ABSTRACT: Facies and stratigraphic analysis were carried out in Neoproterozoic-Lower Paleozoic carbonate-siliciclastic deposits of Cacoal and Pimenta Bueno formations exposed on basement rocks and into the Pimenta Bueno Graben, northwestern portion of Parecis Basin, southwesternmost Amazon Craton. The redescription and redefinition of this succession confirmed the previous interpretation for the Cacoal Formation as a Marinoan (~ 635 Ma) cap carbonate. The Cacoal Formation is subdivided here in two units separate by sharp contact found exclusively overlying Mesoproterozoic crystalline basement rocks: 1) a homonymous formation characterized by diamictites, sandstones and siltstones with dropstones interpreted as glacio-marine deposits; and 2) the Espigão d’Oeste Formation that consists of dolostone, dolomitic stromatolites, dolostone-siltstone rhythmite and siltstone interpreted as shallow to moderately deep platform deposits. The Ordovician to Silurian Pimenta Bueno Formation is a filling of Pimenta Bueno graben and overlies locally the Mes and Neoproterozoic rocks. This unit consists in diamictites, sandstones, siltstones and pelites interpreted as glacial-marine and tide- to storm-influenced platform deposits, recording a glacio-eustatic regressive-transgressive event. This new stratigraphic proposal modify the current stratigraphy for the Parecis Basin and suggest, at least, two levels of glaciation exposed in the southwesternmost Amazon Craton related to the Marinoan and Late Ordovician-Early Silurian events.

KEYWORDS: Pimenta Bueno Graben; Parecis Basin; Amazon Craton; stratigraphic redefinition; Neoproterozoic.

INTRODUCTION

The more ancient sedimentary cover in the Southwesternmost Amazon Craton is represented by a carbonate-siliciclastic succession which overlies Precambrian crystalline basement rocks and fill the Pimenta Bueno Graben (PBG), a geotectonic feature linked to the evolutive history of the Paleozoic Parecis Basin (Fig. 1). This succession has been traditionally attributed to the Cacoal and Pimenta Bueno formations of Lower Paleozoic age (Siqueira 1989, Siqueira & Teixeira 1993, Pedreira & Bahia 2000, Pedreira & Bahia 2004, Bahia et al. 2006, Bahia 2007). Originally, conglomerates and dolostones included in Cacoal Formation were described and interpreted, respectively, as alluvial fans and deltaic depositional system developed in rift-phase of the Paleozoic Parecis Basin (Bahia et al. 2006). However, Gaia et al. (2017) based on facies analysis, carbon isotope and correlation with previously carbonate occurrences in the State of Mato Grosso, Mid-western Brazil, the Cacoal Formation was reinterpreted as glacial and shallow to moderately deep platform deposits, which represent a Neoproterozoic cap carbonate linked to the Marinoan glacial event (~ 635 Ma). In this new conception, Neoproterozoic Cacoal deposits represent a sedimentary cover of Amazon Craton completely disconnected of the Parecis Basin evolution.

Outcrop-based stratigraphic and facies analysis carried out in the Cacoal, Pimenta Bueno and Espigão d’Oeste regions, State of Rondônia, allowed the redescription
and redefinition of the carbonate-siliciclastic succession exposed in the Pimenta Bueno Graben, Northwestern portion of Parecis Basin, Southwesternmost Amazon Craton (Fig. 1). This analysis corroborates the proposal of Gaia et al. (2017) for the Cacoal Formation and subdivides this unit into:

- a basal homonymous unit composed basically of diamictites and sandstone; and
- the Espigão d’Oeste Formation, that represents the cap dolomite following the formal definition in the context of Snowball Earth hypothesis (cf. Hoffman & Schrag 2002, Nogueira et al. 2003).

