




Stratigraphy and tectonic setting of the Barriga Negra Formation in Uruguay: an update

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Abstract

The aim of this work is to propose a new stratigraphic scheme of the Barriga Negra Formation, in order to solve the controversies in one of the most discussed units of Uruguay. Here, we introduce a new map (unmodified since 1984) and amend the stratigraphic profile for the Barriga Negra Formation, establishing the correct sequence, order and thickness, dividing it in four members (Volcaniclastic, Arkosic Conglomerate, Calcareous Conglomerate and Petromictic Conglomerate Member). We describe by first time the presence of basal volcanic and volcanoclastic rocks that implies a tectonic active environment. Volcaniclastic rock dating yield an U-Pb concordia age of 633 ± 3.4 Ma. Moreover, we show that this unit has no stratigraphic continuity with other units that previously were used to constrain its stratigraphic position, age and paleoenvironment. We confirm unequivocally that the unit is as a continental conglomeratic sequence deposited in arid and active tectonic conditions, and not transitional passive margin deposits as some works claim. Finally, we revisit the metamorphism, deformation, stratigraphy, structural relationships of this unit and identify new basement units. As consequence of this new evidence, we reexamine its correlation with other regional units. This work is also a key to understand the chaotic stratigraphic proposals of Uruguay.

KEYWORDS: Barriga Negra Formation; Paleoenvironment; Sedimentation-tectonics; Neoproterozoic; South America.

INTRODUCTION

Several low-grade metamorphic volcano-sedimentary and sedimentary (conglomerate) units have been described overlying the igneous and metamorphic basement of Uruguay and Rio Grande do Sul (Midot 1984, Frago-Cesar *et al.* 1987, Basei *et al.* 2000). However, due to a tectonically complex history and the lack of appropriate geological maps, the Uruguayan units are subject to constant stratigraphic controversy. The Barriga Negra Formation is one of these controversial units; it is a thick succession of reddish conglomerates, arkoses and pelites, which is assumed to be Neoproterozoic in age (*e.g.*, Midot 1984, Fambrini *et al.* 2005a). It has been described as it rests unconformably over its basement (Walther 1919, Midot 1984, Fambrini *et al.* 2005a, Masquelin *et al.* 2017), as concordant (Preciozzi & Fay 1988, Gaucher 2000) or even interbedded with it (Caorsi & Goñi 1958). Its bedding was described with regular dip around 10° - 20° E (Midot 1984, Preciozzi &

Fay 1988, Bossi & Navarro 1991) and 40° - 45° E (McMillan 1933, Frago-Cesar *et al.* 1987). These rocks were even associated and mapped together indistinctly with sedimentary and metamorphic units (Preciozzi *et al.* 1979, 1985, Gaucher 2000). Its tectonic interpretation is also controversial. It was interpreted as molasse deposits (Bossi *et al.* 1975, Preciozzi *et al.* 1979, Frago-Cesar *et al.* 1987), as intracontinental rift deposits (Fambrini *et al.* 2005a), and as passive margin transitional marine-coastal environment (Gaucher 2000, Gaucher *et al.* 2003). Moreover, the Barriga Negra sedimentary sequence was defined by Midot (1984) and redefined by many others, changing several times their stratigraphic position (Preciozzi *et al.* 1985, Frago-Cesar *et al.* 1987, Preciozzi & Fay 1988, Bossi & Navarro 1991, Gaucher 2000, Sánchez Bettucci *et al.* 2010b). Furthermore, Barriga Negra Formation is a key part of several stratigraphic proposals and controversies in the Uruguayan Neoproterozoic successions, especially regarding to the interpretation of the Dom Feliciano Belt, and tectonic subdivisions of Uruguay. For example, some authors consider Barriga Negra Formation as a post-orogenic sequence part of the Dom Feliciano Belt, overlaying a meta-volcano-sedimentary sequence (a schist belt) and granitic intrusions formed in an orogenic environment (Basei *et al.* 2000, Sánchez Bettucci *et al.* 2010b, Masquelin *et al.* 2017, and references therein). Others authors (Gaucher 2000, Gaucher *et al.* 2003, Bossi & Gaucher 2004, 2014, Blanco *et al.* 2009) do not accept the existence of the Dom Feliciano Belt in the area, and interpret the opposite scenario; they consider Barriga Negra Formation as the middle or bottom of a marine-coastal sequence, that overlies

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sedimentary units (not metamorphic as the previous model) and the surrounding granitic intrusions as anorogenic, related to a passive margin in an extensional tectonic environment.

The aim of this work is to present the results of a new detailed structural, stratigraphic and petrographic study of the Barriga Negra Formation, with the focus on:

- to present a new stratigraphic, petrographic and geochronological study for the unit expanding and reordering the original ones;
- to check the stratigraphic continuity with other units that previously were used to constrain its stratigraphic position, age and paleoenvironment;
- to describe the different lithofacies and members;
- to discuss its stratigraphic relationships, diagenesis, metamorphism, deformation, and age;
- to discuss the tectonic setting and the regional meaning of the new proposal.

GEOLOGICAL FRAMEWORK

The Archean to Proterozoic basement outcrops mainly in the southern portion of Uruguay. At the north, it is restricted to the so-called “crystalline islands” (Cuñapirú-Vichadero in Rivera and Aceguá in Cerro Largo Department). This basement represents 44% of the outcrops in Uruguay (Fig. 1). It consists of metamorphic and plutonic intrusive rocks, as well as various hypabyssal dyke swarms. The metamorphic rocks comprise gneisses, schists and amphibolites and gradual transitions between gneisses, migmatites and granitic rocks. These units were affected by several events involving folding, intrusions, anatexis, erosion, and intense weathering. These units are distributed within several tectonic blocks and terranes as shown in Figure 1. Besides, in its full extent, interbedded metamorphic belts are observed (Fig. 1). These belts comprise rocks with volcanic and sedimentary protolith, and its metamorphism and/or deformation vary between medium and very low degree, and are commonly affected by igneous intrusions.

The basement units are covered by Phanerozoic sedimentary deposits. Most of the southern Phanerozoic deposits in Uruguay are linked to the main extensional event during the Atlantic Ocean formation. This event was responsible for a strong fracturation and volcanic activity, that generated the Mesozoic Santa Lucía and Laguna Merín basins (Fig. 1). Both basins record volcanic flows during the Middle Jurassic and Early Cretaceous times, that are grouped in the Puerto Gómez Formation (Walther 1927, Caorsi & Goñi 1958, Bossi 1966), Arequita Formation (Bossi 1966) and Valle Chico Formation (Ferrando & Fernández 1971, Gómez Rifas & Masquelin 1996, Muzio 2000, Muzio *et al.* 2009). Associated with this volcanism, a syn-rift, alluvial reddish conglomerates deposits occur, as part of the Migueles Formation (Bossi & Navarro 1991) or as the Cañada Solís Formation (De Santa Ana & Ucha 1994).

The Dom Feliciano Belt

This orogenic belt groups lithologies that are understood to be associated with the Brasiliano orogenic event (Fig. 1),

limiting to the North-West with the Nico Perez Terrane (Bossi & Campal 1992, Basei *et al.* 2000, Sánchez Bettucci *et al.* 2010b, Oyhantçabal *et al.* 2010). This structural domain includes a metamorphic schist belt known as Lavalleya Group (Sánchez Bettucci 1998) the Polanco Marbles (Goñi 1958), the Carapé Complex, the Campanero Unit (Sánchez Bettucci *et al.* 2003, 2010b, Oyhantçabal *et al.* 2011) and Las Tetras Complex (Hartmann *et al.* 2001). Several authors have contributed to the knowledge of this belt of igneous and metamorphic rocks, generating different models for its genesis and evolution. All studies consider that this orogenic belt is the result of a complex evolution, comprising a collisional orogenic event followed by a continental transcurrent movement and post-collisional collapse, correlated with African orogenic belts (Hasui *et al.* 1975, Frago-Cesar 1980, Frago-Cesar *et al.* 1987, Fernandes *et al.* 1992, Chemale Jr. 2000, Sánchez Bettucci 1998, Basei *et al.* 2000, 2005, 2008, Konopásek *et al.* 2005, 2008, Oyhantçabal *et al.* 2010, 2011, Goscombe & Gray 2008, Gross *et al.* 2009, Almeida *et al.* 2010, Sánchez Bettucci *et al.* 2010b, Masquelin *et al.* 2011, Saalman *et al.* 2011, among others).

Lavalleya Group

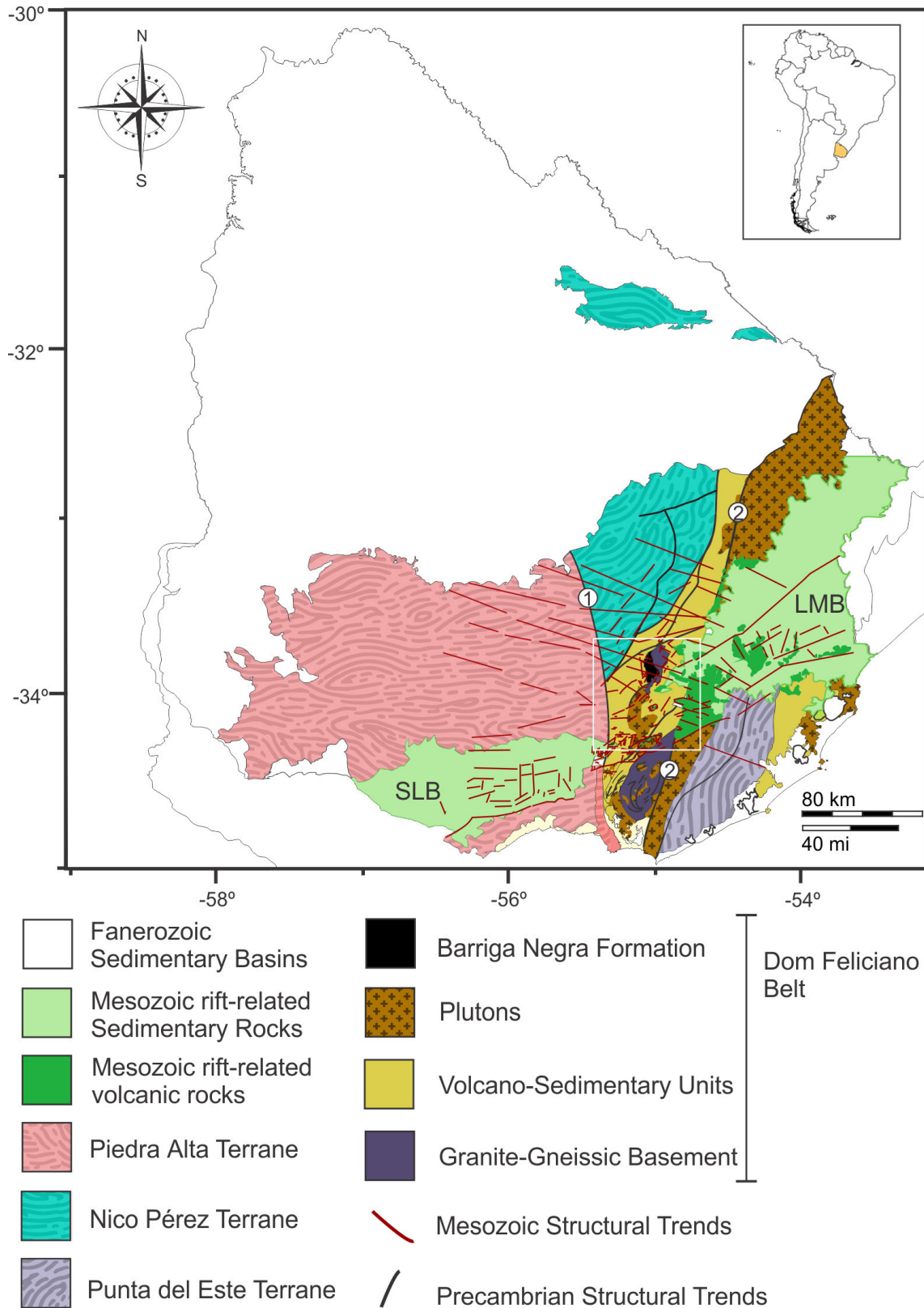
Lavalleya Group, was originally defined as the Minas Series (MacMillan 1933), then Lavalleya Metamorphic Series (Goñi 1958, Goñi & Hoffstetter 1964), but Bossi & Navarro (1991) rename it following modern nomenclatures. Sánchez Bettucci (1998) performed an extensive mapping and petrological analyses of the southern portion of de Dom Feliciano Belt amending the Lavalleya Group following the stratigraphic criteria of Midot (1984) and Preciozzi (1989), grouping three formations (*i.e.*, Minas, Fuente del Puma and Zanja del Tigre) with intensely deformed meta-sedimentary and meta-volcanic successions. This unit, considered basement of Barriga Negra Formation, is one of the most recognized units in the region (Sánchez Bettucci & Ramos 1999, Sánchez Bettucci *et al.* 2003, 2010b, Pazos *et al.* 2008, Fambrini *et al.* 2005a, Masquelin *et al.* 2017, Oyhantçabal *et al.* 2010, 2011), and an equivalent of the Porongos and Brusque groups from Southern Brazil (Sánchez Bettucci & Ramos 1999, Basei *et al.* 2000, Sánchez Bettucci *et al.* 2003, 2010b, Pazos *et al.* 2008, Fambrini *et al.* 2005a, Masquelin *et al.* 2017, Oyhantçabal *et al.* 2010, 2011). Although, some authors had published other alternative stratigraphy proposals (Gaucher 2000, Chigliano *et al.* 2010, Blanco *et al.* 2010, Poiré *et al.* 2005, Pecoits *et al.* 2016), in which the definition and interpretation of Dom Feliciano belt has been questioned (see Bossi & Gaucher 2014).

Polanco Marbles

The Polanco Marbles composed by calcareous and dolomitic marbles was defined by Goñi (1958) and formally published by Goñi & Hoffstetter (1964) in the *Lexique Stratigraphique International* (Fig. 2). However, there have been some controversies about its authorship because other authors (*e.g.*, Preciozzi & Fay 1988) used it as an informal unit (see Sánchez Bettucci *et al.*

2010a vs. Blanco *et al.* 2010). This unit was narrowly mapped by several authors (Midot 1984, Preciozzi & Fay 1988, Preciozzi *et al.* 1981, Díaz *et al.* 1990, Bossi & Navarro 1991, Gaucher 2000), but no general detailed map of the unit and its limits were ever published (see Fig. 2). This unit constitutes the

basement of Barriga Negra Formation and was considered as discordant over the Lavalleya Group (Preciozzi & Fay 1988, Gaucher 2000), being part of the Lavalleya Group (Midot 1984) and even underlying the Lavalleya Group (Hartmann *et al.* 2001, Bossi & Gaucher 2014).



SLB: Santa Lucia Basin; LMB: Laguna Merin Basin; 1: Sarandí del Yí Shear Zone; 2: Sierra Ballena Shear Zone.

