karst cavities have been extensively infilled with red mudstones of the overlying Barriga Negra Formation. (D–E) Detailed views of outcrop surfaces with visible paleo-karst features, including solution features, breccias, collapse structures and extensive infill along bedding planes and fractures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1.2. Age

3.1.2.1. Geochronology

3.1.2.1.1. Basement

Arroyo Mangacha Granite

The Arroyo Mangacha Granite is undeformed, porphyritic, and composed of quartz (40%), orthoclase (38%), oligoclase (17%) and biotite (5%), with accessory microcline, titanite, zircon and opaque minerals (Gaucher et al., 2008). This intrusion is part of the Barriga Negra batholith defined by Preciozzi et al. (1988), which is characterized by pink, leucocratic, fine to coarse-grained granites, and is considered to be part of a suite of late- to post-tectonic granites (Fig. 1). Gaucher et al. (2008) reported a U–Pb SIMS zircon age of 583 ± 7 Ma for this granite and concluded that this age represents the best maximum depositional age constraint available for the Arroyo del Soldado Group because the Cerros San Francisco Formation rests unconformably on this granite.

Although small, the area mapped by Gaucher et al. (2008; their Fig. 9) is crucial for two reasons. First, it potentially provides the maximum age constraint for the Arroyo del Soldado Group (i.e., the dated granite). Second, it shows the relationship between three different lithostratigraphic units, namely, (i) a carbonate-

siliciclastic succession, (ii) sandstones of the Cerros San Francisco Formation, and (iii) the Arroyo Mangacha Granite. Although now considered part of the basement of the Arroyo del Soldado Group by Gaucher et al. (2008, 2009) and Frei et al. (2013), the carbonate-siliciclastic unit was previously thought to be part of the Cerro Espuelitas Formation (Arroyo del Soldado Group) and considered conformable with the overlying sandstones of the Cerros San Francisco Formation (Gaucher, 2000; his Fig. 27). Importantly, this is one of three outcrops where the Cerro Espuelitas Formation was considered to be conformable with the Cerros San Francisco Formation. The second outcrop is located at the stratotype of the Cerro Espuelitas Formation (Gaucher et al., 1996; their Fig. 4). However, as with the first area, it was later recognized that such continuity does not exist (Gaucher, 2000; his Fig. 17). The third outcrop is located in the Cerro Carreras (Gaucher, 2000; his Fig. 24). At this location, the iron formation assigned to the Cerro Espuelitas Formation is interpreted to be conformable with sandstones of the Cerros San Francisco Formation (Gaucher, 2000). However, the iron formations at Cerro Carreras are discordant with the sandstones. In turn, the iron formations are conformable with pink marbles, tourmaline-bearing quartzites and micaceous quartzites. All these lithologies

belong to the metamorphic (amphibolite facies) basement (Las Tetras Complex of Hartmann et al., 2001). The same conclusion was reached by Campal and Schipilov (1998; their Fig. 13). Furthermore, the Cerro Espuelitas Formation does not contain iron formations (Pecoits et al., 2008; Pecoits, 2010).

This stratigraphic issue was acknowledged by Pecoits et al. (2008) who proposed a new stratigraphic scheme whereby the Cerros San Francisco Formation and the overlying Cerros Victoria Formation were removed from the Arroyo del Soldado Group (Pecoits et al., 2008; their Fig. 2). Therefore, the relationship between the sandstones of the Cerros San Francisco Formation and the Arroyo Mangacha granite cannot be used to constrain the age of the Arroyo del Soldado Group (see also Aubet et al., 2013). In addition, the unconformity between the granite and the sandstones is not observed in the field, which is not surprising given the lack of zircons younger than ~2.19 Ga in these sandstones (Gaucher et al., 2008).

Puntas del Santa Lucía Pluton

The leucocratic granodiorite is pale pink, medium- to coarse-grained, and composed of quartz (40%), plagioclase (45%) and orthoclase (14%), with accessory biotite, opaque minerals and apatite (Bossi et al., 1998). This batholith forms part of the late- to post-tectonic Arroyo del Soldado Granitic Complex defined by Preciozzi et al. (1988), which includes a number of calc-alkaline granites and granodiorites (Figs. 1 and 3). The intrusion exhibits cataclastic and microgranular textures (Bossi et al., 1998; Preciozzi et al., 1988). Extensive field work did not reveal any unit of the Arroyo del Soldado Group resting unconformably on the granodiorite (Aubet et al., 2013). Only sandstones of the Cerros San Francisco Formation, which belongs to the Arroyo de la Pedrera Group (as explained above), are in contact with the granodiorite. Moreover, this contact is tectonic, as previously reported by Gaucher et al. (1996) and Bossi et al. (1998). Despite both of these observations, Gaucher et al. (2004) suggested that this batholith is part of the basement of the Arroyo del Soldado Group, and thus it can be used to constrain the maximum depositional age of the group. The dated sample is a medium-grained and equigranular monzogranite, composed of quartz (35%), plagioclase (34%), microcline (20%), hornblende (6%), biotite (3%), and accessory opaque minerals, zircon and apatite, and yielded a zircon SHRIMP U–Pb emplacement age of 633 ± 8 Ma (Hartmann et al., 2002). Detrital zircon analysis of the Yermal and Cerros San Francisco formations did not yield any zircon population younger than ca. 1000 Ma (see discussion on detrital zircons and diagenetic clays below). Therefore, the Puntas del Santa Lucía Pluton shows neither field nor geochronological evidence of being older than the Arroyo del Soldado Group.

3.1.2.1.2. Intrusives. There are several granites intruding the Arroyo del Soldado Group (Preciozzi et al., 1988 and references therein), including (i) Minas, (ii) de los Guazunambí, (iii) Polanco, (iv) Yermal, and (v) Sobresaliente (Figs. 1 and 3). Some of them have been dated but using different, including Rb–Sr, geochronological methods. The Guazunambí and Polanco granites yield Rb–Sr isochron ages of 532 ± 11 and 548 ± 11 Ma, respectively (Kawashita et al., 1999; Umpierre and Halpern, 1971). SHRIMP U–Pb zircon dating of the Sobresaliente granite yielded an age of 585 ± 2 Ma (Oyhantjabal et al., 2012), and thus constitutes the minimum age constraint for the Arroyo del Soldado Group (Fig. 2). This minimum age is further supported by K–Ar ages of diagenetic illites from the uppermost Yermal Formation (see below).