The inference of Neoproterozoic age for the basal glaciogenic deposits and cap carbonate (Cacoal and Espigão d’Oeste formations) opens a discussion about the age for the overlaid glaciogenic deposits of the Pimenta Bueno Formation, previously considered as Carboniferous (Pedreira & Bahia 2004, Bahia et al. 2006). The detailed stratigraphic and paleoenvironmental reconstitution proposed here indicate,

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Figure 1. Geologic map of studied area. (A) Location of the Amazon craton and Neoproterozoic cap carbonate occurrences. (B) Pimenta Bueno Graben (PBG) showing sections studied and occurrences of Neoproterozoic cap carbonate successions generally overlying crystalline basement rocks. (C) Quarry of the Rondônia Mining Company - RMC quarry.
at least, two glacial levels for the lithostratigraphy of the PBG and its basement, providing a better understanding of the evolutionary history during the Late Neoproterozoic to Early Paleozoic in this part of the Amazon Craton.

GEOLoGICAL SETTING AND STRATIGRAPHIC NOMENCLATURE

The PBG together with the Colorado Graben form a distinct forked structure trending NW-SE and SW-NE restricted to the Northwestern Parecis Basin (Fig. 1). For decades, both grabens were included in the Rondônia sub-basin, belonging to the Paleozoic Parecis Basin, an intracratonic basin with approximately 500,000 km², covering the central and north regions of the State of Mato Grosso and the eastern part of the State of Rondônia, Mid-western Brazil. The Parecis Basin is filled with Phanerozoic sedimentary deposits and, locally, volcanic rocks which unconformably overlie the Paleoproterozoic/Mesoproterozoic basement rocks of the Amazon Craton (Almeida 1983, Siqueira 1989, Tassinari & Macambira 1999, Santos et al. 2000).

Stratigraphic proposals for PBG started in the late 1970’s with the study by Pinto Filho et al. (1977), who distinguished three sequences informally nominated PCI, PCII and PCIII. Siqueira (1989) proposed, for the first time, a formal stratigraphic framework for the PBG that included, from base to the top, the Cacoal, Pimenta Bueno and Fazenda da Casa Branca formations. Caputo (1984) described the occurrence of foraminifera (fusulinids) in carbonate sediments above the Pimenta Bueno Formation and suggested a correlation with the Itaituba Formation (Solimões/Amazonas Basin) and the Tarma Formation (Peru). However, this unit proposed by Caputo (1984) was never recognized in surface and subsurface investigation, and fossil data never was published and really confirmed.

The siliciclastic and carbonate rocks in the PBG were grouped by Scandalora et al. (1999) in the Primavera Group, but this term fell into disuse. The nomenclature suggested by Siqueira (1989) was kept on subsequent works (Bahia & Pedreira 1996, Bahia et al. 1996, Pedreira & Bahia 2000, 2004, Bahia et al. 2006). Rizzotto et al. (2004) used the name Rolim de Moura Formation in substitution to Cacoal Formation, due to the duplicity of name with the Intrusive Suite Cacoal. Recently, Quadros & Rizzotto (2007), based purely on lithological criteria, proposed the division of the Pimenta Bueno Formation, creating the Pedra Redonda Formation for the diamictites beds (Fig. 2). Although this new denominations simplifies the lithostratigraphic terms, it does not clarify a distinction between different diamictites, hindering a possible separation of glacial events. Nevertheless, at least two glacial levels have been described in the stratigraphy of Parecis Basin, with the one considered more ancient being Ordovician-Silurian age (Fig. 2). The previous lithostratigraphic studies of this basal interval do not differentiate units belonging to the Precambrian basement from those exclusively linked to the evolution of the Paleozoic basin. In fact, the differentiation of diamictites of same provenance is not a easy task, because glacial processes occurs in continental scale and generally transpass the basin limits, resulting in the overlap of different glaciogenic deposits, which causes misunderstanding of interpretation.