Source: modified from Sánchez Bettucci *et al.* (2010a, 2016), Rossello *et al.* (1999, 2000), Oyhantçabal *et al.* (2010), Preciozzi *et al.* (1979, 1985) and Masquelin *et al.* (2017).

Figure 1. Main tectonic features of the Uruguayan Precambrian Shield, Neoproterozoic structural trends and Mesozoic basins. The white rectangle indicates the location of Figure 2.

Arroyo del Soldado Group

The Arroyo del Soldado Group is represented by pelites, psamites, banded iron formation (BIF's), limestones, and conglomerates *sensu* Gaucher *et al.* (1996). These authors suggested that there were units so far incorporated into the Lavallega Group, without metamorphism (*sic*) and with

different ages. Therefore, they defined this group bringing together these lithologies and separating them from metamorphic successions (*sic*). One of the considered sedimentary was the Polanco Marbles referred as Polanco Formation (Gaucher *et al.* 1996, Blanco *et al.* 2010, Bossi & Gaucher 2014). However, several authors indicate that low-grade

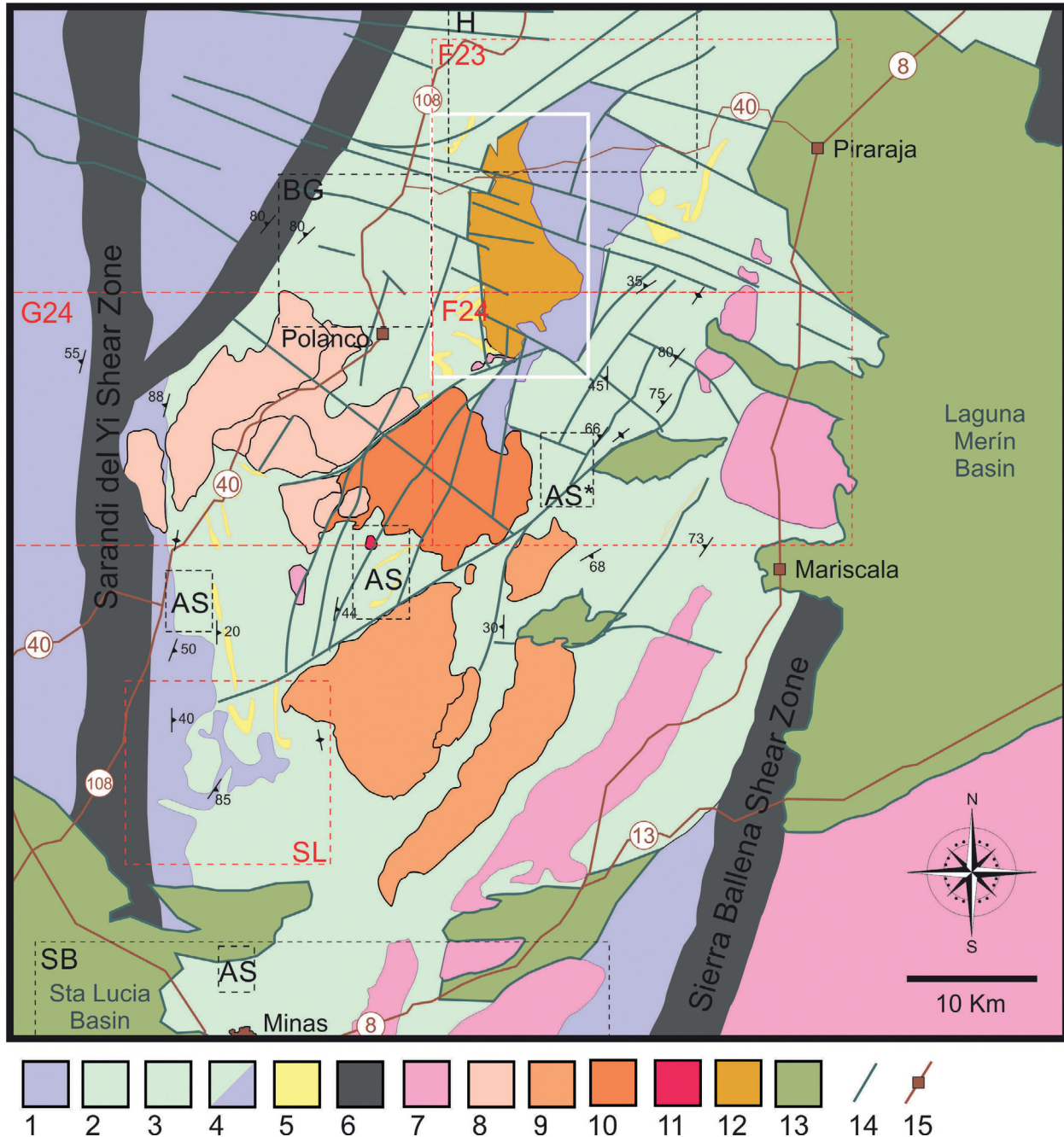


Figure 2. Regional geological and structural map of southern portion of the Dom Feliciano Belt — location in Figure 1. (1) Undifferentiated basement: gneiss, muscovite schists, mylonites, BIFs, and meta-conglomerates and quartzites; (2) Lavallega Group: marbles, schists and quartzites undifferentiated; (3) Polanco marbles; (4) units identified as Las Tetras Complex by Hartmann *et al.* (2001); (5) quartzites and meta-sandstones; (6) shear zones; (7) undifferentiated granitoids; (8) Polanco Granitic Complex; (9) and (10) Santa Lucia Batholith; (10) Barriga Negra Granite *sensu* Preciozzi *et al.* (1981) or Mangacha Granite *sensu* Díaz *et al.* (1990); (11) Mangacha Granite *sensu* Gaucher (2000) and Bossi & Gaucher (2014); (12) Barriga Negra Formation; (13) Mesozoic basins; (14) main faults systems; (15) roads and cities. Published maps in the area: (F23) Preciozzi & Fay (1988); (F24) Díaz *et al.* (1990); (G24) Preciozzi *et al.* (1981); (SL) Sanchez Bettucci & Loureiro (1999); (SB) Sánchez Bettucci (1998); (AS) all the existing maps of the Arroyo del Soldado Group in the area *sensu* Gaucher (2000), Gaucher *et al.* (2008) and Bossi & Gaucher (2014). AS* Type Area where was defined the Stratotype of Polanco Formation *sensu* Gaucher (2000); (BG) map area of the Manguera Azul Formation proposed by Bossi & Gaucher (2014). The white rectangle indicates the location of Figure 4. Published maps by the “Uruguayan geological survey” (DINAMIGE) are signalized in dashed red. This map was elaborated in basis of the previous maps of Midot (1984), Preciozzi & Fay (1988), Preciozzi *et al.* (1981), Díaz *et al.* (1990), satellite images and the new detailed magnetic and radiometric survey of Uruguay (Sánchez Bettucci *et al.* 2016).

metamorphism affects the Arroyo del Soldado Group (Goñi & Hoffstetter 1964, Midot 1984, Preciozzi & Fay 1988, Hartmann *et al.* 2001, Sanchez Bettucci *et al.* 2010b, Bossi & Gaucher 2014). In addition, different authors defined differently this group (see Gaucher 2000, Sánchez Bettucci *et al.* 2010b). Recently Bossi & Gaucher (2014) excluded, from the Arroyo del Soldado Group, its main calcareous unit (in the Polanco Marbles type area *sensu* Goñi & Hoffstetter 1964, see Fig. 2) and amended it as a new unit (Manguera Azul Formation) based on isotopic differences with other carbonatic successions (in the Polanco Formation type area *sensu* Gaucher 2000, see Fig. 2). Although, this new interpretation contravenes stratigraphic code — by using chemical criteria for separate units — ; it matches exactly as the original Polanco Marbles definition, but with a new name.

Stratigraphic controversies

Bossi *et al.* (2002) and Bossi & Gaucher (2004, 2014) proposed a whole new stratigraphy for the Uruguayan basement, redefining, regrouping and discarding previously coined units like as Lavallega Group (Sánchez Bettucci 1998), Carapé granitic complex and Campanero unit (Sánchez Bettucci 1998, Sánchez Bettucci *et al.* 2003). They also proposed different limits for the Nico Perez Terrane, including units pertaining to the Dom Feliciano Belt. Bossi & Gaucher (2014) argue that the ages of Lavallega Group no longer correspond to the Brasiliano orogenic event, but with the Grenvillian cycle and therefore they should be removed and re-defined (see Bossi *et al.* 2002 *vs.* Sánchez Bettucci & Ramos 2002). These authors consider all the calcalkaline Neoproterozoic granitic bodies at the west of Sierra Ballena Shear Zone (Fig. 1) as rift-related magmatism, and the Arroyo del Soldado Group as marine deposits related to a passive margin (Gaucher 2000, Gaucher *et al.* 2003, Bossi & Gaucher 2004, 2014, Blanco *et al.* 2009).

On other hand, Hartmann *et al.* (2001) defined Las Tetas Complex, putting together meta-conglomerates, quartzites, marbles, calc-silicate rocks and basement gneisses, at the north of Minas city. However, these units were previously mapped as independent units by different authors (*e.g.*, Midot 1984, Preciozzi & Fay 1988, Sanchez Bettucci 1998) and identified as Lavallega Group, Polanco Marbles and a “basal gneissic complex” (see Fig. 2).

All those new units and their interpretations (like other proposals by Aubet *et al.* 2014, and Pecoits *et al.* 2016) should be considered alternative proposals as there are not accepted by main part of the national and regional scientific community (see: Sánchez Bettucci & Ramos 2002, Basei *et al.* 2000, Pazos *et al.* 2008, Rapalini & Bettucci 2008, Sánchez Bettucci *et al.* 2010b, Oyhançabal *et al.* 2010, 2011, Almeida *et al.* 2010, Fambrini *et al.* 2005a, Núñez Demarco 2014, Oriolo *et al.* 2016, Masquelin *et al.* 2011, 2017, among others).

The main reason why there are so many stratigraphic alternatives and redefinitions is mainly due the lack of appropriate mapping. Stratigraphic units and profiles, and geochemical data are continuously being created in very restricted areas, without any appropriate geological context. The units are mapped in regional scale (1:500,000) or detailed mapped

in narrow and unconnected areas without correct definition of their extension, limits nor contacts (see Figs. 2 and 3). As example, the Lavallega Group is only accurately mapped in its southern half (Preciozzi *et al.* 1981, Midot 1984, Cosarinsky 1997, Sánchez Bettucci 1998, Sánchez Bettucci & Ramos 1999, Mallmann *et al.* 2007), and all show the geological complexity of the region, but there are only inaccurate sketches of their northern portion that vary among different authors (see Gaucher *et al.* 2003, Rapalini & Bettucci 2008, Sánchez Bettucci *et al.* 2003, 2010b, Oriolo *et al.* 2016, Masquelin *et al.* 2011, 2017, Pecoits *et al.* 2016). Yet, despite the fact that there are published dozens of stratigraphic profiles and chemical analyses, there are no detailed maps showing the complete extension of the Arroyo del Soldado Group nor its constituent formations: there are only narrow maps in key-areas (see Fig. 2, and Gaucher 2000, Gaucher *et al.* 2008, Pecoits *et al.* 2016, Bossi & Gaucher 2014) and only regional maps of the Group (Fig. 3), but their extension remarkably differs among publications (see Gaucher 2000, Gaucher *et al.* 2003, 2008, Hartmann *et al.* 2001, Mallmann *et al.* 2007, Rapalini & Bettucci 2008, Sánchez Bettucci *et al.* 2003, 2010b, Chigliano *et al.* 2010, Blanco *et al.* 2009, 2010, Oyhançabal *et al.* 2010, Oriolo *et al.* 2016, Pecoits *et al.* 2016, Masquelin *et al.* 2017). This lack of concordance in geological records and their structural limits — beyond nomenclature and interpretation differences — proves that there is no real and basic geological knowledge about that units.

Barriga Negra Formation is linked to the aforementioned units, its controversies, redefinitions and interpretations in the Neoproterozoic of Uruguay (Figs. 2 and 3). It belongs to the Dom Feliciano Belt overlaying the northern portion of Lavallega Group (Preciozzi *et al.* 1993, Sánchez Bettucci 1998, Sánchez Bettucci & Ramos 1999, Fambrini *et al.* 2005a, Sánchez Bettucci *et al.* 2010b), the Polanco Marbles (Midot 1984) and its granite-gneissic basement. Conversely, Gaucher (2000) and Bossi & Gaucher (2014) included it in the Arroyo del Soldado Group in purportedly stratigraphic continuity with other sedimentary units of the group. In first instance, it was considered overlying the Polanco Marbles (Gaucher 2000), and more recently considered the base of the group, subjacent to the Polanco Formation (Bossi & Gaucher 2014). Also, it is affected — as well as their related units — by the Mesozoic faulting and magmatism, which distort the already complicated regional stratigraphy (see Figs. 1 and 2). Thus, the right knowledge of the Barriga Negra Formation lithology, limits, internal structure, stratigraphy, and tectonics is fundamental for the support and interpretation of the different stratigraphic proposals of the area.