3.1.2.1.3. Detrital zircons and diagenetic clays

Detrital Zircons

A total of six samples for detrital zircon analysis were analyzed by Gaucher et al. (2008) and Blanco et al. (2009) using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Detrital age spectra from the Barriga Negra Formation (one sample, 34 detrital zircons) revealed four major peaks: (a) Mesoarchean (2890–3155 Ma), (b) Paleoproterozoic (2157–2284 Ma and 1795–1723 Ma), and (c) Neoproterozoic (631–566 Ma) (Blanco et al., 2009). Thus, the youngest detrital zircon age (566 ± 8 Ma) has been used to constrain the maximum depositional age for the Barriga Negra Formation.

The Piedras de Afilar Formation (one sample, 91 detrital zircon grains) showed a polymodal age distribution with mainly Mesoproterozoic and Paleoproterozoic ages. They are as follows; (a) a dominant Mesoproterozoic population with four distinct peaks at 1009, 1242, 1347 and 1487 Ma; (b) a Paleoproterozoic population with peaks at 2005–2068 Ma and 1779–1876 Ma, and (c) a single zircon with an Archean age of 2890 Ma (Gaucher et al., 2008). Accordingly, the maximum age of this formation is 1009 Ma.

Two samples were analyzed from the Yermal Formation. One sample (92 detrital zircon grains) yielded an essentially unimodal age mode centered at 2450 Ma, two grains have an age of 2044 Ma, and five grains were dated between 2895 and 2662 Ma (Gaucher et al., 2008). The second sample (28 zircon grains) showed a predominance of Paleoproterozoic ages ranging from 1898 to 2220 Ma, but also has a significant Late Mesoproterozoic cluster (1009–1063 Ma). The oldest zircon population is of Mesoarchean age (3027 Ma), the youngest, and the only Neoproterozoic-aged zircon, is dated at 664 Ma (Blanco et al., 2009). The latter age is statistically insignificant and was not observed in any other sample from the Yermal Formation, and thus it should be viewed with caution.

Two samples were analyzed from the Cerros San Francisco Formation. One sample (86 detrital zircon grains) showed a polymodal distribution, with mainly Archean and Paleoproterozoic ages. Two prominent Archean peaks were recognized, one double peak at 2778–2715 Ma and a minor one between 3225 and 3045 Ma. The younger Paleoproterozoic cluster occurs at 2188 Ma (Gaucher et al., 2008). The other sample (39 detrital zircon grains) displayed a predominance of Paleoproterozoic sources in the age range of 1990–2122 Ma, along with zircon grains derived from Archean rocks. One single zircon showed a Neoproterozoic age (605 Ma) (Blanco et al., 2009). Similar to the sample from the Yermal Formation with a single Neoproterozoic zircon, this youngest zircon age from the Cerros San Francisco Formation should be treated with caution.

When age spectra for both samples of the Cerros San Francisco are compared, they show a similar range of ages between 1990 and 3551 Ma, and only slight differences in the size of the peaks are observed. Crucially, the sample that does not show the Neoproterozoic zircon was taken proximal to the 583 ± 7 Ma-old Arroyo Mangacha granite. As mentioned above (see Arroyo Mangacha section), this observation further supports the fact that this Ediacaran granite is not the basement for the sandstones and as such, the sandstones must be older than the granite. This is not surprising when considering that extensive magmatism (granite intrusions and felsic volcanism) is recorded in the entire region between ca. 570 and 640 Ma (see Figs. 1, 3 and 5) and is not represented as a detrital zircon population either in the sandstones of the Cerros San Francisco and Piedras de Afilar formations or in the Yermal Formation (Arroyo del Soldado Group). Conversely, the Barriga Negra Formation records this magmatism, particularly between 570 and 600 Ma, which confirms its younger age than that for other units. Therefore, we suggest the following maximum age constraints for these units: Barriga Negra Formation: 566 ± 8 Ma; Yermal Formation: 1009 Ma; Cerros San Francisco Formation: 1990 Ma; and Piedras de Afilar Formation: 1009 Ma (Fig. 5).