The inference of Neoproterozoic age for Cacoal Formation by Gaia et al. (2017), related to the Marinoan glacial event (~ 635 Ma), basically indicates the ages of glacial levels in the studied region (Fig. 2). Following this new conception, it is important to verify which of the more ancient units of the Parecis Basin are exposed only in the PBG and Colorado Graben. More than 95% of the sedimentary deposits in this basin are post-Silurian. Pointedly, we conclude that the PBG and Colorado Graben are uplifted features with Precambrian basement rocks (crystalline rocks and Neoproterozoic cap carbonate) underlaid by Paleozoic siliciclastic deposits, in part glaciogene, that fill this depressions.

FIELD PROCEDURES AND METHODS

The stratigraphic framework proposed here is based on standard procedure for redescriptions and redefinitions, according to Petri et al. (1986). The units show expressiveness, lithological uniformity, continuity and mappability along the northeastern edge of the PBG, where we concentrate the main stratigraphic sections. Facies analysis and stratigraphic correlation followed the concepts showed in Walker (1992). The sections carried out in open pit quarries and outcrops were sampled, measured, and examined in detail. The samples collected followed the facies separation, submitted afterwards to petrography and x-ray diffraction analysis. The thin sections were stained by a mixed solution of alizarin red and potassium ferrocyanide, in order to distinguish between calcite and dolomite (Dickson 1960). The carbonate rocks nomenclature was based on the classification introduced by Dunham (1962).

LITHOSTRATIGRAPHY AND DEPOSitional SYSTEM

The siliciclastic-carbonate succession in the studied area has an estimated thickness of up to 250 meters, obtained by stacking of stratigraphic sections, forming
a composite section separated by two main stratigraphic surfaces or sequence boundaries (Fig. 3). In our proposal, the basement rocks include both crystalline and sedimentary rocks, considering which Neoproterozoic cap carbonate succession (diamictites and carbonates) represents a basement sedimentary cover redefined as the Cacoal Formation, composed of diamictites, and the Espigão d’Oeste Formation, made up of carbonates (Fig. 4). The proposition of Espigão d’Oeste Formation is fully justified by its mappability and because it represents the dolomitic unit of a post-glacial cap carbonate (Nogueira et al. 2003, Allen & Hoffman 2005, Gaia et al. 2017). Thus, as in other Precambrian sites worldwide, the cap carbonates are formally contextualized in lithostratigraphic units and, similarly, the basal contact is considered the limit between Late Cryogenian and Ediacaran periods (Kennedy 1996, Hoffman & Schrag 2002, Nogueira et al. 2003, Xiao et al. 2016).

Based on stratigraphic relationships, we corroborate with Gaia et al. (2017), considering the Pimenta Bueno as exclusively Lower Paleozoic (Fig. 4). Table 1 shows a brief description and depositional settings of the sedimentary succession described in the PBG.

### Cacoal Formation

#### Description

The Cacoal Formation unconformably overlies the basement rocks of the Amazonian Craton in the northeastern border of the PBG. The 10m-thick Cacoal Formation consists in lenticular to sub-horizontal beds of diamictites and sandstone (Figs. 3 and 4). The reddish to purplish clayey/silty matrix of massive diamictites exhibits poorly sorted clasts composed of angular to subrounded pebbles and cobbles (Figs. 5A and 5B). The clast composition include granite, gneiss, schist, volcanic rocks, rhyolite, sandstone, quartzite and other undifferentiated rock fragments. Faceted, polished and striated clasts are commonly found (Fig. 5C). The diamictite is overlaid by laminated siltstone and fine- to medium-grained sandstone with massive bedding or climbing ripple-cross lamination (Figs. 5D and 5E). Locally, isolated clasts disrupt and cut the underlying laminae.

#### Interpretation

The diamictites of the Cacoal Formation were previously interpreted by Bahia et al. (2006) as alluvial fans and, afterwards, considered as glacial deposits by Gaia et al. (2017). The glaciogene origin is corroborated here, considering the...
Figure 3. Stratigraphic sections of the Pimenta Bueno Graben. The composite section reach almost 250 meters thick. The SB1 represent the Marinoan post-glacial marine transgression surface and SB2 is interpreted as limit between Neoproterozoic (Ediacaran) and Paleozoic (Ordovician-Silurian) deposits.
Figure 4. Lithostratigraphy of the Pimenta Bueno Graben, Southwesternmost Amazon Craton.