THE BARRIGA NEGRA FORMATION

The first descriptions of different rocks units around the region of Barriga Negra stream were due to Sellow (*apud* Weiss 1830), Walther (1919, 1927), MacMillan (1933) and Caorsi & Goñi (1958). They described the geology along the channels of the Barriga Negra and Polanco streams, producing the first geological sketches around the lands of President Francisco

Vidal. Since Bossi (1966) to Preciozzi *et al.* (1979), the clastic deposits in this region were considered as a member of the Piedras de Afilar Formation (Walther 1927, Jones 1956). Midot (1984), based on the unpublished geological data of

Fay & Arrighetti (1981), formally defined the Barriga Negra Formation (see Fig. 3A); separating the clastic rocks located near the Barriga Negra stream from the Piedras de Afilar Formation based on lithology, maturity and selection (Midot

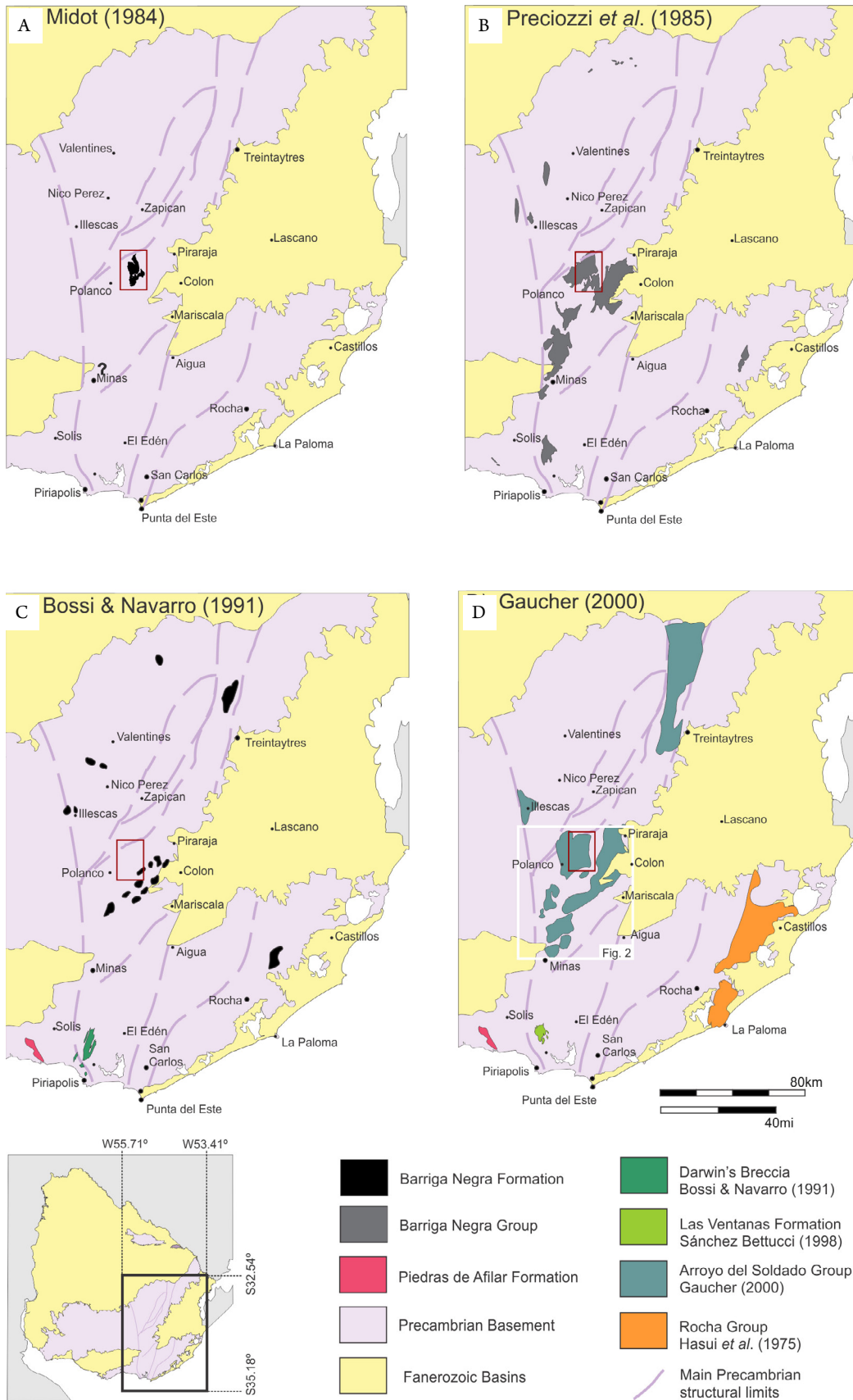


Figure 3. Geological map evolution of the Barriga Negra Unit and correlated units according to Midot (1984), Preciozzi *et al.* (1985), Bossi y Navarro (1991), Sánchez Bettucci (1998), and Gaucher (2000). Red rectangle indicates the studied area, shown in Figure 4.

1984). Nevertheless, Preciozzi *et al.* (1985) formally published it in the Uruguayan Geological Map, the Barriga Negra Group (see Fig. 3B) linking together lithologies that putatively comprise a discordant sedimentary sequence. This group associated several conglomeratic units in the region — that are not spatially related — : sandstones, arkoses, interbedded conglomerates and even quartzites and the underlying calc-pelitic and marble rocks (Polanco Marbles, Goñi 1958, Goñi & Hoffstetter 1964). Otherwise, Frago-Cesar *et al.* (1987) reviewed the geology of the region and defined the Barriga Negra Formation assembling immature clastic sequences of the Barriga Negra Group, separating them from the surrounding metamorphic rocks (probably without knowing Midot's work, see Fambrini *et al.* 2005a).

On the other hand, Preciozzi & Fay (1988) maintained the Barriga Negra Group, and described three units: Paso de los Talas (conglomerates), Arroyo del Soldado (sandstones and quartzites) and Polanco (calcareous rocks), although these authors considered it as *informal units* (Preciozzi & Fay 1988). Meanwhile, Díaz *et al.* (1990) and Bossi & Navarro (1991) resumed and emended Barriga Negra Formation of Midot (1984) adding to it other conglomeratic units of the region (see Fig. 3C). Gaucher (2000) includes the Polanco Formation — purportedly without metamorphism — and the Barriga Negra Formation (*sensu* Midot 1984) in the Arroyo del Soldado Group (see Fig. 3D), arguing a gradual and concordant transition between them (Gaucher 2000), against the previous authors that reported a lithological unconformity between them (Midot 1984, Frago-Cesar *et al.* 1987). Additionally, Gaucher (2000) presents the first detailed stratotype for this formation, but not a detailed geological map.

Hence, this formation is associated and mapped together with sedimentary and metamorphic units (Preciozzi *et al.* 1979, 1985, Gaucher 2000, Bossi & Gaucher 2014), and even its bedding was described inconsistently with regular dip around 10°-20° E (Midot 1984, Preciozzi & Fay 1988, Bossi & Navarro 1991) and 40°-45°E (McMillan 1933, Frago-Cesar *et al.* 1987). In recent works, Fambrini *et al.* (2005a) took the definition of Frago-Cesar *et al.* (1987), and they indicate the presence of the discordance between conglomerates and calcareous metamorphic basement (Polanco Marbles). While, Pecoits *et al.* (2016) considered it discordant with Arroyo del Soldado Group and the Polanco Marbles in basis to “compelling evidence of this unconformity” (Aubet *et al.* 2014). However, both research groups used in their articles the geological map of Preciozzi *et al.* (1985), in which the Polanco Marbles are one with the Barriga Negra Formation (Fambrini *et al.* 2005a, Aubet *et al.* 2014, Pecoits *et al.* 2016). It proves that the different authors did not know neither the real geologic extent nor the stratigraphy of the studied unit, raising doubt their stratigraphic proposals.

RESULTS

Redefinition, lithology, facies, and age

In this work, the Barriga Negra Formation (Midot 1984) is amended. The detailed mapping and petrography (Fig. 4)

provide valuable information that allow undertake stratigraphic corrections. The sequence occupies a NS-oriented pull-apart graben, controlled by normal and strike-slip faults. It is also affected by tenuous-open folds with vertical axis in its southernmost and northernmost portions. Moreover, the Barriga Negra Formation is affected by very low-grade and hydrothermal metamorphism — according to the petrographic information and the Kübler index in clay minerals (Cingolani *et al.* 1990), and cut by some rhyolitic dikes in the southernmost section.

Previous interpretations (Gaucher 2000, Fambrini *et al.* 2005a) indicate a thickness of ca. 1500 m, but that sequence has variable dips, increasing from E to W, from less to 10 to 60° and striking in average 340° (Fig. 4). This explains previous discrepancies in the dip measurement of the unit. Geometric reconstruction models of tilting suggest a maximum thickness of ca. 3200 ± 40 m for the non-eroded sequence (Núñez Demarco 2014).

The exposed sequence of Barriga Negra Formation (using the Hallsworth & Knox 1999 classification scheme) exhibits four members, from bottom to top:

- a Volcaniclastic Member, about 425 m thick, composed by volcanic and pyroclastic acidic rocks;
- an Arkosic Conglomerate Member, about 912 m thick, characterized by intraformational arkosic-granule ortho-conglomerates and arkosic-pebble ortho-conglomerates;
- a Calcareous Conglomerate Member, about 200 to 400 m thick, composed by clast supported oligomictic calcareous-clastic diamictites with sandy matrix;
- Petromictic Conglomerate Member, constituted by grain supported petromictic blocks-grade conglomerates with sandy matrix, with interbedded levels of arkosic sandstones and mudstones, reaching a maximum thickness of 1,650 m (see Fig. 3).

Volcaniclastic Member

The Volcaniclastic Member is located at the west of the study area, overlying the Polanco Marbles and the Cerro de los Bueyes Quartzites in angular unconformity. Lithologically, it is mainly composed of, about 425 m thick, acid volcanic and pyroclastic rocks, presenting strong hydrothermal alteration and greenish colorations. Volcanic rocks present vacuoles and phenocrysts reaching 0.5 mm, while the pyroclastic rocks present preserved flow structures, with a mean orientation of 332° / 48°, low angle cross bedding and lithoclasts (see Fig. 5A), which are typical of pyroclastic flows and pyroclastic surge deposits. Volcaniclastic rocks are acidic to intermediate rocks (rhyolites and/or trachytes), according to modal observations. However, specific rock type cannot be determined due the porphyritic texture or strong alteration of the rocks (see Fig. 6). Relict feldspar, plagioclase, hornblende phenocrysts, and opaque minerals are observed. The matrix is composed by fine relictual grains and recrystallized quartz. Secondary crystals of chlorite, actinolite, epidote, sericite and carbonates replacing the feldspar phenocrysts in pseudomorphs are common, suggesting a metasomatic assemblage (Fig. 6).

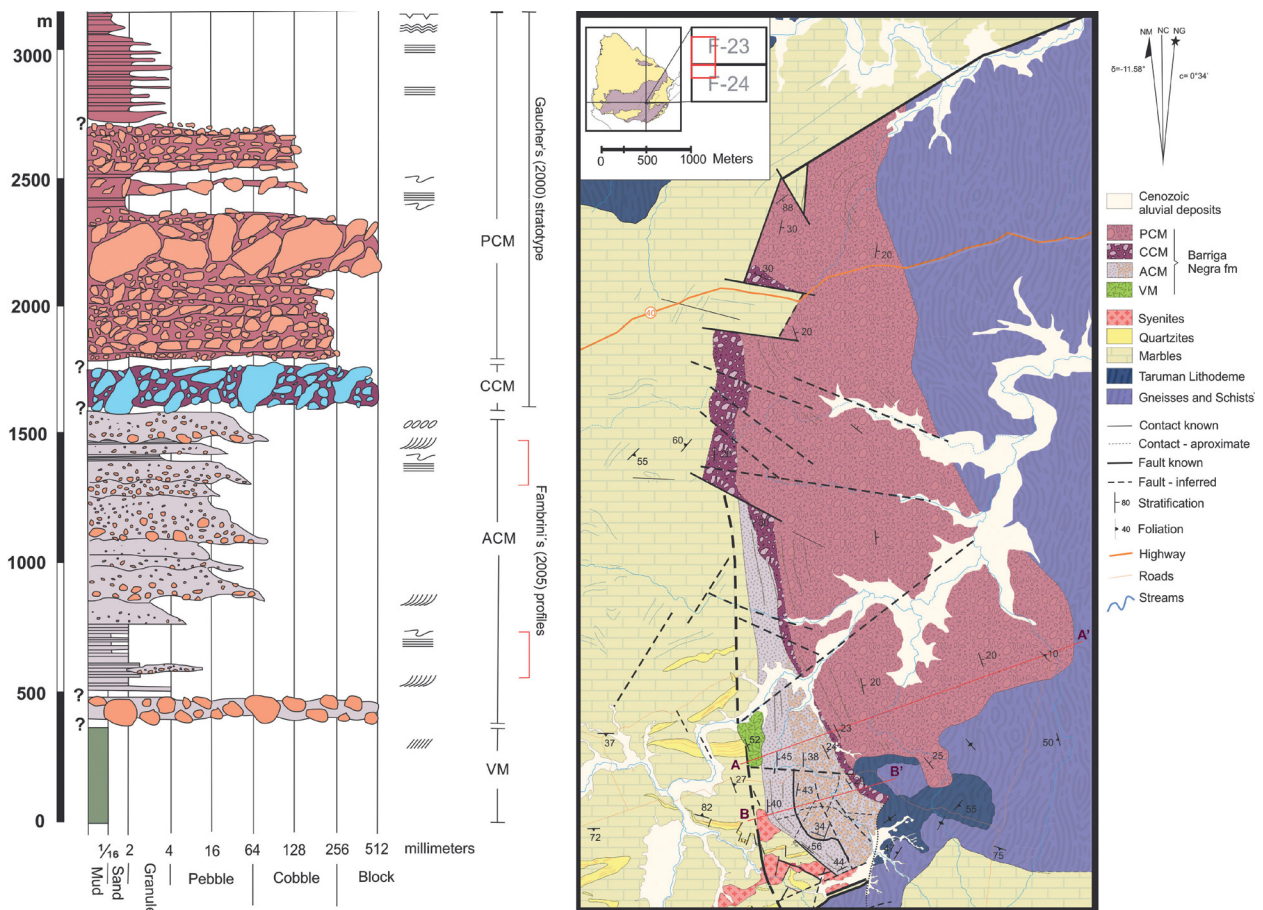
One sample was collected (BN-286; latitude S33°51'47.1", longitude W55°2'1.8" W) from the pyroclastic rocks on the

Volcaniclastic Member. About 80 zircons were separated by standard gravimetric and isodynamic techniques. Then, zircons were selected mounted into epoxy resin discs, and scanning electron microscope (SEM) imaging of the zircons under backscatter electron and cathodoluminescence (CL) were obtained to aid in identifying morphological and textural features (cores, overgrowths, and unwanted fractures) using them for the final selection of spot analyses. U-Pb age determinations by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) were carried out at Institute of Geosciences, Universidade de São Paulo (São Paulo, Brazil), according to standard procedures using a Thermo-Fisher Neptune laser-ablation multicollector inductively coupled plasma mass spectrometer equipped with a 193 Photon laser system. All LA-ICP-MS zircon analyses are shown in Table 1. The data are represented in a Tera Wasserburg diagram (Fig. 7C) generated with the program MatLab®.

Zircon presents good morphological coherence, in two or three dominant forms. There is a majority of individual subhedral crystals (2/3), whereas few are euhedral and well faceted. They have a homogenous axial relationship, from short to intermediate prisms. One third of the sample is from larger crystals (up to 150 µm long) subrounded zircons. On the other hand, the typology is variable. The most euhedral grains present pinacoids (Fig. 7A). According to zircon typology studies (Pupin 1980), these zircons would correspond to crystallized zircons

in a magma of intermediate to low temperature (700 – 600°C). Zircon population presents a small variance in size. Although there is some roundness, the presence of well-developed faces in different typologies suggests that zircons were generated by fractional crystallization process in a magma chamber and did not suffer major geological processes after this crystallization (e.g., regional metamorphism). However, due to the tectonic conditions to which the volcanic rock was subjected, late processes of hydrothermalism leaching / corrosion of zircons or even crystallization by hydrothermal precipitation should not be ruled out. Cathodoluminescence images of BN-286 sample show most zircons having a regular oscillatory zoning (90%). These zircons do not show any distinct core-rim division, but they have a CL illumination gap between an internal oscillatory zoned part with dark CL and external oscillatory zoned part with brighter CL (Fig. 7B). The other zircons (10%) exhibit cores of different nature. There are extremely dark CL-illuminated, homogeneous rounded cores (four grains). Some grains have two cores like them, which suggest an incompletely magmatic digestion process, initiated from larger xenocrysts.