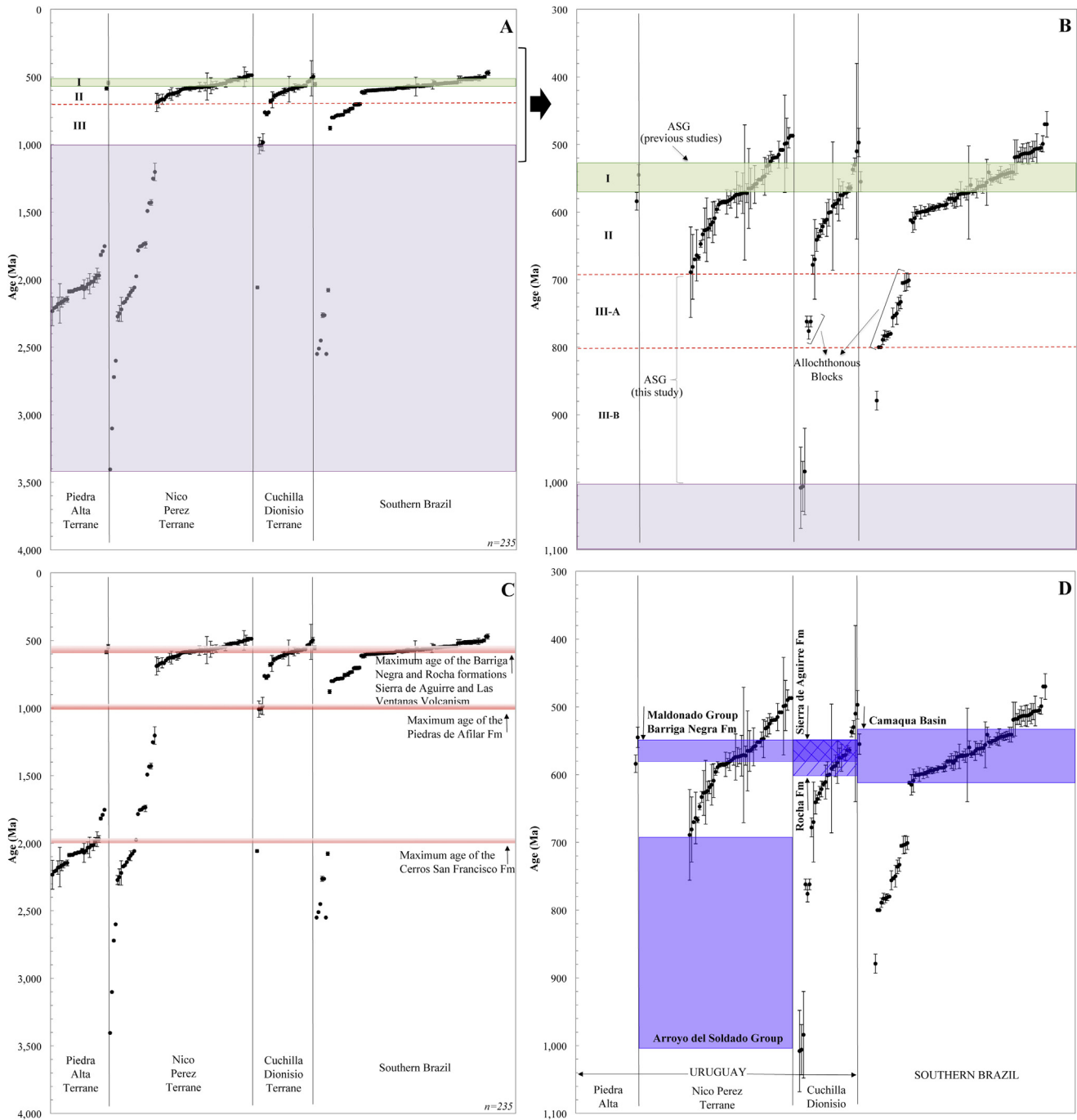


Fig. 5. Compilation of radiometric ages and their error bars measured for intrusive and volcanic rocks from Uruguay and southernmost Brazil (n = sample size). The Uruguayan portion comprises three main units: Piedra Alta, Nico Pérez and Cuchilla Dionisio Terranes, while the Brazilian side comprises the Sul-Rio-Grandense Shield with its four main blocks: Taquarém, São Gabriel, Santana da Boa Vista and Pelotas (see Fig. 1). (A–B) There exist time periods during the evolution of these crustal blocks that are characterized by either intense magmatic activity or magmatic quiescence. Particularly important are the periods during approximately (1) 530 and 570 Ma, (2) 570 and 700 Ma, and (3) 700 and 1000 Ma; identified in Figs. A and B with the symbols I, II and III, respectively. The first period (ca. 530–570 Ma) is defined by the deposition of the Arroyo del Soldado Group (ASG), as suggested by previous studies, but also by an important magmatic activity in all the tectonic blocks. The voluminous magmatism recorded within this interval (25% of the radiometric ages plotted) contradicts the idea of an Atlantic-type passive margin for the deposition of the unit. The second period (ca. 570–700 Ma) is also characterized by important magmatic activity. Although 27% of the data plotted correspond to this interval, no detrital zircons of this age are found within the Arroyo del Soldado Group. Therefore, it is very unlikely that the Arroyo del Soldado Group had been deposited during the Ediacaran, either during period I or II of Figures A and B (i.e., between 700 and 530 Ma). The third period (ca. 700–1000 Ma) is characterized by magmatic quiescence in the Nico Pérez Terrane, where we propose the Arroyo del Soldado Group occurs. The beginning of this interval coincides with the youngest detrital zircon ages (i.e., maximum age) reported for the Arroyo del Soldado Group (1000 Ma). The upper part of this period reflects: (i) the oldest Neoproterozoic magmatic ages recorded in the Nico Pérez Terrane (ca. 700 Ma; Period III-A of Fig. B), and (ii) the oldest magmatic Neoproterozoic ages recorded in the Cuchilla Dionisio “Terrane” and Southern Brazil (ca. 800 Ma; Period III-B of Fig. B). Therefore, the deposition of the Arroyo del Soldado Group took place sometime between 1000 and 700 Ma. The absence of zircons sourced from the allochthonous blocks, with ages between 700 and 800 Ma, suggests that either these blocks were located far oceanward from the Arroyo del Soldado Basin or that the group is even older; i.e., deposited between ca. 800 and 1000 Ma. (C) Maximum ages for the Cerros San Francisco and Piedras de Afilar formations (Arroyo de la Pedrera Group) and Barriga Negra Formation, which have been removed from the Arroyo del Soldado Group (see text for explanation). (D) Synthetic chronostratigraphic chart showing volcano-sedimentary Neoproterozoic units (shaded rectangles) from Uruguay and their correlatives in Southern Brazil. The Arroyo del Soldado Group, including the Yerbal, Polanco Limestones and Cerro Espuelitas formations, was deposited between 1000 and 700 Ma. The Maldonado Group s.l. (Playa Hermosa, Las Ventanas and San Carlos formations) was deposited between 590 and 550 Ma and overlaps with the Sierra de Aguirre Formation (590–550 Ma) and the Rocha Formation (ca. 600–550 Ma). The age of the Arroyo de la Pedrera Group cannot be firmly established, but the available data would suggest a similar age to the Arroyo del Soldado Group. Data sources: Borba and Mizusaki (2003), Oyhançabal (2005), Saalman et al. (2011), Oyhançabal et al. (2012), Janikian et al. (2012), and references therein.

Diagenetic clays

K–Ar ages of diagenetic illites from the uppermost Yerbal Formation were presented by Pecoits (2010) and Aubet et al. (2012), where the authors used the most conservative maximum age estimate for the Arroyo del Soldado Group as suggested by Gaucher et al. (2004); i.e., 633 ± 8 Ma (Puntas del Santa Lucía pluton). Even in this case, the Ar diffusion calculations clearly indicate a minimum age of 600–580 Ma for the uppermost Yerbal Formation (see also Aubet et al., 2013).