Table 1. Description and paleoenvironmental interpretation for units of the Pimenta Bueno Graben, Southwesternmost Amazon Craton.

| Period                          | Unit                             | Description                                                                                                                                                                                                 | Depositional settings                                      |
|---------------------------------|----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------|
| Cryogenian                      | Cacoal Formation                 | Sheet-like to lenticular bodies (dm to m-scale) of matrix-supported massive diamictite showing granules to boulders. Siltstone and fine-medium grained sandstones with ripple cross lamination and massive bedding occurring upsection. Dropstones are found locally in the diamictite matrix. | Glacio-marine                                              |
| Ediacaran                       | Espigão d’Oeste Formation        | Meters-thick tabular beds, composed of doloboundstone showing irregular and millimetric microbial lamination, and pinkish dolomudstone/dolopackstone with even parallel lamination, gently undulated lamination and low-angle truncations. Microcrystalline peloids are the major components, occurring isolated or in aggregates (clotted texture). Dolostone/siltstone rhythmite and even parallel laminated reddish siltstone predominate in the upper portion of this formation. | Shallow-marine to moderately deep mixed platform           |
| Late Silurian to Early Ordovician | Pimenta Bueno Formation          | Lower Member: Metric layers composed of matrix-supported massive diamictite with granular to boulder clasts interbedded with sigmoidal cross-stratified sandstone and pelites displaying scattered clasts. Upper Member: Tabular sandstone beds separated by mud drapes with metric thickness, laterally continuous for dozens to thousand meters. The well-sorted, fine-grained sandstone exhibit hummocky and swaley cross stratification, even parallel stratification and low-angle truncation interbedded with laminated pelite. Tidal rhythmite and fine- to medium-grained sandstone with tabular/tangential cross bedding and mud drapes in the foresets. Fine- to medium-grained sandstone with concave to sigmoidal cross bedding and massive bedding are locally bioturbated by Planolites, Lockeia and Skolithos | Glacio-marine and glacio-deltaic Lower to upper shoreface/subtidal and lacustrine-deltaic |
immature sedimentary texture and the poorly sorted grains in diamictites, indicating the low capacity of glaciers to select sediments during transport. Faceted, polished and striated clasts indicate abrasion of the particles among themselves and with the substrate during transport (Eyles & Eyles 1992). The clayey/silty matrix of the diamictite was formed by abrasive process during glacier displacement. In the final stages of Marinoan glaciation, the ice retreat provided the installation of platformal and coastal environments where sediments supplied by ice-melt waters were reworked by wave and weak currents. The presence of scattered clasts (dropstone) in siltstone and sandstone are interpreted as rain-out or ice-rafted debris (Brodzikowski & Van Loon 1987, Brodzikowski & Van Loon 1991, Eyles & Eyles 1992, 2010).

Espigão d’Oeste Formation

Description

The Espigão d’Oeste Formation consists of a 20 m-thick succession formed by tabular beds of dolostone and fine-grained siliciclastics, laterally continuous for hundreds of meters (Fig. 3). The sedimentary bedding trends NW-SE (~120° Az), dipping gently (3° up to 15°) towards SSW to the center of PBG. The facies/microfacies of this unit include microbial laminates (doloboundstone), peloidal dolomudstone/dolopackstone, dolostone/siltstone rhythmite and siltstone (Figs. 3 and 4).