U-Pb (LA-ICP-MS) dating (Fig. 7 and Tab. 1) of 36 spots in 33 zircons, yield an age of 631.9 ± 3.4 Ma. The $^{206}\text{Pb} / ^{238}\text{U}$ ages are between 613 and 662, whereas the mean square weighted deviation (MSWD) of concordance is 0.66. Six zircon ages with high degree of inheritance were eliminated. Indeed, all the eliminated grains are rounded, and two of



VM: volcaniclastic member; ACM: arkosic conglomerate member; CCM: calcareous conglomerate member; PCM: petromictic conglomerate member. **Figure 4.** Stratotype and map of the Barriga Negra Formation. Sections previously described by other authors are indicated in the stratotype (Fambrini *et al.* 2005a, Gaucher 2000).

them (10.1 and 27.1) have dark CL-illuminated elliptical cores, whose geochemical content were probably enriched in common Pb, and could be the source of contamination.

Arkosic Conglomerate Member

The Arkosic Conglomerate Member of Barriga Negra Formation outcrops at the south-west of the study area, along

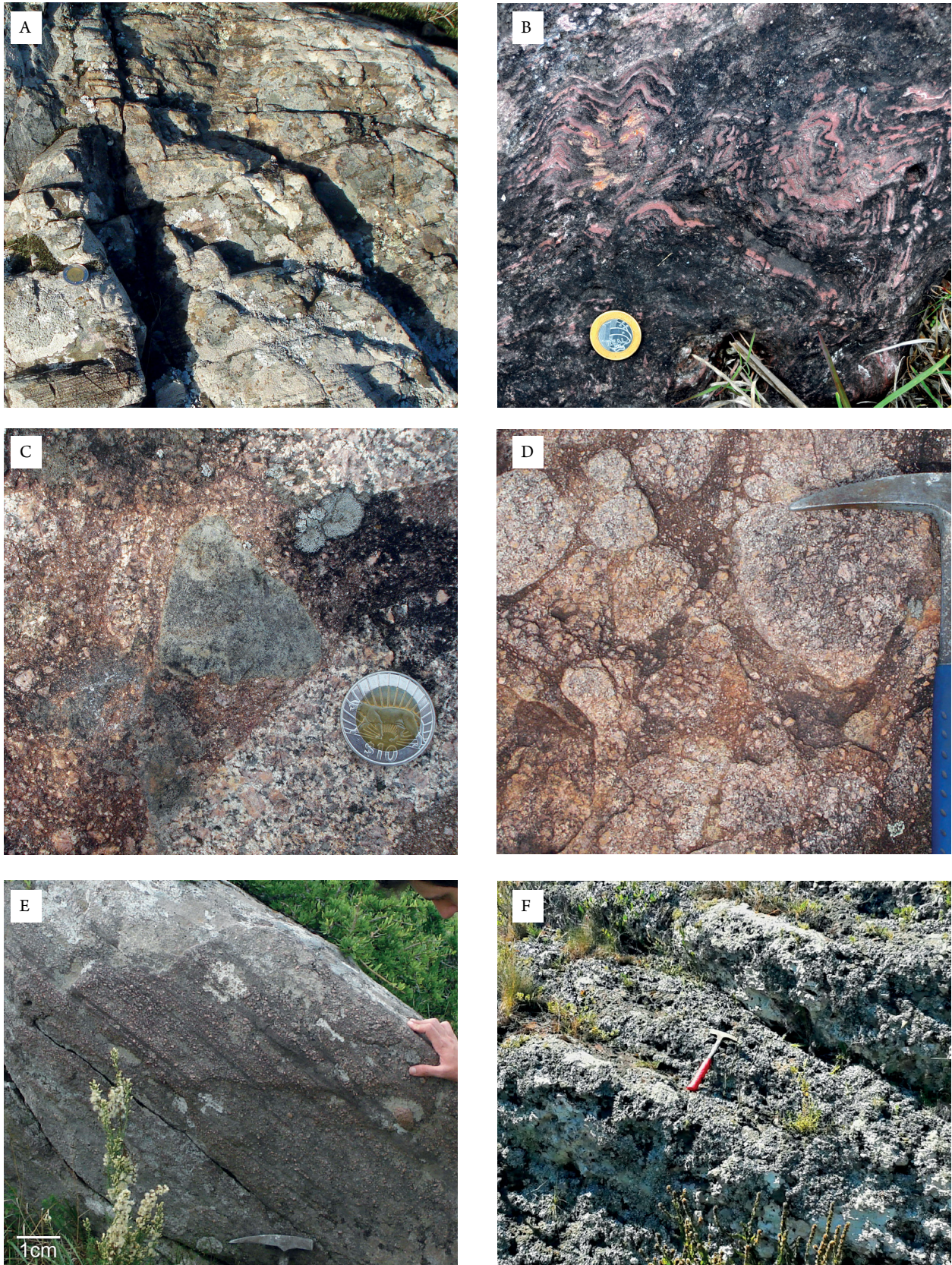


Figure 5. (A) Cross stratification in the pyroclastic levels in the volcanoclastic member; (B) convolute lamination in pelitic levels of the lower arkosic conglomerate member of Barriga Negra Formation; (C) and (D) basal conglomerate with clast of syenite and the volcanoclastic member in contact with the syenite Doña Eustaquia; (E) outcrop of the lower part of the arkosic conglomerate member, parallel, wavy and cross stratification can be observed; (F) outcrop of the upper part of the arkosic conglomerate member, parallel stratification in cobble conglomerates is shown.

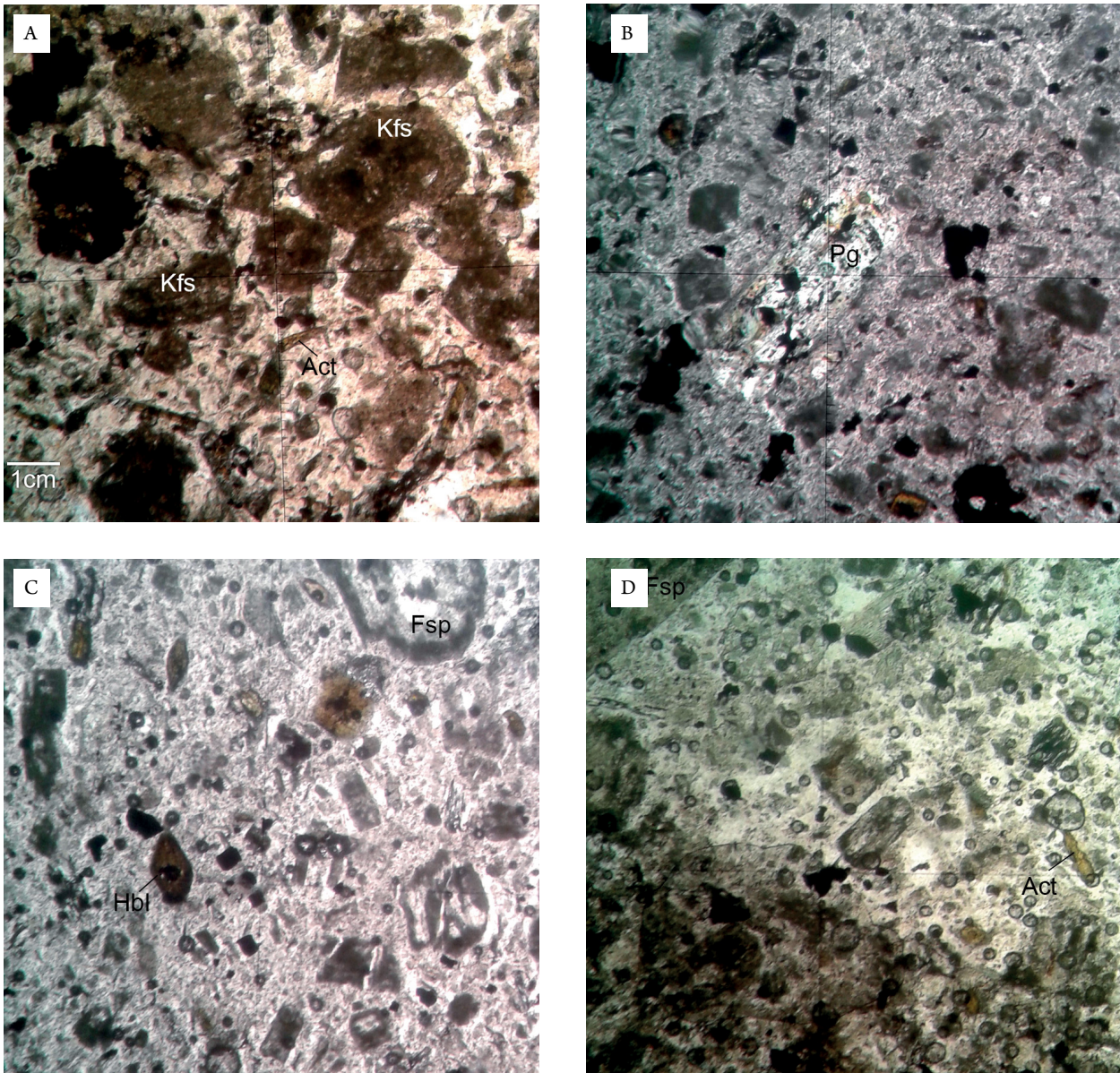


Figure 6. Photomicrographs of the Barriga Negra volcaniclastic member. The rock is composed mainly by feldspar (Fs), plagioclase (Pg), hornblende (Hbl) and opaque minerals, in quartz rich matrix. Chlorite, actinolite, epidote and sericite are common secondary minerals. Minerals are mostly relictual. (A) volcanic matrix; (B) strong saussuritization and corrosion affect the feldspar and plagioclase crystals; (C) volcanic clast in pyroclastic rock; (D) limit between a volcanic clast and the volcanic matrix. All images have the same scale, as shown in Figure 6A.

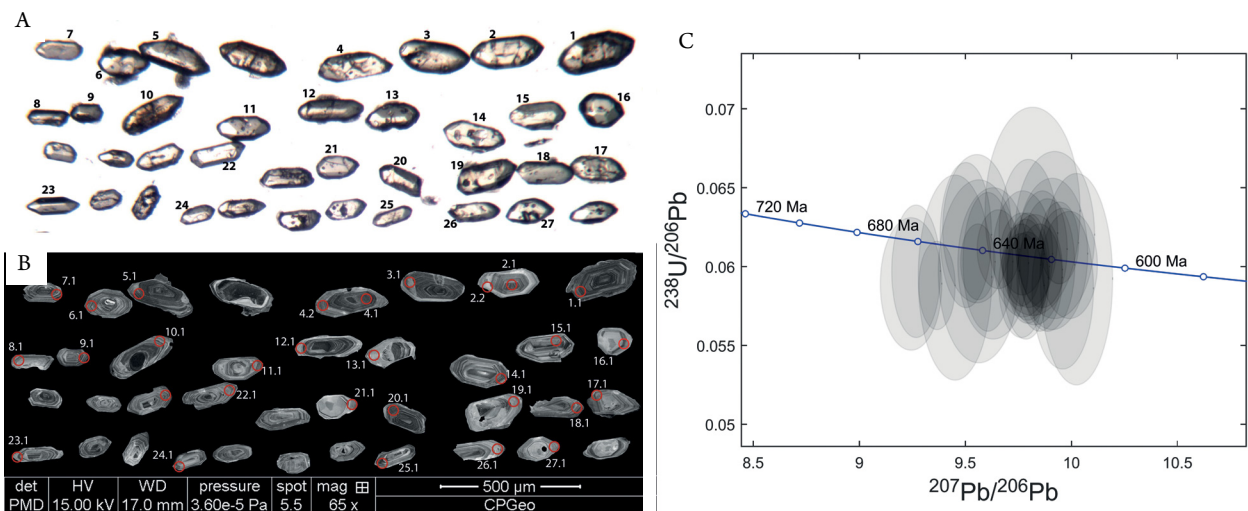


Figure 7. Zircon plate of sample BN-286 showing (A) the morphology of grains by using binocular microscope, and (B) the internal texture of zircon crystals by catholuminescence (CL); red circles are the setting of laser ablation. Tera-Wasserburg diagram (C) for zircons of the sample BN-286 showing an age of 631.9 ± 3.4 Ma.

Table 1. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Th-Pb data on zircons of the volcanoclastic member sample BN-286 (latitude S33°51'47.1", longitude W55°2'1.8") of the Barriga Negra Formation. SPL 2,491, Excimer Laser — 193 nm, 6 Hz, 7 mJ, 32 mm, ablation time — 40 s. All isotopic ratios are radiogenic lead.

Spot	Total \				Ratios						corr.	
	common	Pb	Th	U	Th/U	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ	coef.	²³⁸ U/ ²⁰⁶ Pb	1 σ
	Pb	(ppm)	(ppm)	(ppm)								
33,1	2,01	8,8	26,8	66,3	0,404	0,8139	0,0834	0,0998	0,0017	0,68	10,0232	0,1703
12,1	1,95	23,3	162,7	171,8	0,947	0,8296	0,0427	0,1001	0,0013	0,16	9,9904	0,1316
30,2	0,62	13,1	52,1	92,8	0,561	0,8113	0,0686	0,1004	0,0015	0,04	9,9584	0,1449
4,2	0,48	29,6	63,8	216,2	0,295	0,8531	0,0344	0,1006	0,0009	0,46	9,9426	0,091
21,1	1	15,7	115,6	107,8	1,072	0,8615	0,0631	0,1008	0,0019	0,3	9,921	0,1878
16,1	1,53	20	62,6	142,6	0,439	0,8455	0,0585	0,1009	0,0017	0,19	9,9094	0,167
2,1	0,82	13,8	75,6	103,1	0,733	0,838	0,0547	0,1011	0,0013	0,25	9,887	0,1285
7,1	0,4	22	56,8	145,9	0,389	0,8538	0,048	0,1014	0,0012	0,25	9,8633	0,1162
9,1	2,08	28,1	148,5	168,7	0,88	0,8295	0,0435	0,1015	0,0011	0,8	9,8496	0,1069
14,1	0,5	28,8	170,5	186,8	0,912	0,8385	0,0437	0,1018	0,0014	0,01	9,827	0,1304
13,1	0,3	12,8	14,1	90,6	0,156	0,8926	0,0807	0,1019	0,0023	0,28	9,8167	0,224
6,1	0,7	16,6	27,2	108,6	0,251	0,8743	0,0605	0,1021	0,0014	0,42	9,7966	0,1382
4,1	0,54	27,5	41,6	201,9	0,206	0,8342	0,0382	0,1021	0,001	0,05	9,7927	0,0975
30,1	0,59	25	68,2	205,6	0,331	0,8445	0,0463	0,1021	0,0011	0,79	9,7933	0,1037
28,1	1,08	20,5	56,2	138,3	0,406	0,8345	0,0497	0,1022	0,0011	0,35	9,7849	0,1086
18,1	0,59	23,5	-	152,1	-	0,8574	0,0492	0,1023	0,0015	0,01	9,7707	0,1409
20,1	0,08	33,2	27	245,3	0,11	0,8581	0,0342	0,1024	0,0011	0,86	9,7677	0,1036
3,1	1,45	23,2	45,1	181,5	0,248	0,8302	0,0442	0,1024	0,0011	0,11	9,7643	0,1074
5,1	1,34	34	140,9	251,1	0,561	0,8493	0,0345	0,1024	0,0009	0,11	9,7637	0,0905
15,1	0,22	32,9	31,5	281,4	0,112	0,8721	0,0336	0,1036	0,0011	0,01	9,6555	0,1005
11,1	1,6	20,8	45,4	136	0,334	0,8622	0,0599	0,1038	0,0018	0,01	9,631	0,1666
31,1	3,52	16,4	59,6	112,5	0,529	0,865	0,0581	0,1041	0,0013	0,01	9,6061	0,1176
22,1	0,37	17,6	27,2	122,7	0,222	0,8607	0,0713	0,1046	0,0021	0,01	9,563	0,1911
25,1	0,5	34,4	77,5	256	0,303	0,8703	0,0337	0,1046	0,0009	0,27	9,5588	0,0814
17,1	1,46	18,4	30	121,3	0,247	0,9002	0,0587	0,1047	0,0018	0,54	9,5543	0,1615
24,1	1,49	15	37,6	96	0,392	0,8997	0,0617	0,1052	0,0013	0,46	9,502	0,1212
8,1	3,21	12,5	26,5	83,6	0,317	0,8647	0,0852	0,1058	0,0019	0,42	9,4511	0,1736
29,1	0,6	28,5	79,4	188,6	0,421	0,8649	0,0396	0,1068	0,001	0,22	9,3659	0,0859
23,1	0,65	20,8	87,1	136,6	0,638	0,8886	0,0597	0,1079	0,0013	0,77	9,2674	0,1148
19,1	1,42	14,9	68,8	103,8	0,663	0,8782	0,0563	0,1082	0,0017	0,31	9,2439	0,1448
32,1	1,32	57,9	139,9	358,1	0,391	0,9167	0,0264	0,1104	0,0007	0,66	9,0573	0,0614
2,2	3,77	8,3	18,7	53,1	0,351	1,0496	0,107	0,1286	0,0025	0,58	7,7789	0,1506
27,1	15,92	17,8	103,1	115,2	0,895	0,8172	0,0538	0,1018	0,0012	0,4	9,8243	0,1156
10,1	9,43	22,2	77,3	148,3	0,521	0,8334	0,0541	0,1036	0,0013	0,08	9,6505	0,1217
26,1	14,67	19,7	1,3	121	0,011	0,8759	0,0662	0,1048	0,0014	0,57	9,5432	0,1302
1,1	10,37	35	102,7	219,6	0,468	0,9434	0,0349	0,1103	0,001	0,01	9,0664	0,0788