3.1.2.2. Biostratigraphy. Another age constraint is based on the purported presence of the index fossil *Cloudina* (Gaucher, 2000). The apparent discovery of *Cloudina* in the uppermost Yerbal Formation (Gaucher, 2000, 2003, 2004) deserves special attention because it is the only potential fossil that can provide precise stratigraphic constraint (for discussion see Pecoits et al., 2008; pp. 710). The wide geographic distribution and geochronologically calibrated stratigraphic occurrences, between 549 ± 1 and 542 ± 1 Ma, make *Cloudina* an excellent index fossil for the biostratigraphic subdivision of the Ediacaran System (Grotzinger et al., 1995; Saylor et al., 1998; Martin et al., 2000; Amthor et al., 2003; Knoll et al., 2004; Hua et al., 2005). Therefore, its occurrence would indicate a maximum age of 550 Ma for the overlying Polanco Limestones Formation. However, the occurrence of *Cloudina* in Uruguay poses some peculiarities (see for example Aubet et al., 2013). First, considering the radiometric data available (see below) the presence of *Cloudina* would be at least 40 Ma older than any *Cloudina* reported before (Hua et al., 2005) and its temporal span would be four times longer, which seems very unlikely for what is considered an index fossil of the late Ediacaran Period. Second, *Cloudina* was only reported unambiguously from one single small (5 m²) outcrop of the Yerbal Formation (Gaucher, 2000; his Fig. 10) and repeated sampling of the *Cloudina*-hosting bed (4 cm thick) by other researchers never yielded any well-preserved and unambiguous *Cloudina* fossil (outcrop coordinates: 32°48'12" S, 54°26'16" W). Third, the same few specimens repeatedly illustrated by Gaucher (2000), Gaucher et al. (2003, 2004) and Gaucher and Poiré (2009) are poorly preserved, and even the original carbonate shell was apparently dissolved and replaced by iron-oxides or silica (Gaucher, 2000). This is an unusual mode of preservation for *Cloudina*, which typically occurs in large population densities, and not as sparse individuals as reported above. Fourth, the stratigraphic range of *Cloudina* postdates the Shuram(–Wonoka–Johnnie) $\delta^{13}\text{C}$ excursion worldwide (e.g., Hua et al., 2005; Verdel et al., 2011), and thus the occurrence of *Cloudina* in the upper Yerbal Formation is inconsistent with an inferred Shuram excursion (>551 Ma) for the negative $\delta^{13}\text{C}$ anomaly of Polanco Limestones Formation (cf. Gaucher et al., 2009). Therefore, in the absence of further confirmation for the presence of *Cloudina* in Uruguay, its 'occurrence' must be regarded as equivocal.

A further complication is that the acritarchs reported for the whole group have no stratigraphic significance. Some of them have been reported in strata ranging from Mesoproterozoic to Silurian and others were shown to be contaminants. As an example, one of the dominant species (*Leiosphaeridia*) reported in the Arroyo del Soldado Group is common even in Mesoproterozoic strata (Javaux et al., 2001, 2004). Other species (e.g., *Soldadophycus*) have only been described by the same authors (Gaucher et al., 2009). In fact, Gaucher et al. (1996) reported a list of more than 30 species of organic-walled microfossils, many of which the authors regarded as stratigraphically important. However, in Gaucher (2000), 80% of these specimens turned out to be contaminants.

Finally, the occurrence of the *Thalassinoides* – *Gyrolithes* – *Palaeophycus* assemblage described by Sprechmann et al. (2004) has no stratigraphic implication for the Arroyo del Soldado Group because they occur in the Cerro Victoria Formation (Arroyo de la Pedrera Group). Based on these trace fossils the authors placed the Cerro Victoria Formation in the lowermost Cambrian (541–535 Ma). However, the illustrated structures resemble diagenetic concretions of inorganic origin (Pecoits et al., 2008).

3.1.3. C- and Sr-Chemostratigraphy

As highlighted by Melezhik et al. (2001), $\delta^{13}\text{C}_{\text{carb}}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values cannot be used with confidence for 'blind dating' without independent geochronologic support. It is even more problematic when considering local $\delta^{13}\text{C}_{\text{carb}}$ variations that may have nothing to do with global fluctuations. Both problems are applicable to the Polanco Limestones Formation and have added more inconsistencies with regard to the age of the entire group. Although Gaucher (2000) assigned the entire Arroyo del Soldado Group to the Kotlin horizon (550–542 Ma) of the East European Platform (mainly based on the occurrence of *Cloudina* and the acritarch assemblage), a Valdai age (>570–542 Ma) was later suggested using C- and Sr-isotopic data (Gaucher et al., 2003). Subsequently, based on exactly the same Sr-isotopic data, Gaucher et al. (2004) assigned an age of 580 Ma for the base of the Polanco Limestones Formation. The latter two ages, however, are in clear contradiction with the presence of *Cloudina* in the underlying Yerbal Formation (see above). This inconsistency was recognized by Pecoits et al. (2008) who highlighted that the mineralized metazoan *Cloudina* occurs between 550 and 540 Ma (Grotzinger et al., 1995; Saylor et al., 1998; Martin et al., 2000; Knoll et al., 2004; Hua et al., 2005). Hence, and following the report of *Cloudina* by Gaucher et al. (2000, 2003; 2004) in the uppermost Yerbal Formation, Pecoits et al. (2008) proposed a maximum age of ca. 550 Ma for the overlying Polanco Limestones Formation.

Despite the 580 Ma age assigned by Gaucher et al. (2004) to the Polanco Limestones Formation, Gaucher and Poiré (2009) correlated the most negative C-isotope shift in this unit with those reported in Oman (Shuram Formation), Namibia (Nama Group), China (Doushantuo Formation), Australia (Wonoka Formation) and USA (Johnnie Formation) at ~551 Ma (Condon et al., 2005, and references therein). Although no glacial conditions have been associated with the Shuram–Wonoka–Johnnie anomaly elsewhere (Cozzi et al., 2004; Le Guerroué, 2010; Swanson-Hysell et al., 2010), a glacially-related interpretation of the $\delta^{13}\text{C}$ drop in the Polanco Limestones Formation was suggested by Gaucher et al. (2009). Aubet et al. (2012, 2013) presented arguments negating a correlation with the Shuram–Wonoka–Johnnie and instead concluded that the negative excursion recorded in the Polanco Limestones Formation is facies-controlled and only occurs in shallow-water strata associated with storm events. It thus appears more likely to be a local rather than a basin-wide phenomenon. Furthermore, the Shuram anomaly can be clearly distinguished from other Neoproterozoic anomalies due to its amplitude ($\delta^{13}\text{C}_{\text{carb}} < -10\text{‰}$) and duration as reflected by its persistence for several hundreds of meters (~700 m) in several sections worldwide (Le Guerroué et al., 2006; Halverson et al., 2010). The carbonates from the Polanco Limestones Formation, however, fall into the higher range (i.e., $> -5\text{‰}$), and unlike the rapid onset of the Wonoka anomaly, the Polanco negative excursion at the Recalde section defines a rather gradual trend that persists for no more than 250 m. Furthermore, a $\delta^{13}\text{C}_{\text{carb}}$ excursion of the magnitude and duration of the Shuram–Wonoka anomaly, thought to span between 20 and 50 Ma (Le Guerroué, 2010),