A basal sharp contact that separates glaciogene sediments (Cacoal Formation) from the cap carbonate succession (Espigão d’Oeste Formation) is exposed in the northeastern border of the PBG. The contact zone is extremely irregular and, commonly, form metric-scale open folds with interlimb angle between 120° to 70°, differentiating from small undulation of microbialites (Fig. 6A). Light-gray to pinkish-gray doloboundstone exhibits distinct to diffuse parallel lamination. Fibrous calcite is locally present, partly lined following the lamination, sometimes filled with microporous dolomudstone/dolopackstone (Fig. 7A) overlies the doloboundstone. Locally, even-parallel and low angle truncated lamination. Fibrous calcite is locally present, alternating with dolostone beds. The lamination consists of millimetric laminae of microcrystalline dolomite with well-preserved micropeloids, interbedded with thick laminae of macropeloids and micropeloids (Fig. 7B). The interpeloidal cement is characterized by xenotopic crystals of dolomite (Fig. 7B). Micropeloids range up to 0.05 mm in diameter, and are well-sorted and well-rounded, isolated and exhibit clotted (grumose) texture. Macropeloids are common in dolomudstone/dolopackstone, with even parallel and low angle truncated lamination, generally forming discontinuous inverse-graded lenses (Fig. 7C). Macropeloids generally are spherical to subspherical, ranging from 2 to 5 mm in diameter, and are constituted of micropeloid clusters (Fig. 7D).

The upper portion of the Espigão d’Oeste Formation is characterized by dolomudstone/dolopackstone, alternating with fine siliciclastics forming rhythmites of usually less than 3 or 4 mm (Fig. 7E). Even parallel lamination is locally undulated, occasionally associated with ripple marks, representing the main structure of the succession. Thin laminations are composed by millimetric layers of microcrystalline and microparticulate dolomite. Very fine silt to very fine sand-sized detrital terrigenous form the granulometry of the environment, gradually develop stratiform laminae showing even parallel lamination (Figs. 3 and 7G).

Interpretation

The fine laminated dolostone and siltstone of the Espigão d’Oeste Formation have been interpreted as deposits formed in shallow marine platform environment that gradually become moderately deeper (Gaia et al. 2017). The presence of thickly microbial laminites with peloids and fenestral porosity, suggest carbonate precipitation induced by microbial activity, probably sulfate, reducing bacteria in microbial mats (Riding 2000, James et al. 2001, Font et al. 2010, Pruss et al. 2010, Bosak et al. 2013, Romero et al. 2016). The recurrent laminae (biofilms) is the result of microbial activity, alternating with periods of low activity or biochemical inactivity (Pruss et al. 2010, Bosak et al. 2013). The irregular wavy macroscopic form of the microbial laminites implies initially a colonization of irregular substrate that, due the low energy of the environment, gradually develop stratiform laminae (Figs. 6A and 6B).

Waves action are indicated by dolomudstones/dolopackstones with even-parallel lamination, quasi-planar lamination, ripple marks and low angle truncated lamination. Macropeloids associated with low angle truncated lamination and ripple marks suggest and environment with relatively high-energy waters. Therefore, the preservation and
Figure 5. Deposits of the Cacoal Formation. (A) Massive (matrix-supported) diamictite showing blocks and faceted clasts. (B) Reddish to purplish clayey/silty matrix of diamictite. (C) Volcanic clast displaying grooves and striations (white arrows). (D) Massive sandstone with scattered clasts. (E) Fine-grained sandstone with climbing ripple-cross lamination and isolated clasts. Pen in the photos=15 cm, hammer=30 cm.
Figure 6. Contact zone between the Espigão d’Oeste and Cacoal formations. (A) Microbial lamination in doloboundstone on first centimeters of the Espigão d’Oeste Formation. (B) Schematic representation of (A). Note that microbial undulated laminae grade vertically to stratiform stromatolite. (C) Photomicrography showing the alternation of microbial laminites texture marked by fenestras, peloidal dolomite and dolomicrospar. Abbreviations, Dbm, microbial doloboundstone, Dp, peloidal doloboundstone. Hammer=30 cm.
Figure 7. The upper portion of the Espigão d’Oeste Formation. (A) Even parallel laminated dolomudstone/dolopackstone. (B) Peloidal dolopackstone with normally graded bedding; arrows indicate dolomite cement in interpeloidal porosity. (C) Dolumudstone/dolopackstone with quasi-planar and low angle truncated laminations marked by macropeloids lens (white arrows). (D) Macropeloids (Mp) and micropeloids cemented by dolomicrospar. (E) Dolomudstone/dolopackstone interbedded with siltstone forming rhythmite. (F) Siltstone laminae interbedded with dolomudstone in rhythmic facies, quartz grains are detached by light blue color. (G) Metric layers of reddish siltstone with even parallel lamination. Pen in the photo=15 cm, hammer=30 cm.
irregular distribution of macropeloid lens indicate deposition in situ, with little or no transport (James et al. 2001). In addition, the well-preserved peloids also indicate rapid cementation (Kennedy 1996, James et al. 2001).