Spot	Ratios				AGES						Conc.	
	²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁸ Pb/ ²⁰⁶ Pb	1 σ	T _{206/238}	1 σ	T _{207/235}	1 σ	T _{207/206}	1 σ	²⁰⁶ Pb/ ²³⁸ U	²⁰⁶ Pb/ ²³⁸ U
												²⁰⁷ Pb/ ²³⁵ U
33,1	0,0592	0,0067	0,2926	0,0292	613	10	605	48	573	242	101	106
12,1	0,0601	0,0034	0,2869	0,0368	615	8	613	24	608	125	100	101
30,2	0,0586	0,0051	0,3106	0,0176	617	9	603	38	552	196	102	111
4,2	0,0615	0,0026	0,311	0,0092	618	5	626	19	657	92	98	93
21,1	0,062	0,0053	0,3771	0,0336	619	11	631	36	674	185	98	91
16,1	0,0608	0,0048	0,3532	0,0143	620	10	622	31	631	160	99	98
2,1	0,0601	0,0042	0,1571	0,0702	621	8	618	29	607	143	100	102
7,1	0,0611	0,0037	0,4212	0,0187	623	7	627	26	642	128	99	96
9,1	0,0593	0,0034	0,4911	0,0259	623	7	613	24	577	117	101	108
14,1	0,0598	0,0035	0,4142	0,0151	625	8	618	24	595	126	101	104
13,1	0,0635	0,0066	0,2861	0,0234	625	14	648	45	727	256	96	86
6,1	0,0621	0,0047	0,417	0,0172	627	8	638	34	678	173	98	92
4,1	0,0593	0,0029	0,2516	0,0135	627	6	616	21	576	105	101	108

Continue...

Table 1. Continuation.

Spot	Ratios										AGES	
	$^{207}\text{Pb}/^{206}\text{Pb}$ 1 σ		$^{208}\text{Pb}/^{206}\text{Pb}$ 1 σ		$T_{206/238}$	1 σ	$T_{207/235}$	1 σ	$T_{207/206}$	1 σ	Conc.	Conc.
											$^{206}\text{Pb}/^{238}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$
											$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$
30,1	0,06	0,0034	0,0976	0,0299	627	6	622	25	603	120	100	103
28,1	0,0592	0,0038	0,3849	0,0134	627	7	616	27	575	132	101	109
18,1	0,0608	0,004	0,4198	0,0204	628	9	629	27	631	140	99	99
20,1	0,0608	0,0026	0,2914	0,0271	628	6	629	19	632	94	99	99
3,1	0,0588	0,0033	0,1872	0,0158	629	7	614	24	560	120	102	112
5,1	0,0601	0,0026	0,2431	0,0088	629	6	624	19	609	93	100	103
15,1	0,0611	0,0025	0,0799	0,0121	635	6	637	18	642	91	99	99
11,1	0,0602	0,0048	0,4033	0,0234	637	11	631	33	612	164	100	104
31,1	0,0603	0,0044	0,3661	0,0159	638	7	633	31	613	159	100	104
22,1	0,0597	0,0058	0,3311	0,0163	641	12	631	39	593	211	101	108
25,1	0,0603	0,0024	0,202	0,0079	641	5	636	19	616	92	100	104
17,1	0,0624	0,0047	0,3541	0,0193	642	10	652	33	687	172	98	93
24,1	0,062	0,0046	0,4987	0,0433	645	8	652	33	674	161	98	95
8,1	0,0593	0,0065	0,3216	0,0197	648	11	633	48	577	254	102	112
29,1	0,0588	0,0028	0,4496	0,029	654	6	633	21	558	103	103	117
23,1	0,0597	0,0042	0,3239	0,0166	661	8	646	32	594	158	102	111
19,1	0,0589	0,0042	0,2666	0,0153	662	10	640	30	563	153	103	117
32,1	0,0602	0,0018	0,3599	0,0145	675	4	661	14	611	65	102	110
2,2	0,0592	0,0072	0,3485	0,0389	780	14	729	60	575	250	106	135
27,1	0,0582	0,0041	0,3473	0,0145	625	7	607	29	538	148	103	116
10,1	0,0583	0,004	0,2757	0,0317	636	8	616	29	542	143	103	117
26,1	0,0606	0,0046	0,4036	0,0277	642	8	639	35	626	163	100	102
1,1	0,062	0,0024	0,3178	0,0156	675	6	675	18	675	85	99	99

Corr. coef.: correlation coefficient.

the Talas stream. Bedding presents an attitude of ca. $345^\circ / 37^\circ$ E. Their southern portion is folded where the directions varies from $246^\circ / 55^\circ$ to $290^\circ / 33^\circ$ NE. This member overlays the Doña Eustaquia Syenite (Núñez Demarco 2014) in non-conformity, the Polanco Marbles and the Cerro de los Bueyes Quartzites in either angular conformity or para-conformity, and the Volcaniclastic Member (Figs. 5C and 5D) in conformity or paraconformity. A description with two detailed profiles and provenance analysis in the lower half and upper half of this member can be found in Fambrini *et al.* (2005a) (see Fig. 4). At the South, the first 100 m of this member consists of a massive conglomerate, characterized by 95% of well-rounded syenite blocks, up to 40 cm, and 5% of quartzites and volcanic clasts, with an arkosic massive matrix of reddish color (Figs. 5C and 5D and Figs. 8I and 8J), in the contact with the Doña Eustaquia Syenite and close to the outcrops of the Volcaniclastic Member. The rest of the unit, about 812 m, is characterized by arkosic-granule-conglomerates and arkosic-pebble-conglomerates, lithic and feldspathic sandstones and mudstones (Figs. 5E and 5F). Beds are decimetric to centimetric and have crude stratification (Fig. 5F). This member is thickening and coarsening-upward, although each package is fining-upward. It is composed by clast supported rock, with inequigranular texture, angulate sand-size to sub-rounded clasts, composed mainly by feldspar (90 to 60%), quartz (10 to 40%), and to a lesser extent by lithic fragments (syenite, leucogranite), plagioclase, micas, titanite, opaque minerals, and lithic fragments of gneises and cherts (see also Fambrini *et al.* 2005a). Metamorphic and chloritized micas, irregular to concave-convex contacts, saussuritization of Ca-plagioclase, undulose extinction in quartz,

and serpentinization are common (see Fig. 8). Its matrix is scarce of arkosic composition, and commonly substituted by epidote, chlorite, and iron oxides, with a range of colors from yellowish gray (5Y 8/4 grayish yellow, Munsell Color 2009), reddish (dusky red 5R 3/4) to pale green (moderate yellowish green 10Gy 6/4). Fractures and hollows are filled with fractured grains and mineralizations of sericite, muscovite, epidote, iron oxides, and/or carbonates. Mineral concentrations of iron oxide, biotite, sphene, apatite and zircon are common within grains. Locally, this member presents calcret-, silcret- and ferricretization, attributed to the increased pedogenetic activity during late Cretaceous-early Eocene that affected large areas of Uruguay (Ford & Gancio 1988, Bossi *et al.* 1998, Rapalini & Bettucci 2008, Tófaló & Morrás 2009).

The conglomeratic facies are characterized by centimetric to metric tabular packages, presenting a plane parallel stratification, somewhat wavy at the bottom and top (Fig. 5F). It is common the occurrence of decimetric sandstones beds and lenses, with frequent occurrence of cross stratification (grooved or tabular; Fig. 5E). According to Fambrini *et al.* (2005a), there are hummocky cross-stratification, asymmetric ripple marks and undulose lamination, indicating probably paleocurrents with direction WNW. Some pebbly beds have very rounded clasts with imbrication, being more common toward the top (Fragoso Cesar *et al.* 1987). Fine to medium sandstone beds are generally plane laminated and, occasionally, massive with symmetric ripple marks.

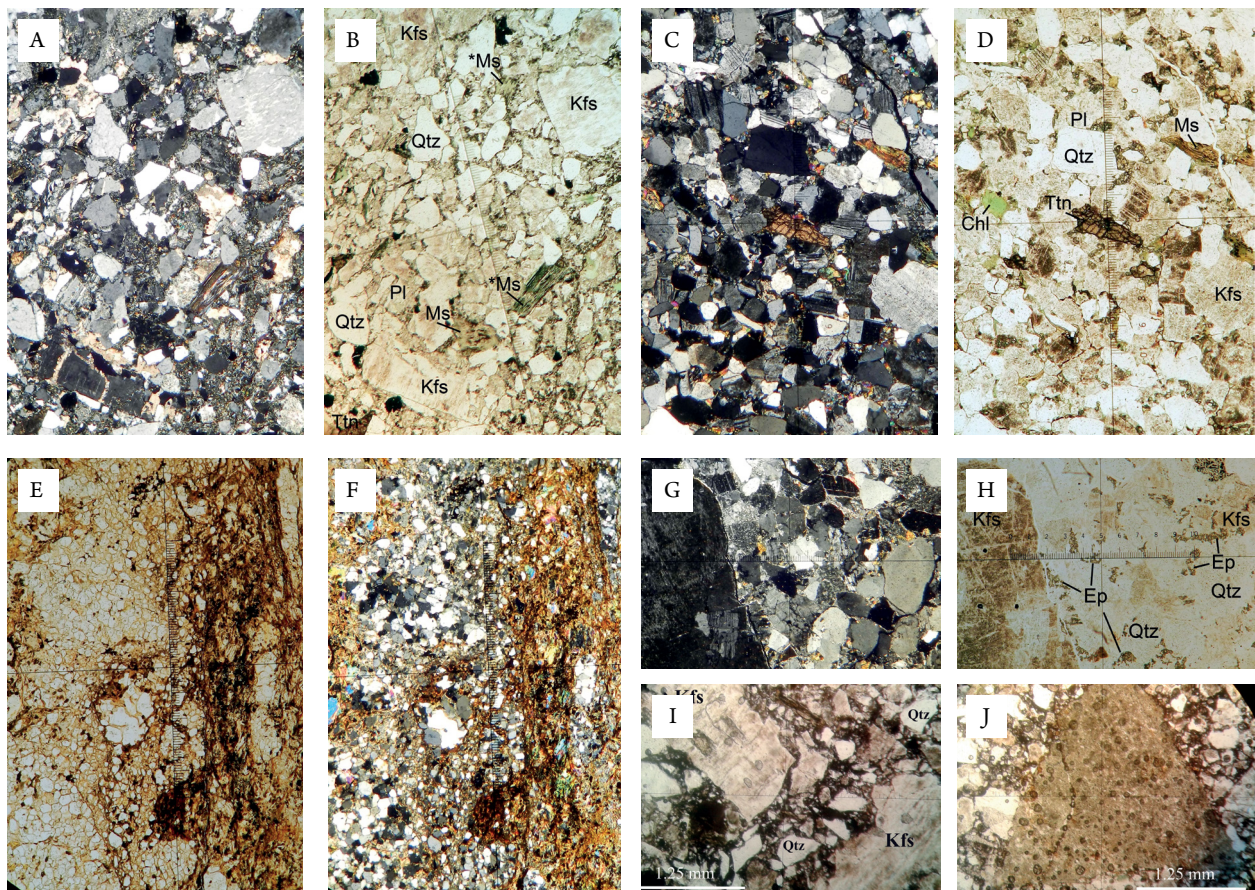
The lower half of this lithological unit (about 300-m thick) is interpreted to have been deposited in a coast environment, dominated by the sandy bedforms (SB) facies (following

Miall 2006; Tab. 2) and the presence of sedimentary structures (Fambrini *et al.* 2005a). Towards the upper portion, a continentalization occurs, being dominated by gravelly bedforms (GB) facies, where channelled deposits are characterized by facies Gh, Gp and Gt with lithofacies of sandstones (Sp, St, Sr, Sh). The roundness and clasts imbrication indicate that the unit was dominated by currents. In addition, four interbedded mudstone levels appear in the upper half of this unit, showing planar stratification and slumped beds, representing mud flows (Fig. 5B). These associations represent shallow to deep, gravel-bed braided river or gravel-bed wandering rivers, or alluvial fans dominated by braided rivers (Miall 2006). Towards the top, in the last 300 m, Gcm facies dominate, with debris flow characteristics of alluvial fans. The facies transition involves a change in the depositional regime with nearby source area, involving active tectonic processes.