should be noticed in different portions of the shelf above the pycnocline. The new stable isotope data and radiometric ages presented by Aubet et al. (2012) do not support the age suggested by Pecoits et al. (2008) for the Polanco Limestones Formation either, which, as mentioned above, was mainly based on the report of the index fossil *Cloudina* by Gaucher et al. (2000, 2003; 2004). Aubet et al. (2012) inferred a depositional age of ca. 590 Ma for the lower Polanco Limestones Formation. However, this age is also problematic because it took into consideration a maximum age of 633 ± 8 Ma (Puntas del Santa Luc  a pluton) for the Arroyo del Soldado Group, which is highly controversial as discussed above.

3.1.4. Geological setting

The Arroyo del Soldado Group is thought to have been deposited on either a stable, Atlantic-type continental shelf (Gaucher, 2000; Gaucher et al., 2004) or in a foreland basin (Basei et al., 2000; Pecoits et al., 2004, 2008; Sanchez Bettucci et al., 2010; Aubet et al., 2012). This contradiction is mainly rooted in the upper Ediacaran–lowermost Cambrian age assigned to the succession (Gaucher, 2000, 2004). The stable Atlantic-type continental shelf setting is incompatible with the extensive evidence indicating an extensive tectono–magmatic activity during the Ediacaran in Uruguay and southern Brazil (see Pecoits et al., 2008 p. 711). Widespread magmatism, including volcanic and intrusive units, high-strain transcurrent faults, and very similar volcano–sedimentary successions deposited in strike-slip basins on both sides of the Sierra Ballena Shear Zone indicate an unstable tectonic setting (Figs. 1, 3 and 5). Hence, many authors have proposed that during continental collision (along the Sierra Ballena Shear Zone), the original basin evolved into a foreland basin (Arroyo del Soldado and Arroyo de la Pedrera groups) (e.g., Pecoits and Oyhan  abal, 2004). At first glance, this scenario could satisfactorily explain some of the geochronological data and geological features observed in the region. However, supporting sedimentary evidence indicating a foreland setting for the Arroyo del Soldado Group has remained elusive.

In summary, there is extensive evidence arguing against a stable passive margin setting during the upper Ediacaran–lowermost Cambrian, but there is also no compelling sedimentological evidence supporting a foreland basin setting for this succession. Therefore, two scenarios are conceived here: (i) the age of the Arroyo del Soldado Group is substantially older than assumed, and (ii) convincing evidence for a foreland setting remains to be found. As discussed above, we propose that the first scenario might better explain all the available evidence, but new radiometric ages are needed to confirm this hypothesis.

3.2. Maldonado Group

3.2.1. Lithostratigraphy

The Maldonado Group includes the Playa Hermosa and Las Ventanas formations and consists of mafic and felsic volcanic rocks, pyroclastic rocks, diamictite, sandstone, conglomerate and pelite (Pecoits (2003a,b); Pecoits et al., 2004). Masquelin and Sanchez Bettucci (1993) suggested that both units were deposited in the same basin and that the Las Ventanas Formation was deposited later with the development of alluvial fans sourced from the Sierra de las   nimas Complex, located to the west (Fig. 3). Accordingly, it would be younger than the Playa Hermosa Formation (see also Midot, 1984). Nonetheless this relationship between the Playa Hermosa Formation and Las Ventanas Formation is often difficult to observe in the field due to poor outcrop between the type areas of both units. Furthermore, they show similar facies, which seem to be interlayered. Similarly, the relationship between these two units

and the San Carlos Formation, which was informally included in the group, is not fully understood. Sedimentary facies of the San Carlos Formation are similar to those of the middle Las Ventanas Formation (Pecoits et al., 2008). In this regard, two possible explanations can be drawn. First, the San Carlos Formation is a lateral equivalent to the middle and upper parts of the Las Ventanas Formation, or both units, although broadly contemporaneous, were deposited in different basins.

3.2.2. Age

Pecoits et al. (2004) suggested a depositional age of ca. 600 to 565 Ma for the group (see also Pecoits, 2002, 2003). This interpretation was supported by field relationships and the following geochronological data: (i) hypabyssal rocks of the Sierra de las   nimas Complex (520 ± 5 Ma; Bossi et al., 1993) and the Pan de Az  car Granite (559 ± 28 Ma; Preciozzi et al., 1993) intrude the Las Ventanas Formation; (ii) the Puntas del Pan de Az  car Lineament, which affects the Las Ventanas Formation, has a K–Ar age of 572 ± 7 Ma (Bossi and Campal, 1992); and (iii) Sanchez Bettucci and Linares (1996) reported radiometric ages of mafic rocks occurring at the base of the Las Ventanas Formation between 615 ± 30 and 565 ± 30 Ma (K–Ar). Despite the low quality and wide range of these data, the age suggested for the group is in agreement with new U–Pb SHRIMP ages from interbedded felsic volcanic rocks (see geochronology section below). The age of the San Carlos Formation is less well constrained. However, it is deformed by the Sierra Ballena Shear Zone whose last displacement is believed to have occurred at around 525 Ma (Bossi et al., 1993; Oyhan  abal, 2005).

Pazos et al. (2003) suggested that the Playa Hermosa Formation is a glacially- influenced succession that records the Varanger glaciation on the R  o de la Plata Craton. The assignment of this unit to the Ediacaran is based on Masquelin and Sanchez Bettucci (1993), who recognized chilled margins at the contact between the sedimentary strata and trachytic dykes (see also Sanchez Bettucci et al., 2009). These hypabyssal rocks, which are part of the Sierra de las   nimas Complex, have produced Rb–Sr and K–Ar ages between 615 and 500 Ma (Bossi et al., 1993; Sanchez Bettucci and Linares, 1996). Similarly, Pecoits (2003a,b) and Gaucher et al. (2008) recognized probable glacial influence on the Las Ventanas Formation and also proposed a Varanger age (Pecoits et al., 2004). Based on the radiometric age constraints discussed above, a glacial event occurring sometime between ca. 590 and 570 Ma (Gaskiers) seems to be most reasonable (Pecoits et al., 2008, 2011).