The predominance of rhythmic deposition of dolomuds and fine siliciclastics in the upper portion of the Espigão d’Oeste Formation indicated increased water depth, similarly to what was observed in others cap carbonate worldwide, such as in the Amazon Craton (Hoffman & Schrag 2002, Nogueira et al. 2003). Additionally, the higher siliciclastic input probably contributed to the inhibition of carbonate precipitation in the moderately deep platformal environment (Williams et al. 2008, Gaia et al. 2017).

**Pimenta Bueno Formation**

**Description**

The Pimenta Bueno Formation consists essentially of siliciclastic rocks that unconformably overlie the Marinoan cap carbonate of the Espigão d’Oeste Formation (Figs. 3 and 4). The lower portion of this unit is characterized by diamicites interbedded with sandstones, siltstones and pelites. The diamicites are massive and display a fine-grained purplish to reddish matrix (silt and clay) with poorly sorted, subangular to angular clasts, ranging from millimeters to centimeters in diameter (Fig. 8A). The clasts composition includes granite, gneiss, schist, siltstone, basic volcanic rocks, and other undifferentiated lithotypes (Fig. 8B). The clasts are commonly faceted and striated. The diamicite is recurrent in the succession and generally are interbedded with fine-to-coarse-grained sandstone showing sigmoidal cross-stratification and massive bed ding (Fig. 8C). Locally, metric-scale lens of massive sandstones are found interbedded with diamicites (Fig. 8D). Dump structures and synsedimentary subvertical faults occur at the base of sandy lobe (Fig. 8E). Even parallel laminated siltstone occurs in the lower portion of unit (Fig. 8F).

The upper portion of the Pimenta Bueno Formation is marked by the disappearance of diamicites and pelite with dropstone. Tabular beds and laterally continuous from dozens to hundred meters of sandstone, siltstone, rhythmite and pelitic rocks prevail. The reddish-brow fine- to medium-grained sandstones present well-sorted and rounded grains, displaying hummocky and swaley cross-bedding and, subordinately, ripple cross-lamination, low-angle and even parallel laminations (Fig. 9A). Moreover, there are sandstones with tabular/tangential cross stratification exhibiting mud drapes in the foresets (Figs. 9B and 9C). Symmetrical and asymmetrical ripple marks occur in fine-grained sandstone. The sandstone beds are individualized by centimetric layers of purplish laminated pelite. In the sandstone/pelite interface, flow structures and soft-deformation structures, such as sole marks and balls-and-pillows, are observed. flute casts and synaeresis cracks are locally preserved. Sandstone/pelites rhythmite with flaser and wavy bedding occurs associated with cross-bedded sandstone (Fig. 9B). Near to the Cacoal city, pelitic beds interbedded with sigmoidal cross-stratified sandstones and massive sandstones (Fig. 9D) also occur. Bioturbation is rare, and trace fossils were observed locally, such as *Planolites*, *Lockeia* and *Scoilithos* (Figs. 9E and 9F).