Calcareous Conglomerate Member

This unit is a calcareous clast-supported diamictite (an inequigranular conglomerate *sensu* Eyles *et al.* 1983, Lamar

1992, Ramírez 1998, Blikra & Nemeč 1998, Bogs 2009, Elswick & Johnson 2010), with chaotic distribution of the fragments, presenting clasts angular to sub-rounded from pebble size to block size (> 70 cm) and sandy matrix (Fig. 9). At the South, this unit overlies the Arkosic Conglomerate Member in conformity and part of the Taruman Lithodeme in angular unconformity. At the North, it overlies the Polanco Marbles in angular unconformity, although in some areas appear to be in para-conformity due to the folding of the Polanco Marbles. This member reaches a mean of 200-m thick, layers are roughly oriented at $330^\circ / 20^\circ$ being folded at the East in their northern and southern limits. The clast-composition is dominantly marbles, although some clasts of quartz, schist, mylonite, granite and syenite are observed. Three types of calcareous clasts can be identified gray, yellow and pink (Gaucher 2000), being commonly banded and with the presence of quartz veins and chert levels, frequently showing faults and folding. The sandy matrix consists of sand size particles mainly composed by carbonates and in lesser extent quartz, rich in calcareous cement and it has reddish color (moderate red SR 4/6).



Chl: chlorite; Ep: epidote; Kfs: potassic feldspars; Ms: detritic mica; *Ms: metamorphic mica; Pl: plagioclase; Qtz: quartz; Ttn: titanite.

Figure 8. (A) and (B) Thin section of a meta-arkose sample, in plane polarized light and normal light. Metamorphic and chloritized micas, saussuritization of Ca-plagioclase, serpentinization can be observed. Clast is cut by carbonate-filled post-sedimentary fractures and hollows. (C) and (D) Thin section of a meta-arkose sample, in crossed polarizer and normal light. (E) and (F) Thin section of a meta-arkose sample, in plane polarized and normal light. Quartz grains are well selected with 0.5 mm mean size, concave-convex contacts and incipient triple unions. Sample is heavily fractured, with incipient cataclasis. (G) and (H) Thin section of a meta-arkose sample, in plane polarized and normal light. It is a clast supported rock, with angulate and rounded grains, sand-gravel size clasts. Grain contacts are irregular to concave-convex, with contact deformation and fracturation. Epidote is concentrated in the scarce matrix. (I) Thin section of the basal conglomerate in normal light, composed by syenite clasts, feldspar, plagioclase, quartz, opaque and volcanic clast (see Figs. 5C and 5D). (J) Thin section of the basal conglomerate showing volcanic angulate clasts (see Fig. 5C). All scales in the images has 2.5 mm.

Table 2. Lithofacies code used in this work after Miall (2006).

Facies code	Facies	Sedimentary structures
GB	Facies Gm, Gp and Gt	
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication
Gp	Gravel, stratified	Planar crossbeds
Gt	Gravel, stratified	Trough crossbeds
Gcm	Clast-supported massive gravel	
Gci	Clast-supported gravel	Inverse grading
Gmm	Matrix-supported, massive gravel	Weak grading
Gmg	Matrix-supported gravel	Inverse to normal grading
SB	Facies: St, Sp, Sh, Sl, Sr, Se and Ss	
Sm	Sand, fine to coarse	Massive, or faint lamination
Sp	Sand, fine to very coarse, may be pebbly	Solitary or grouped planar crossbeds
St	Sand, fine to very coarse, may be pebbly	Solitary or grouped trough crossbeds
Sr	Sand, very fine to coarse	Ripple cross-lamination
Sh	Sand, v. fine to coarse, may be pebbly	Horizontal lamination parting or streaming lineation
Sl	Sand, v. fine to coarse, may be pebbly	Low-angle (< 15°) crossbeds
FF	Facies: 0 Fm and Fl	
Fm	Mud, silt	Massive, desiccation cracks
fl	Sand, silt, mud	Fine lamination, very small ripples

This calcareous unit is characterized by Gcm or Gci lithofacies, disorganized, poorly sorted, mass-wasting colluvial deposits (*cf.* Blikra & Nemec 1998) and marks a strong lithological, sedimentary and tectonic discontinuity.

Petromictic Conglomerate Member

This member crops out in the northeast of the study area constituted by a clast-supported conglomerate, with chaotic distribution, pebble to block sized clasts with up to 1 meter in diameter (Fig. 10). To the top of the unit, the grain size decreases gradually, passing from a boulder-conglomerate to a pebble-conglomerate with increase of SB facies (Fig. 11). At least four arkose and mudstones levels occur interbedded in this unit. Moreover, sand beds with decimetric intraclasts, slumps and convolute bedding are observed locally (Figs. 10E and 10F) as it was noted previously (Fambrini *et al.* 2005a, Preciozzi & Fay 1988, Fragoso-Cesar *et al.* 1987). This unit reach a maximum of 1,650 m (see profile AA' in Fig. 4). At the West, this member overlies the Calcareous Conglomerate Member in conformity or paraconformity. At the East and South, it overlies in nonconformity gneisses and the Taruman Lithodeme, at the Nort and Northwest, it is in fault contact with the Polanco Marbles. Near the Vidal's old ranch, arkoses and mudstones overlies the basement with subhorizontal dip (Figs. 4 and 12). A description with two profiles and provenance analysis of this member can be found in Gaucher (2000) (see Fig. 4).

The lower part of this member is dominated by massive conglomerates with decimeter to meter tabular stratification, and preferential N 22° trends. Pebble-conglomerates tend to be more rounded, with scarce matrix, showing massive and lenticular stratification geometry (Fambrini *et al.* 2005a). Fining-and-thinning-upward trend predominates, even coarsening upwards are observed, as it is noted in previous works (Gaucher 2000, Fambrini *et al.* 2005a). Clast-composition includes granites, gneisses, mylonites, quartzites, shales, and calcareous (Figs. 10A and 10B). Its matrix is sandy, gray to reddish color, and intergranular interstices are occupied by siliceous cement (Fig. 10A). Often, centimetric to decimetric thick sandstones are interbedded to the conglomerate (Figs. 10C and 10D). They

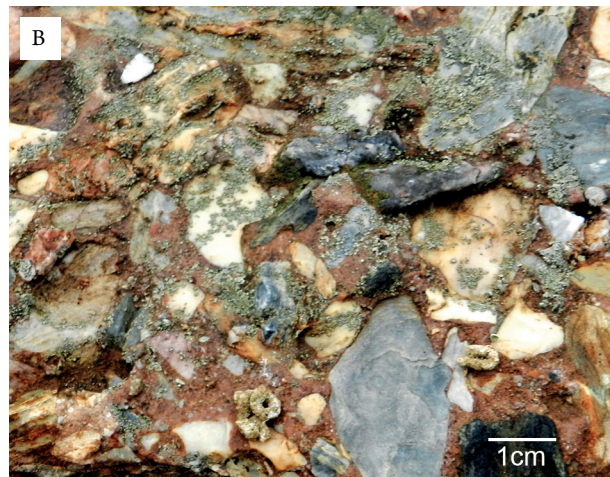


Figure 9. Macroscopic features of the calcareous conglomerate member rocks. Pebble to cobble size conglomerates, clasts are mainly composed of marbles, matrix is composed of sand size particles.

can be classified as coarse to medium arenites with disperse clasts and massive to planar stratification.

The upper part of Barriga Negra Formation occurs nearly Vidal's old ranch, with an apparent thickness of up to 400 m

(Figs. 4 and 11). Lithologically, this is fine- to medium-size arkosic levels and decimetric to metric mudstones, commonly of reddish colors (dusky red SR 3/4), although gray and greenish (moderate yellowish green 10Gy 6/4) also

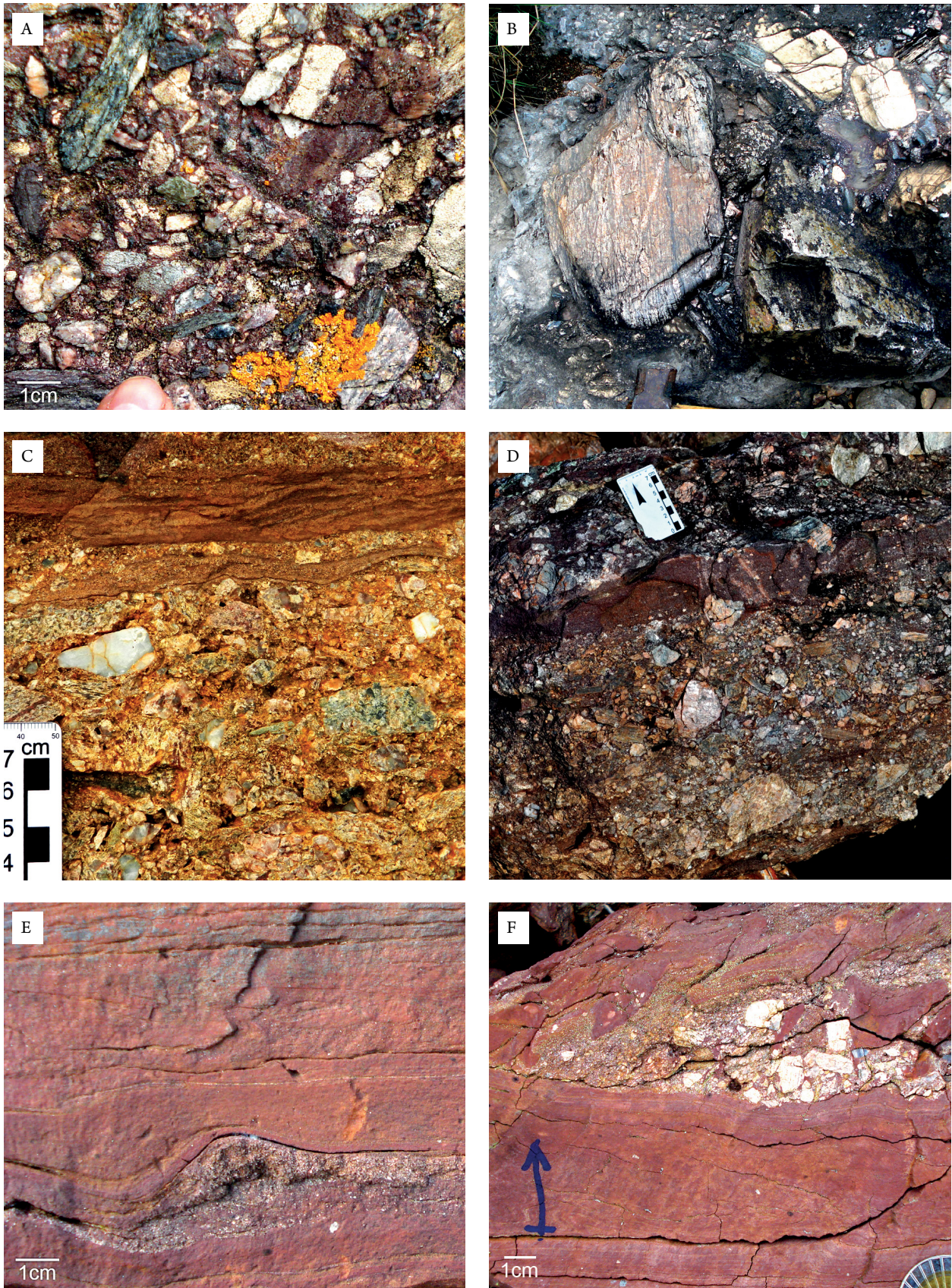


Figure 10. Petromictic conglomerate member: (A) detail of the conglomerate matrix with clast of schists, gneisses, mylonites, granitoids and quartzites; (B) basal conglomerates with clasts of gneisses, mylonites and marbles; (C) and (D) psammitic levels; (E) and (F) slumped beds, convolute lamination and liquefaction structures due detrital flows.

are present (Fig. 11). Commonly, they occur interspersed by millimetric levels of coarse sand, granule-conglomerates, and scattered clasts. Micaceous sandstones levels are also common (Preciozzi & Fay 1988). The plane-parallel stratification is dominant. Near Vidal's old ranch commonly occurs ripple marks, drying shrinkage cracks (Fig. 11, Walther 1919, Fragoso-Cesar *et al.* 1987, Díaz *et al.* 1990) and preservation of raindrops (Fig. 11B). Mud-cracks warps upward at the margins and might imply that they were formed in fresh water (*cf.* Kindle 1917, Baria 1977, Plummer & Gostin 1981). Bedding-planes usually dips 7° to 20° towards the E. This upper level preserves characteristics of alluvial fan deposits dominated by currents due to the scarcity of mudflows facies Gmm, Gmg and Sm. The scarcity of these mudflows is considered as an indicator of an arid environment. Towards the top, fluvial signatures with SB facies and appearance of Sr, Sl, and FF (Fl and Fm) facies reacquire. The presence of desiccation cracks at higher levels (Fm) confirms, in turn, aridity conditions.

Basement and structural controls

The basement of the Barriga Negra Formation consists of various lithotectonic associations corresponding to different

ages. The basement outcrops to the east and consists of deformed granites, gneisses, muscovite schists, mylonites and BIF's, trending to N-NE with subvertical foliation. At the south-east subjacent to Barriga Negra Formation, a succession of foliated and folded marbles, calcareous phyllites, meta-sandstones, very mature and deformed quartz conglomerates and massive quartzites named Taruman Lithodeme outcrops (Núñez Demarco 2014).

The north and western basement is made up of two interbedded and folded units:

1. Polanco Marbles (Goñi & Hoffstetter 1964, Sánchez Bettucci *et al.* 2010b, Núñez Demarco 2014, among others);
2. de los Bueyes Quartzites (Núñez Demarco 2014).

The first one is composed by marbles, impure marbles and calc-silicate schist rocks; the second one is represented by massive quartzites and mature meta-sandstones (Figs. 4, 12 and 13). Both basement units are considered here as part of the Lavallega Group (Sánchez Bettucci *et al.* 2001, 2010a), but they were also mapped as part of Las Tetas Complex (Hartmann *et al.* 2001; Fig. 2).