3.2.2.1. Geochronology

3.2.2.1.1. Basement and upper contact. The group lies with an angular unconformity on metamorphic rocks of the Neoproterozoic Fuente del Puma Formation and Cerro Olivo Complex (ca. 770 Ma), the Mesoproterozoic Zanja del Tigre Formation (ca. 1.4 Ga) and granitoids of undetermined age (Fig. 3). Although the Maldonado Group was thought to underlie the Arroyo del Soldado Group (Gaucher et al., 2008), the relationship and nature of the contact between the Maldonado Group and the Arroyo del Soldado Group is not firmly established. Reconnaissance work to the north of the Minas area, where both units are closely exposed but not in contact, suggests the presence of an angular unconformity between them. Here, the Maldonado Group is clearly less deformed than the Arroyo del Soldado Group, which suggests that the former is younger, further supporting other geochronological evidence.

Metamorphic basement

Las Ventanas strata lay unconformably on the Neoproterozoic Fuente del Puma Formation and Mesoproterozoic Zanja del Tigre

Formation (cf. [Oyhantçabal et al., 2001](#)). The San Carlos Formation overlies the metamorphic Cerro Olivo Complex (770–800 Ma) of [Masquelin \(2004\)](#) whose metamorphism, which was not recorded in the San Carlos Formation, occurred ca. 670–630 Ma ([Oyhantçabal et al., 2009](#); [Lenz et al., 2011](#); [Masquelin et al., 2011](#); [Fig. 3](#)).

Granitoids

The Playa Hermosa and Las Ventanas formations unconformably overlie pink leucocratic granites of unknown age ([Pecoits et al., 2008](#)). In the case of Las Ventanas Formation, the granitic body (La Nativa Granite of [Pecoits \(2002, 2003\)](#)) is cross-cut by Cambrian syenitic and trachytic dykes of the Sierra de las Ánimas Complex ([Fig. 3](#)). Similar to the granite underlying the Playa Hermosa Formation, this granite does not show strong ductile deformation, and thus both granites are most likely of Neoproterozoic age.

3.2.2.1.2. Intrusives. Field relationships show that syenites and trachytes of the Sierra de las Ánimas Complex intrude the Las Ventanas Formation, thereby providing definite evidence of the older age of the Las Ventanas strata. Trachytes, syenites and granophyres dated by K–Ar and Rb–Sr methods yield ages between 487 and 552 Ma ([Umpierre, 1966](#); [Bossi et al., 1993](#)). Mafic dykes cross-cutting the Las Ventanas Formation, immediately to the south of Minas City, yield a K–Ar age of 485 ± 13 Ma ([Poiré et al., 2005](#)).

3.2.2.1.3. Volcanic rocks and faults. To the author's knowledge, no detrital zircon or clay geochronology has been published on the Maldonado Group or the San Carlos Formation. Mafic volcanics (El Ombú Basalt) interbedded with sedimentary rocks of the Las Ventanas Formation display ages between 615 ± 30 and 565 ± 30 Ma (K–Ar method; [Sanchez Bettucci and Linares, 1996](#)). Basal volcanoclastic rocks of the Las Ventanas Formation dated at 573 ± 11 Ma (U–Pb SHRIMP on zircon; [Oyhantçabal et al., 2009](#)) constitute the best age constraint for the group.

The last reactivation of the Puntas del Pan de Azúcar Lineament affected the Las Ventanas Formation and took place at 572 ± 7 Ma (K–Ar in syn-kinematic muscovites) ([Bossi and Campal, 1992](#)). The San Carlos Formation is intensely deformed by the Sierra Ballena Shear Zone, in which the third and final deformation phase occurred at ca. 550–500 Ma ([Oyhantçabal, 2005](#)).

3.2.2.2. The problem of the volcanic rocks and metamorphism. Volcanic and intrusive rocks of the Sierra de las Ánimas Complex have produced Rb–Sr and K–Ar ages between ca. 615 and 500 Ma ([Umpierre, 1966](#); [Bossi et al., 1993](#); [Sanchez Bettucci and Linares, 1996](#); [Oyhantçabal et al., 2007](#)). This geochronologic data suggests the presence of at least two main magmatic pulses at approximately (i) 590–560 Ma and (ii) 550–500 Ma (cf. [Sanchez Bettucci and Linares, 1996](#); [Sanchez Bettucci et al., 2009](#)). During the older pulse, volcanic rocks were generated and assigned to the lower Las Ventanas Formation ([Pecoits \(2003a,b\)](#); [Pecoits et al., 2004](#)) and upper Playa Hermosa Formation ([Sanchez et al., 2009](#)). However, the rhyolitic tuffs that were assigned to the top of the Las Ventanas Formation by [Blanco and Gaucher \(2005\)](#) and [Gaucher et al. \(2008\)](#) do not belong to the unit and are dykes cross-cutting the conglomerates. These rhyolites were dated by U–Pb (TIMS) method and yielded an age of 65 ± 1 Ma (see [Appendix](#); outcrop coordinates: $34^{\circ}41'56''$ S, $55^{\circ}13'22''$ W). Furthermore, the volcanic rocks originally described for the Las Ventanas Formation ([Pecoits \(2003a,b\)](#); [Pecoits et al., 2004](#)) are located in the base of the unit, not in top.

One crucial aspect that demands further research is the distinction between volcanic rocks assigned to the older pulse of the Sierra de las Ánimas Complex, which are intercalated with

sedimentary strata of the Maldonado Group, and those traditionally assigned to the Neoproterozoic Fuente del Puma Formation (previously called the Lavalleya Group) in the type area of the Las Ventanas Formation. Although the structural and metamorphic characteristics of both units might provide some clues, it is difficult to observe such differences in the field, particularly in felsic volcanic units. To date, the stratigraphic relationship between the Fuente del Puma Formation and the Maldonado Group remains unclear.