**Interpretation**

The Pimenta Bueno Formation was deposited in a complex environment, including glacial and post-glacial conditions, and a storm- and tide-dominated setting. The massive diamicites and pelitic beds with scattered clasts suggest the influence of glaciers covering an extensive area in the Amazon Craton during the Ordovician-Silurian. Diamictons were produced by intense abrasion of glacier on basement rocks (Eyles et al. 1985, Powell 1990, Eyles 1993, Eyles & Eyles 2010). The recurrence of phases of retreat and advance of ice generated different environments and explain the cyclicity observed in the Pimenta Bueno succession. During the advance phase the diamictons were the main sedimentation formed mainly on the base of glaciers as lodgement till (Eyles et al. 1985, Powell 1990, Eyles 1993, Eyles & Eyles 2010). The ice cover retreat episodes were characterized by the increase of discharge of ice-melt waters, allowing the installation of stream flows and progradation of deltaic system. The melting icebergs or floating ice shelves released sediment incorporated by ice directly over deltaic and platformal deposits (Eyles & Eyles 2010). Lens of pebbly sandstone found in the deltaic deposits of the Pimenta Bueno Formation suggest ice-rafted debris from icebergs during phases of ice-reatreat.

After the main glacial episode, the post-glacial eustatic rise allowed the development of storm- and tidal-dominated environments. The presence of hummocky cross-stratified sandstone and amalgamated layers swaley cross-stratified sandstone suggest recurrence of storms in shallow marine environment (Harms et al. 1975, Dott & Bourgeois 1983, Duke 1985, Dumas & Arnott 2006, Vakarelov et al. 2012). Coastal environments were installed on the border of Amazon Craton, and the occurrence of storms suggests subtropical paleolatitude.

Deformational structures and synaeresis crack were induced by compaction and rapid sedimentation by a high amount of sedimentary overload of sandstone/pelite (Plummer & Gostin 1981, Allen 1982, Pratt 1998). Tidal processes in the Pimenta Bueno Formation are characterized by intervals showing rhythmic bedding and tabular/tangential cross-bedded sandstones with mud drapes in
Figure 8. Faciologic aspect of the Lower Pimenta Bueno Formation. (A) Massive diamictites in the base of the Pimenta Bueno Formation. (B) Boulder-sized clats of granite. (C) Massive sandstone bodies overlying purplish diamictite. (D) Detail of (C) showing the alternance of coarse- to fine-grained sandstone with dimictite beds and lenses. (E) Pebby sandstone in irregular lenses interpreted as dump structure. (F) Even parallel laminated siltstone. Hammer=30 cm.
Figure 9. Upper portion of the Pimenta Bueno Formation. (A) Amalgamated hummocky cross-stratified fine sandstones and interbedded laminated pelites. (B) Rhythmic alternance of very fine-grained sandstone and pelites, the top of sandstones are undulated and mud drapes separated the beds (arrows). (C) Detail of thin mud drape in the foresets and separating beds. (D) Sandstone exhibiting sigmoidal lobe geometry. (E) Trace fossils of Planolites (P) and Lockeia (L). (F) Vertical burrows of Skolithos (S). Hammer = 30 cm. Pen = 15 cm.
the foresets interpreted as tidal bundles, suggesting alternation of bed load and suspension load deposition linked to tidal cycles (Dalrymple & Choi 2007, Dalrymple 2010, Longhitano et al. 2012). The presence of tidal processes in the upper portion of the Pimenta Bueno succession indicates connection to ocean and seas, most likely devoid of glaciation, representing an expressive interval of long term transgression.

The expressive beds, composed of pelites interbedded with amalgamated sigmoidal to complex cross-bedded sandstone, constitute the uppermost unit of the Pimenta Bueno Formation (Fig. 3). The rapid deceleration of terrigenous