The gneissic basement, Taruman Lithodeme and Polanco Marbles are equivalent to the Las Tetas Complex (Hartmann

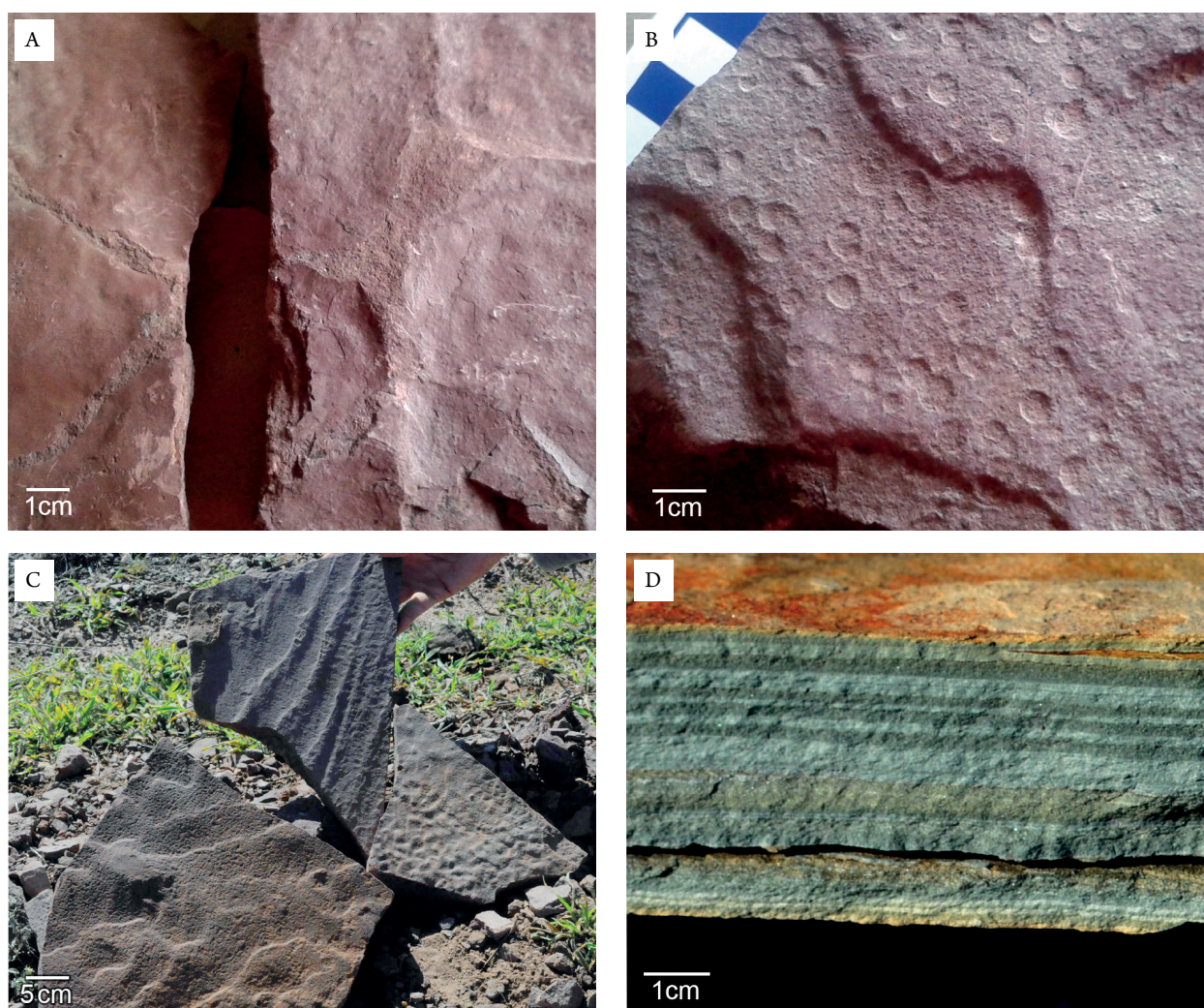


Figure 11. Structures in the petromictic conglomerate member uppermost levels: (A) desiccation cracks; (B) preserved water drops and ripples in red-colored levels; (C) different preserved ripples in psammites as well as “wrinkle” structures; (D) planar bedding and cross lamination in green colored slate levels.

et al. 2001), of Archean age (Figs. 2, 4 and 13), and affected by greenschist to amphibolite facies metamorphism. In the southern portion of the study area, the Doña Eustaquia Syenite crops out (Núñez Demarco 2014). This body is contiguous to two granitic complexes (see Fig. 2). Hence, it could belong either to the Polanco Granitic Complex (Preciozzi *et al.* 1981) with and Rb-Sr age of 548 ± 15 Ma (Umpierre & Halpern 1971, Bossi *et al.* 1998) and U-Pb zircon age of 586 ± 11 Ma (Bossi & Gaucher 2014), or to the Santa Lucia Batholith (Bossi *et al.* 1998) with U-Pb sensitive high resolution ion microprobe (SHRIMP) ages of crystallization at 633 ± 8 Ma and metamorphism at 607 ± 7 Ma (Hartmann *et al.* 2002).

The relationship between the basement and the Barriga Negra Formation is erosional unconformities or tectonics (fault contacts). The Barriga Negra graben was controlled by a NS-fault at the East that turns to a northeast-southwest direction at the North, and by a northeast-southwest fault at its southern limit, parallel to the northern fault. The folding to east, at the North and South borders, may suggest post sedimentary compression of the basin. Westwards, the sequence is cut by a NS fault, being in angular unconformity with the Polanco Marbles and the Cerro de los Bueyes Quartzites. However, in the proximities of the fault zone, the Polanco Marbles are sometimes in structural para-conformity due to a drag folding (Figs. 4, 12 and 13). Near this fault and related ones, hydrothermal metamorphism

and strong silicification in the Barriga Negra Formation are observed. This formation has not continuity with any other sedimentary or metamorphic sequence, and particularly there are no contact nor direct relationship with any other unit of the Arroyo del Soldado Group. In the southern border of the type-locality, it is possible to recognize the metamorphic contact of the Polanco Marbles with the Doña Eustaquia Syenite, and the verticalized Barriga Negra Formation. Furthermore, important hydrothermal (*e.g.*, Cu-mineralized quartz) mineralization occur along this fault system. On the other hand, rhyolitic dikes in the South border of the Barriga Negra Formation is controlled by graben faults. These dikes could be related to the Cretaceous Arequita Formation — related to the Mesozoic rifting —, suggesting that this tectonic activity may be related to the reactivation, hydrothermal alteration and compression of the graben.

DISCUSSION AND CONCLUSIONS

The Barriga Negra Formation is composed of well-preserved immature conglomerates and sands rich in feldspar and lithic fragments. As several authors have already noted, the preservation of large amounts of feldspar, mica, and carbonates during the weathering may be related to very arid conditions, or humid environments with a very sharp relief to allow rapid erosion and burial of the clasts

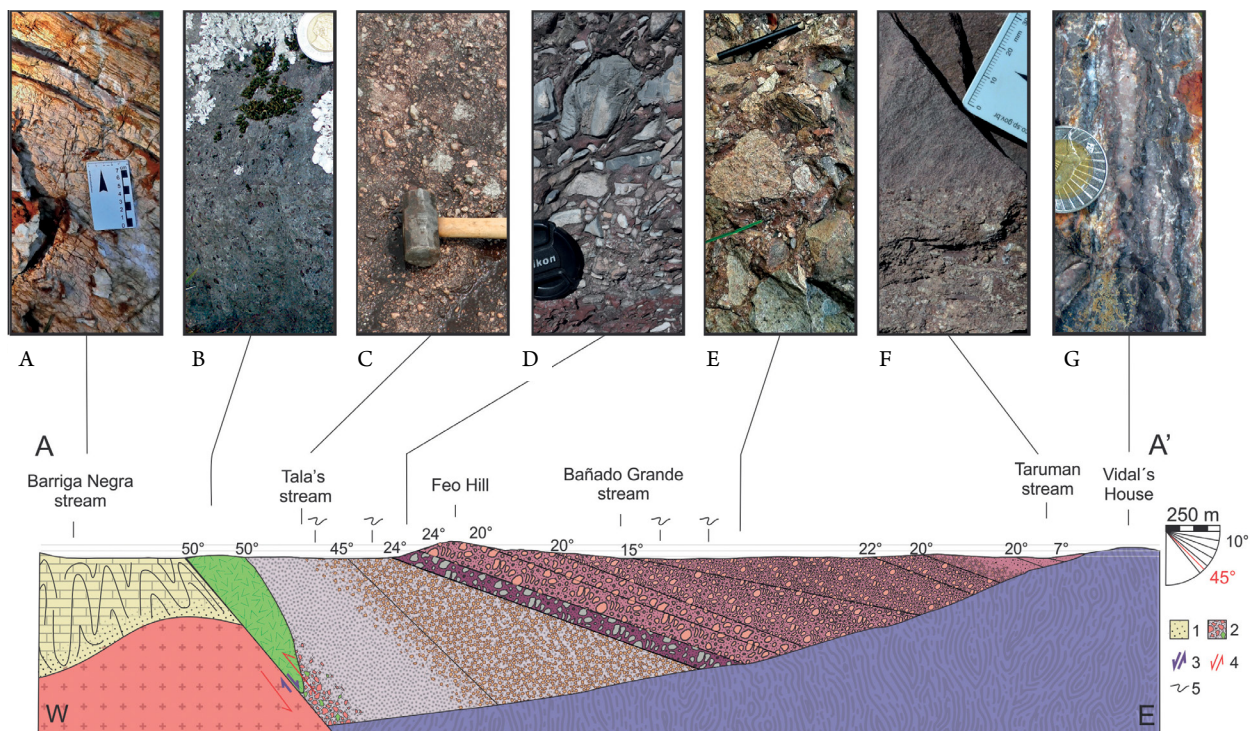


Figure 12. Section A-A' in profile and map of Figure 4. Conglomerates pattern was adjusted to reflect main granulometric trend. (A) Polanco marbles. (B) Vacuolar volcanic rocks. (C) Granule to pebble size arkosic conglomerates. (D) Calcareous conglomerate. (E) Basal conglomerates with clasts of gneisses, mylonites and marbles. (F) Arenites and granule conglomeratic levels. (G) Gneisses. Color references as in Figure 4. Distance and topography are in the same scale, units' depth is inferred. (1) Contact metamorphism in Polanco Marbles; (2) arkosic conglomerate member basal level composed of syenite and volcanic clasts; (3) Neoproterozoic extensional movements; (4) Neoproterozoic and/or Mesozoic compressive movements; (5) slump levels, see profile in Figure 4. Color scheme as in Figure 4.

before they can decompose (Bogs 2009, Pettijohn 1949). Clast maturity, size, composition, and detrital zircon ages indicate a clear provenience of the surrounding basement (Gaucher 2000, Fambrini *et al.* 2005a, Núñez Demarco 2014). The Arkosic Conglomerate Member is composed mainly by fragments of Neoproterozoic syenites and leucogranites outcropping at the South (Doña Eustaquia Sienite, Santa Lucia Batholith) and only in lesser extend by volcanic rocks, marbles and other lithic fragments (Fambrini *et al.* 2005a, Núñez Demarco 2014) consistent with the paleo current directions WNW. The Calcareous Conglomerate Member is composed almost entirely by clast from the Polanco Marbles (Gaucher 2000, Núñez Demarco 2014). The Petromictic Conglomerate Member is composed of lithic fragments, mainly medium- to high-degree metamorphic rocks (mylonites, gneisses, schists), that outcrops only at the East and North of the basin and from Neoproterozoic granitoids located at the South, East and North-East of the area (Figs. 1, 2 and 13, Núñez Demarco 2014). In all the previous works (Midot 1984, Gaucher 2000, Fambrini *et al.* 2005a, among others), the Calcareous Conglomerate Member was believed to be the base of the Barriga Negra formation, and the Arkosic Conglomerate Member was supposed overlying

it, being one with Petromictic Conglomerate Member. However, according to the new revealed stratigraphy, this member cannot be interpreted as the simple cannibalization of the basin basement as in previous works. The appearance of calcareous clasts and the disappearance of quartz-feldspar clasts imply an input area change and may represent a significant hiatus. The increase in the clasts size, also, sets a change in depositional regime, pointing to a rapid increase in the morphological gradients near the basin, involving an active tectonics phenomenon (Lamar 1992, Blikra & Nemeč 1998, Ramírez 1998, Bogs 2009, Elswick & Johnson 2010). According to Gaucher (2000), this unit represents five depositional events. Each of these diamictite deposits suggests an estimated period of hundreds to thousands of years between each deposit or a sudden tectonic event (*sensu* Miall 2006), implying a significant hiatus in the sedimentary input and/or a significant tectonic event.

The new mapping identifies that locally the bottom of the sequence is represented by volcanic rocks as stated above (Figs. 5A, 11 and 12). The presence of volcanic rocks and gravity flows and clast composition and size changes indicate active tectonics conditions during the deposition characterized by faulting and unstable slopes. Barriga Negra

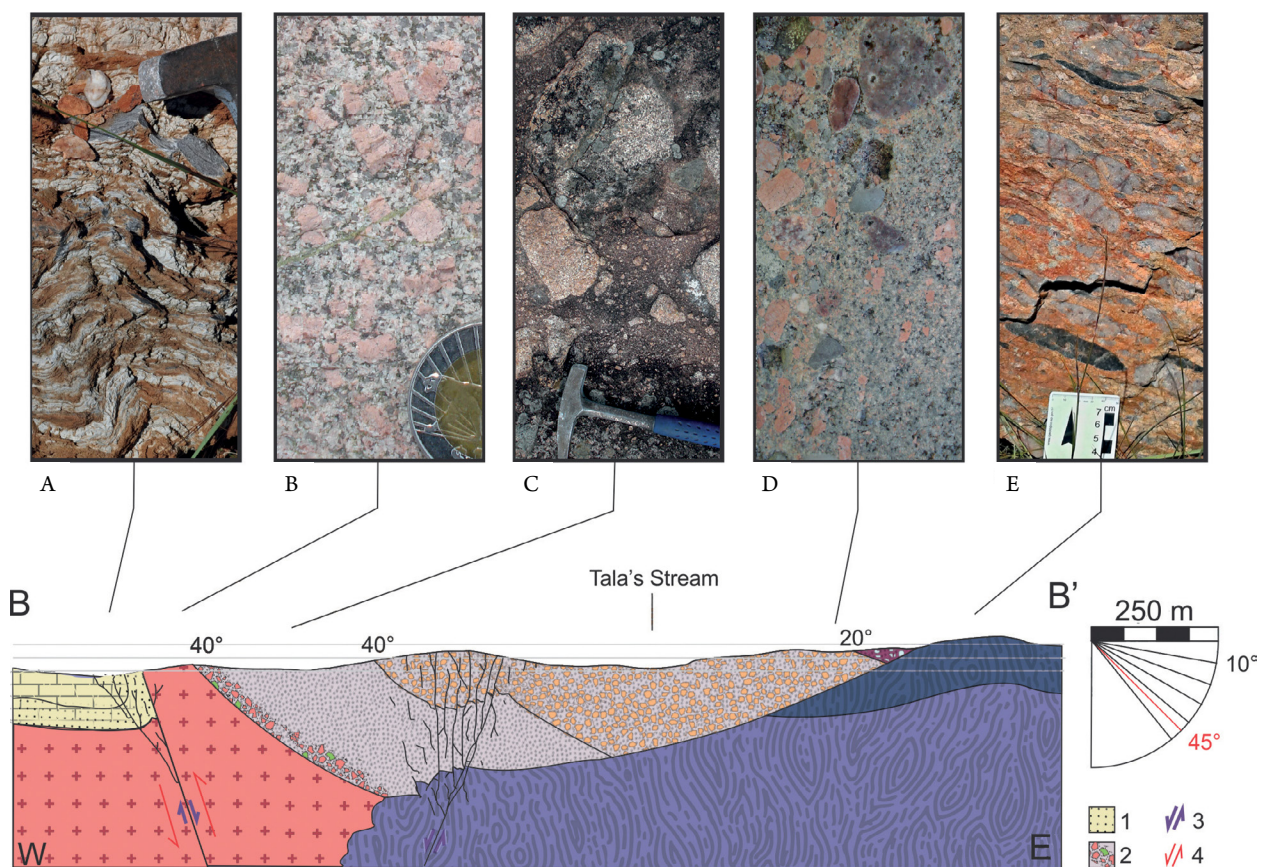


Figure 13. Section B-B' in map of Figure 4. (A) Polanco marbles. (B) Doña Eustaquia Syenite. (C) Basal conglomerate composed by syenite and volcanic clasts at the bottom of the arkosic conglomerate member. (D) Pebble-size conglomerates at the top of the arkosic conglomerate member. (E) Deformed conglomerates of the Taruman Lithodeme. Color references as in Figure 4. Distance and topography are in the same scale, unit depth is inferred. (1) Contact metamorphism in Polanco Marbles; (2) arkosic conglomerate member basal level composed of syenite and volcanic clasts; (3) Neoproterozoic extensional movements; (4) Neoproterozoic and/or Mesozoic compressive movements. Color scheme as in Figure 4.