[Pecoits \(2003a,b\)](#) proposed that the Las Ventanas Formation was deformed and metamorphosed under low greenschist facies conditions (chlorite zone). This suggestion was based on the mineral paragenesis described for the basal mafic lavas: epidote + calcite + quartz + albite + muscovite + chlorite. In the same area, the mafic lavas belonging to the Fuente del Puma Formation show the following mineral paragenesis: chlorite + epidote + actinolite + calcite + plagioclase + quartz + sericite, which also corresponds to the greenschist facies conditions. [Sanchez Bettucci et al. \(2009\)](#) described similar mineral paragenesis for lavas occurring in the upper part of the Playa Hermosa Formation. However, the presence of palagonite in some basalts assigned to this unit argues against pervasive metamorphism because this mineral transforms into chlorite during the late stage of diagenesis or very low-grade metamorphism. When describing the petrography of the Las Flores basalt (Sierra de las Ánimas Complex), [Oyhantçabal et al. \(2007\)](#) suggested that the abundance of chlorite and epidote, and the occurrence of pumpellyite and prehnite, indicate very low to low-grade metamorphism. No metamorphic minerals have yet been reported in the San Carlos Formation or in other occurrences of the Maldonado Group in the Minas area. Hence, it is still premature to conclude that a very low regional metamorphism affected the Maldonado Group because if these rocks underwent localized deuteric or hydrothermal alteration, secondary chlorite, epidote, albite and prehnite could also be generated. In any case, the local metamorphic conditions reached by the Maldonado Group at some locations (e.g., Las Ventanas Formation at its type area) makes difficult its distinction from the Fuente del Puma Formation. Ongoing studies on detrital zircon geochronology on both units will help in determining, if any, the stratigraphic relationship between these two units.

3.2.2.3. Biostratigraphy. The first organic-walled microfossils (*Bavlinella faveolata*) in the Las Ventanas Formation and San Carlos Formation were reported by [Pecoits \(2003a,b\)](#) and [Pecoits et al. \(2004\)](#), respectively. Later, [Blanco and Gaucher \(2005\)](#) reported the presence of *Leiosphaeridia tenuissima*, *Leiosphaeridia minutissima*, *Lophosphaeridium* sp., *Soldadophycus bossii*, *Soldadophycus major*, *Soldadophycus* sp., *Vendotaenia* sp. No fossils have been yet reported for the Playa Hermosa Formation. The above listed microfossils, unfortunately, have little biostratigraphic value for the reasons discussed above.

3.2.3. Geological setting

As discussed above (see geological setting for the Arroyo del Soldado Group), the Ediacaran of Uruguay is characterized by widespread magmatism and tectonic activity. In this regard, [Masquelin and Sanchez Bettucci \(1993\)](#) first suggested that Las Ventanas and Playa Hermosa formations were deposited in a pull-apart basin. [Pecoits et al. \(2008\)](#) also suggested an extensional basin (strike-slip and late-orogenic extensional collapse basins) for the Maldonado Group and the San Carlos Formation. [Pazos et al. \(2003\)](#) described the lower section of the Playa Hermosa Formation and recognized two distinct facies: (i) primarily medium to coarse-grained, and (ii) dominantly fine-

grained units. The coarse-grained units consist of interbedded breccias, conglomerates, sandstones and minor mudstones that occur at the base and top of the succession; they were taken to represent depositional conditions with slope instability and high rates of sedimentation and were interpreted as being proximal to source. The fine-grained units are mainly composed of diamictites, rhythmites, sandstones and mudstones, which are interpreted to have been deposited in a distal, glacially-influenced environment. Both facies accumulated in a sub-aqueous marine environment and represent a proximal to distal depositional trend. The Las Ventanas Formation was interpreted as a product of sheetflood-dominated fan deltas intercalated with minor marine deposits that were generated in a tectonically-active and glacially-influenced basin (Pecoits, 2002, 2003; Pecoits et al., 2004, 2008, 2011). Conglomerate-dominated lithofacies (proximal facies association) dominate the basal part of the Las Ventanas Formation, including clast-supported conglomerate and breccia, diamictite, massive sandstone and conglomerate-sandstone couplets. Upsection, pelites become more abundant with occasional conglomerate beds (pelite-dominated lithofacies or distal facies association). This lithofacies includes laminated siltstone and sandstone-pelite rhythmites, and massive sandstone and conglomerate. Therefore, Pecoits et al. (2008, 2011) concluded that the Las Ventanas and San Carlos formations were deposited in a strike-slip basin as indicated by the diverse depositional facies and their abrupt lateral changes. Furthermore, the Maldonado Group is extensively deformed, although variably, throughout the region. Strike-slip faults, westward-verging detachment faults, and folds with axis sub-parallel to the strike-slip planes are common features (Pecoits et al., 2011). This style of sedimentation, tectonics and associated magmatism is not exclusive of this unit and has been recorded all over the region (e.g., Sierra de Aguirre Formation), which confirms the active strike-slip tectonics and magmatism during that time as discussed above.

4. Final remarks

Earlier stratigraphic models suggested an evolution from a rift basin (Maldonado Group) to a passive margin setting (Arroyo del Soldado Group) (e.g., Blanco and Gaucher, 2005; Gaucher et al., 2008). However, if we discard the controversial biostratigraphic data from the Arroyo del Soldado Group, and instead base our conclusions solely on radiometric age constraints, then the age of this group remains unknown but it was likely deposited between 700 and 1000 Ma (Fig. 5). Even if we take the age inferred in the models discussed above, the Arroyo del Soldado Group would be contemporaneous with the Maldonado Group and thereby subjected to intense syndepositional tectonism and magmatism; this is incompatible with passive-margin tectonics (see below). It also seems difficult to explain the opening and development of a rift basin followed by the generation of an Atlantic-type passive margin and closure of the basin in just 50 Ma. For example, the Red Sea, whose rifting started in the late Oligocene (30 Ma), is still a semi-enclosed and embryonic ocean basin (oceanic spreading centers first appeared at ca. 5 Ma). At its widest point, the basin is 355 km, and shows metal-enriched sedimentation and other characteristics typical of rift-drift phases (Favre and Stampfli, 1992; Bosworth et al., 2005) that are not present in the Arroyo del Soldado Group. In this regard, no evidence exists to support substantially different basin-forming mechanisms, opening rates

and sedimentary filling patterns in the Neoproterozoic. Accordingly, if we accept the principle of uniformitarianism, then the existence of a stable, Atlantic-type margin in the Ediacaran is, at the very least, highly questionable. Although there are alternative models for the development of the Arroyo del Soldado and Maldonado groups (e.g., Basei et al., 2000; Pecoits et al., 2008), no consensus currently exists in terms of their lithostratigraphy and geological setting.