Formation represents a continental conglomeratic sequence in an active tectonic environment (pull-apart, rift-basin), comprising a volcanic unit and basal conglomerates followed by a coastal deltaic sequence with subsequent continentalization, with colluvial fans evolving towards a system of braided rivers.

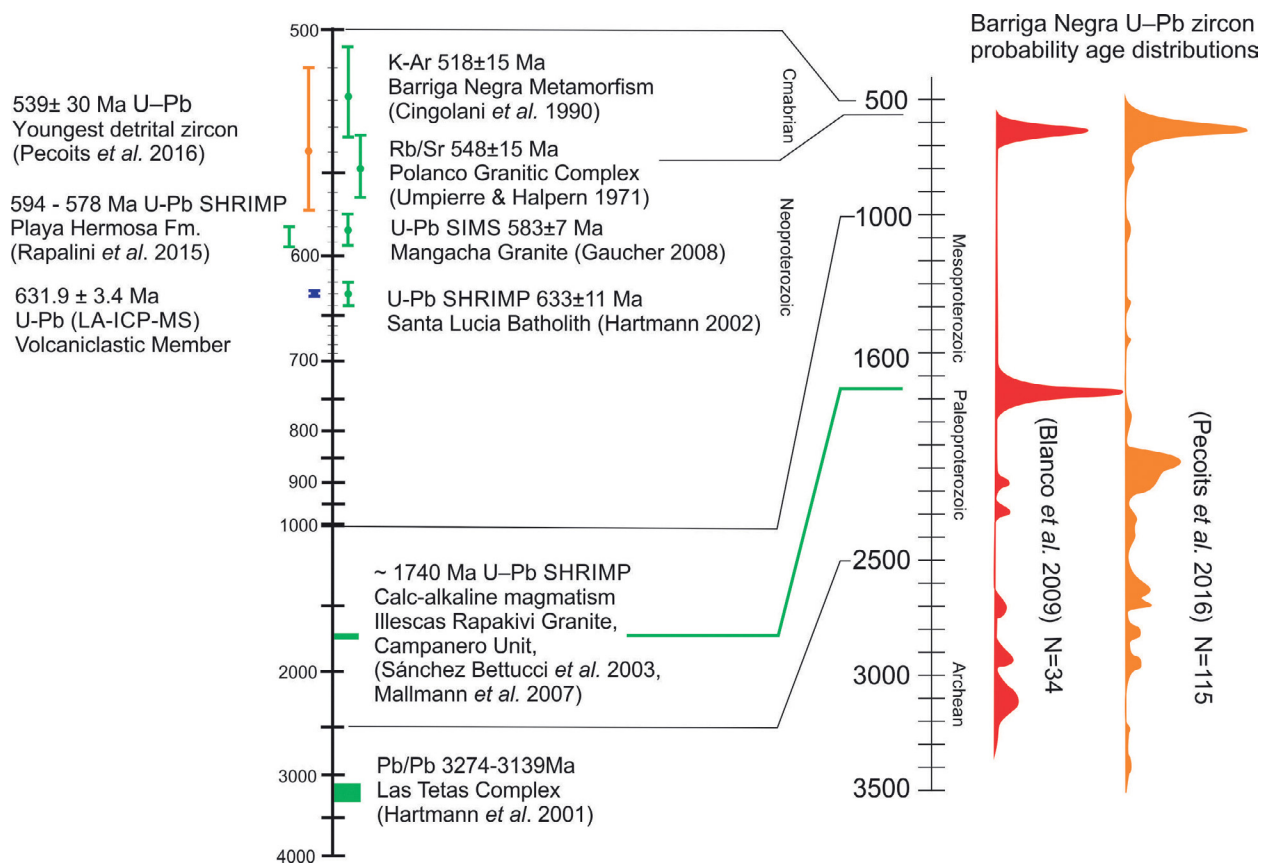
Some authors consider the color of Barriga Negra Formation as primary (Fay & Arrighetti 1981, Gaucher 2000). Field observations suggest that the color variations from gray-green to dark purple (ferrification) on the same shale level (see Fig. 11) are probably due to alteration phenomena after sedimentation, and possibly after consolidation (post-diagenetic). Cenozoic ferrification events, noted in other regions of Uruguay, may be responsible for the current color formation (Ford & Gancio 1988, Bossi *et al.* 1998, Rapalini & Bettucci 2008, Tófaló & Morrás 2009).

According to Gaucher *et al.* (2008) and Blanco *et al.* (2009), the age of Barriga Negra Formation is between 583 ± 7 and 532 ± 11 Ma, supported by stratigraphic relations of the Arroyo del Soldado Group with granitic bodies (see Fig. 2, Mangacha Granite *sensu* Bossi & Gaucher 2014). However, as this work shows, this unit has no continuity nor contacts with other sedimentary units, so age constraints based in its stratigraphic continuity are no longer applicable.

In addition, Gaucher (2000) and Gaucher *et al.* (2003) suggested an Ediacaran age for the sequence based on the

presence of microfossils *Cloudina* (< 550 Ma) in the upper units, while populations show ages from 3400 to 566 ± 8 Ma (Blanco *et al.* 2009). However, Aubet *et al.* (2014) warned that the microfossils found are poorly preserved and that their identification is inaccurate. Also, according to Zhuravlev *et al.* (2012), the described fossils in Uruguay (Gaucher & Sprechmann 1999, Gaucher *et al.* 2003) require further study since it is unlikely to be claudinids. Moreover, it is noteworthy that Neoproterozoic fauna containing the *Cloudina* assemblage was reported in carbonate platform deposits of the Nama Group (Pickford 1995, Grotzinger *et al.* 2000) and is identified in the underlying, discordant and metamorphosed Polanco Marbles, suggesting contamination by reworking of the basal units.

Gaucher (2000) and Bossi & Gaucher (2014) also highlights the presence of glauconite (formed in marine settings and commonly associated with low-oxygen conditions) and *Bavlinella faveolata* species (marine) at the top of the sequence (top of Petromictic Conglomerate Member). Glauconite minerals were not found in our work, but metamorphic assemblages are common (see Fig. 8). Furthermore, the association of lithofacies at the top of the unit (ripples, water drops, mud cracks, etc.) indicates a freshwater fluvial and arid continental palaeoenvironment, making highly unlikely the presence of glauconite or *Bavlinella*. Although the precise place of this glauconite/*Bavlinella* bearing level is not indicated (Gaucher 2000, Fig. 2, point 15), it was indicated that *Bavlinella* occurs



SHRIMP: sensitive high resolution ion microprobe; Fm.: formation; LA-ICP-MS: laser ablation inductively coupled plasma mass spectrometry; SIMS: secondary ion mass spectrometry.

Figure 14. Detrital zircon ages of the Barriga Negra Formation and related regional units ages.

in association with iron-rich shales and BIF, but the shales in Barriga Negra Formation present a clear secondary oxidation, and the BIF in the area belongs to the metamorphic basement. In addition, the mentioned ferrification of this unit makes the palynological studies difficult.

On other hand, Cingolani *et al.* (1990) dated metapelites from the Clastic Member of the Barriga Negra Formation by K-Ar method obtaining an age of 518 ± 15 . These authors interpret this age related to metamorphic or tectonothermal events during the Brasiliano Orogenic Cycle.

Detrital zircon ages of Barriga Negra Formation are presented by Blanco *et al.* (2009) $N = 34$ and Pecoits *et al.* (2016) $N = 115$, yielding ages between the Archean and Neoproterozoic (see Fig. 14) reflecting ages of the basement rocks well known in the region (Oyhantçabal *et al.* 2010). According to Pecoits *et al.* (2016), the mean age of the youngest zircon population is $\sim 581 \pm 6$ Ma, while the youngest zircon yield and age of 539 ± 30 Ma. Considering this data, the end of the sedimentation in Barriga Negra Formation can be roughly constrained between the youngest depositional age given by age of the youngest detrital zircon (539 ± 30 Ma), and the age of the metamorphic event (518 ± 15 Ma). The beginning of sedimentation can be constrained by the age of the volcanic rocks (631.9 ± 3.4 Ma) at the base of Barriga Negra Formation.

Some authors sustain that the Barriga Negra Formation is part of the Arroyo del Soldado Group and it is correlated with the Corumbá (Brazil) and Sierra Bayas (Argentina) groups (Gaucher 2000, Gaucher *et al.* 2003, Blanco *et al.* 2009, Bossi & Gaucher 2014). For these authors, these groups represent Ediacaran-Cambrian marine deposits in a transitional passive margin, in which Barriga Negra Formation is located either at the middle portion or at the base of the stratigraphic profiles and was interpreted as continental deposits in transition to a marine environment at the top (Gaucher 2000, Blanco *et al.* 2009, Bossi & Gaucher 2014, Aubet *et al.* 2014). However, Barriga Negra has no stratigraphic continuity to any other Arroyo del Soldado unit, and its lithology, facies and palaeoenvironment are not consistent with any other unit in the group. According to the International Stratigraphic Code, a group is “a sequence of two or more contiguous or associated formations with significant and diagnostic lithologic properties in common” (sections 5.C.6 and 5.D.3, Salvador 1994). Therefore, in basis of the present evidence, the unit cannot be included in the Arroyo del Soldado Group.

The Barriga Negra Formation has historically been interpreted as an intermountain molassic basin related to the final stages of Brasiliano orogenic cycle (Bossi *et al.* 1975, Preciozzi *et al.* 1979, Fragoso-Cesar *et al.* 1987). However, Fambrini *et al.* (2005a) and Almeida *et al.* (2010) suggested that Barriga Negra formation correlates with the Santa Barbara Group of Brazil, part of the Camaquã basin (Fragoso Cesar *et al.* 2000). The Santa Barbara Group is characterized by an alluvial-fans and fluvial continental sequences generated in a system of pull-apart transcurrent basins in a late- to post-orogenic

context, according NW-SE trending extension, during the Ediacaran-Cambrian period (Fambrini *et al.* 2005b, Janikian *et al.* 2008). On the other hand, Midot (1984) considered in his maps other minor occurrences of the Barriga Negra Formation near the Minas city as El Perdido and the Las Palmas hills. Sánchez Bettucci (1998) and Sánchez Bettucci *et al.* (2003) reinterpreted the Las Palmas outcrops Mesozoic volcanoclastic deposits. By using the microstructures found in pelites, Masquelin *et al.* (2017) argued that El Perdido hill outcrop represents the same lithofacies than the reddish conglomerates, sandstones and shales of the Barriga Negra stratotype, but affected by NE-SW oriented slaty and pencil cleavage, which cannot correspond to the expected tectonic environment of the Santa Lucía-Aiguá-Merín rift (Rossello *et al.* 1999). Furthermore, the Las Palmas conglomerate, which overlays the stromatolitic marbles in the Mina Verdún quarry, is cut by dolerite dykes, yielding a K-Ar age of ca. 485 Ma (González *et al.* 2004). Other areas previously indicated as Barriga Negra at the North were only presented in geological sketches (Fig. 3) without map, stratigraphy nor precise location.

On other hand, Midot (1984) describes another volcanic and conglomeratic unit at the south of Uruguay named Las Ventanas Formation (Midot 1984). The units were not correlated, because it was believed that Barriga Negra Formation was sub-horizontal, undeformed and had no volcanic rocks or volcanic clasts (Midot 1984, Bossi & Navarro 1991, Blanco *et al.* 2010). However, according to the stratigraphy and lithological description presented in this work, both units can be correlated (as it was previously suggested by Sánchez Bettucci *et al.* 2010b). Las Ventanas Formation is grouped with other Neoproterozoic molassic deposits at the south of Uruguay in Playa Verde Basin (Masquelin & Sánchez-Bettucci 1993, Sánchez Bettucci & Pazos 1996, Pazos *et al.* 2003). From base to top, this basin includes the Playa Hermosa, San Carlos and Las Ventanas Formations (Masquelin & Sánchez Bettucci 1993, Masquelin 1990, Midot 1984, Rapalini *et al.* 2015) in which was recorded an interaction of extensional faulting and cold arid climate (glaciation) in a tectonically active basin with locally high subsidence rates (Pazos *et al.* 2003, 2008). Also, an alternative proposal suggested by Pecoits *et al.* (2016) puts together Las Ventanas and Barriga Negra Formations in the Maldonado Group.

In a regional context, Las Ventanas Formation was correlated with the Guaritas Formation, in Brazil (Fragoso-Cesar *et al.* 1987, Masquelin & Sánchez-Bettucci 1993, Pazos *et al.* 2003). However, radiometric data indicate that the Guaritas Formation has 535 Ma (Almeida *et al.* 2010), while Las Ventanas Formation ranges 594 and 578 Ma (Rapalini *et al.* 2015). The volcanic units under Santa Barbara Group: Acampamento Velho Formation shows ages 574 ± 4 (Ar-Ar) and Bom Jardim Group presents ages around 601 Ma (Janikian *et al.* 2008), concordant with the observed ages in Las Ventanas and Barriga Negra formations, making the correlation between these units the most plausible

option. Furthermore, these Brazilian and Uruguayan units were deposited in continental environments, under active extensional tectonism, spanning the time of the Gaskiers Glaciation and ending of Marinoan/Varanger Glaciation (Pazos *et al.* 2003, 2008, Janikian *et al.* 2008).

Finally, it is proposed here a new stratigraphy for the Barriga Negra Formation based on detailed field work, petrography, and structural relationships. This formation is divided into four members, from bottom to top:

1. Volcaniclastic Member;
2. Arkosic Conglomerate Member;
3. Calcareous Conglomerate Member;
4. Petromictic Conglomerate Member.

This succession represents a continental conglomeratic sequence developed in arid and active tectonic environment (rift-basin) deposited after 632 Ma. The relationships between the basement and the Barriga Negra Formation are either erosional unconformities or fault contacts. Different basement rock-successions locate under

the Barriga Negra Formation, including orthogneisses and low-grade metamorphic marbles, schists, metaconglomerates and quartzites, which represent Archean to Neoproterozoic metamorphic series. Also, Neoproterozoic and Mesozoic tectonic events affected the unit showed by ductile deformation and regional and hydrothermal metamorphism. The last event that affected this unit corresponds to the Mesozoic extensional event.

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