The best age constraint obtained for the Las Ventanas Formation (573 ± 11 Ma; Oyhantçabal et al., 2009) from volcanic rocks supports the idea that an important extensional and synkinematic magmatism took place during the Ediacaran in Uruguay (see Pecoits et al., 2008 for discussion). This event, which ranges in age from ca. 560 to 600 Ma, is also represented by other regionally distributed volcanic and volcano-sedimentary successions (e.g., Sierra de Ríos and Sierra de Aguirre formations) and intrusive bodies (Nico Pérez mafic dyke swarm, synkinematic granites). Associated with this magmatism, tectonic activity constituted a primary controlling element on basin development and basin-fill architecture. The two largest, high-strain transcurrent structures present in Uruguay were reactivated during that time. Both, the Sierra Ballena and Sarandí del Yí shear zones (Figs. 1 and 3) where reactivated between ca. 600 and 570 Ma. Collectively, these features suggest important tectono-magmatic activity during basin generation and deposition on both the Nico Pérez and Cuchilla Dionisio terranes. This evidence also does not support the existence of a stable, Atlantic-type continental margin during the Ediacaran-lowermost Cambrian, as proposed for the Arroyo del Soldado Group (Gaucher, 2000; Gaucher et al., 2004). Significantly, the purported glacial evidence from the Playa Hermosa and Las Ventanas formations (Maldonado Group) and in the Tacuarí Formation suggest regional glacial conditions ca. 570–590 Ma. Hence, the Arroyo del Soldado Group is most likely older (pre-Ediacaran) than previously thought (Fig. 5).

Finally, and although not exclusively applicable to the 'Ediacaran' units, a recurrent issue in the Precambrian stratigraphic nomenclature in Uruguay is the use and abuse of stratigraphic names. Naming, revising, ignoring and abandoning formal stratigraphic names with no apparent scientific reason (i.e., without following stratigraphic guides or simply without supporting evidence) has resulted in serious nomenclatural confusion. One such example is the use of different names for the same units by different authors. These recurring problems reveal the lack of a complete understanding of the stratigraphy, distribution, geological setting and age of the different units involved. In this regard, future research should be directed at outlining clear stratigraphic schemes supported by radiometric ages that fully satisfy the observation gathered in the field.

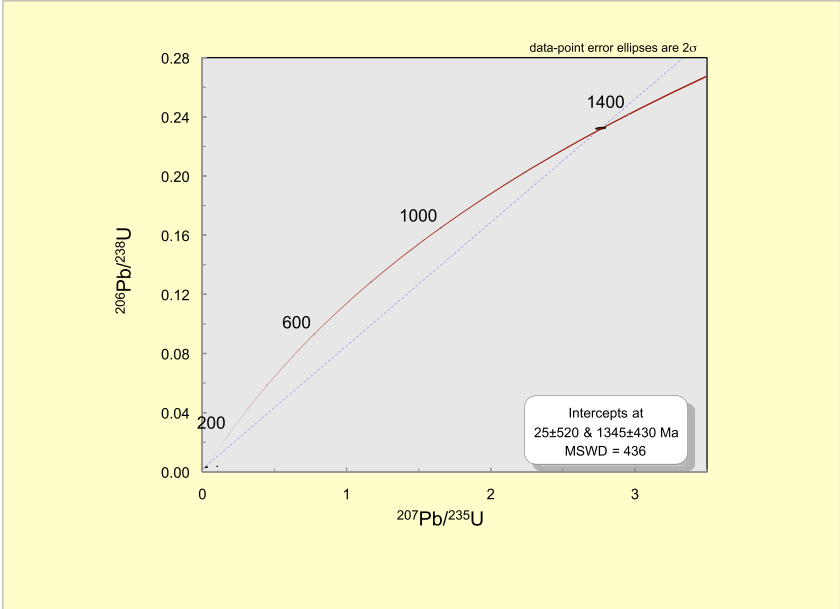
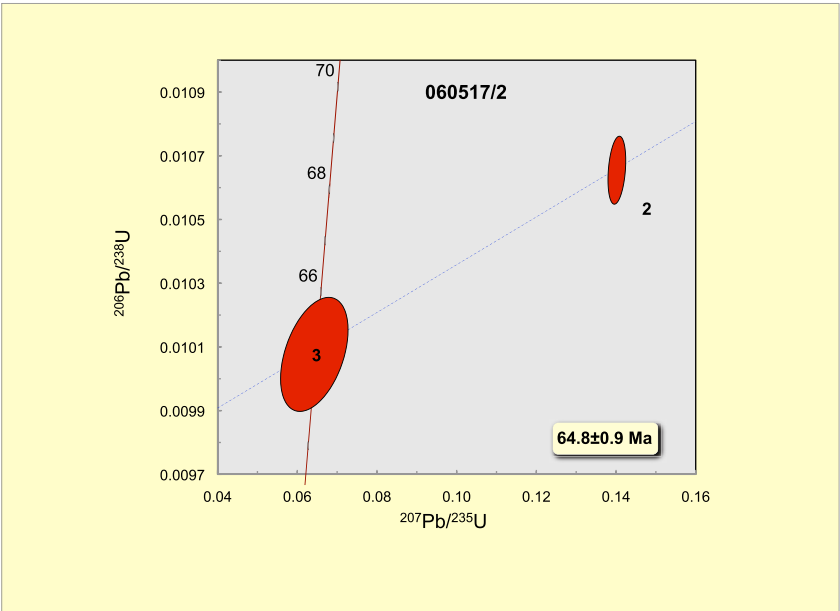
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Appendix

U-Pb Zircon Results for Sample 060517/2.

Description	Weight (μg)	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	TCPb (pg)	Pb*/Pbc	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U	2σ	ρ	Model Ages (Ma)			
														²⁰⁶ Pb/ ²³⁸ U	2σ	²⁰⁷ Pb/ ²³⁵ U	%Disc
1 single large tan	3.2	141	127	46	0.90	27	4.64	264	2.7764	0.0280	0.23335	0.00050	0.461	1352.0	2.6	1349.2	7.5
2 6 equant 3:1	4.2	359	203	7	0.56	11	1.58	108	0.1406	0.0018	0.01066	0.00008	0.281	68.4	0.5	133.6	1.6
3 6 elongate clear	1.6	319	153	4	0.48	1.9	2.81	188	0.0655	0.0068	0.01010	0.00014	0.428	64.8	0.9	64.4	6.5



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