| AGE          | SOUTHWESTERN MOST AMAZON CRATON | SOUTHWESTERN AMAZON CRATON (Nogueira et al. 2006) | PARAGUAY BELT (Nogueira et al. 2008, Bandeira et al. 2011, Santos et al. 2017) |
|--------------|---------------------------------|---------------------------------------------------|---------------------------------------------------------------------------|
| PALEOZOIC    |                                 |                                                   |                                                                           |
| SILURIAN     |                                 |                                                   |                                                                           |
| 443 Ma       |                                 |                                                   |                                                                           |
| CAMBIAN      |                                 |                                                   |                                                                           |
| 485 Ma       |                                 |                                                   |                                                                           |
| ORDOVICIAN   |                                 |                                                   |                                                                           |
| 541 Ma       |                                 |                                                   |                                                                           |
| NEOPROTEROZOIC |                               |                                                   |                                                                           |
| EDIACARAN    |                                 |                                                   |                                                                           |
| E. KRYOGEN  | Espiglo d’Oeste Formation Cap |                                                    |                                                                           |
| 635 Ma       |                                 |                                                   |                                                                           |
| LATE KRYOGEN | Cacoal Formation                | Pug Formation                                     |                                                                           |
| 720 Ma       |                                 |                                                   |                                                                           |
| BASEMENT     | Amazon Craton                   | Amazon Craton                                      |                                                                           |
|              |                                 |                                                   |                                                                           |

Figure 10. Stratigraphic units of the Southwesternmost Amazon Craton and its correlation with Neoproterozoic-Lower Paleozoic units of the Amazon Craton and Paraguay belt.
influx forms the layers of lobate to massive sands. Fine sandstones with cross-lamination corroborate the occurrence of the tractive and suspension processes. This deposits have been interpreted as proximal mouth bars linked to the deltaic deposits. The delta progradation occurred in shallow waters lagoons, lake, or epicontinental ocean (cf. Postma 1990, Nichols 2009, Renault & Gierlowski-Kordesch 2010). The presence of Planolites, Lockelia and Skolithos attest high-energy environments and probably the fully marine character of the succession (Pemberton et al. 1992, Buatois & Mángano 2009, Desjardins et al. 2010, MacEachern et al. 2010, Harazim et al. 2013, Santos et al. 2017).

**STRATIGRAPHIC CORRELATIONS**

The glaciogenic deposits underlying cap carbonates are widely distributed in Neoproterozoic successions but are most commonly associated with the Marinoan event (Corsetti & Lorentz 2006, Fairchird & Kennedy 2007, Li et al. 2013, Shields-Zhou et al. 2016). This event marked the end of the Cryogenian Period (ca. 720–635 Ma) and represents one of the most severe glaciations in Earth history (Hoffman et al. 1998, Fairchird & Kennedy 2007, Prave et al. 2016). Cap dolostones were deposited in transgressive seas over formerly glaciated continental margins during Marinoan snowball glaciation (Creveling & Mitrovica 2014). It is formed by pink-colored, thinly-laminated dolostone that contains unusual sedimentary structures and commonly has negative δ¹³C values (< -5‰) (Kaufman & Knoll 1995, Kaufman et al. 1997, Jiang et al. 2006, Sato et al. 2016). Large negative C-isotope excursions in the Neoproterozoic times are generally associated to the postglacial carbonate succession and probably reflect oceanographic processes (Kaufman et al. 1991, Kaufman et al. 1997, Hoffmann et al. 1998). In Brazil, several studies conducted in the southwestern Amazonian Craton recognized diamicrite underlying post-glacial carbonate Neoproterozoic successions (Nogueira et al. 2006, Alvarenga et al. 2008, Soares & Nogueira 2008, Soares et al. 2013).

The Espigão d’Oeste cap dolostones, which overlay the glacial diamicites of the Cacoal Formation exposed on the edge of the PBG, were compared to other post-Marinoan cap carbonates using sedimentary facies, stratigraphic relationship and carbon isotope profiles (cf. Gaia et al. 2017). The carbonate succession herein described have similarities to other coeval cap carbonates, such as: pink color, finely lamination, crystalline dolostone, presence of microbial laminites and typically peloidal fabric composed of micro and macropeloids. In addition, the δ¹³C of the Espigão d’Oeste cap dolostones exhibits typically negative values around -4‰ and -2‰ (Dardenne et al. 2005, Afonso 2016, Gaia et al. 2017). These values are comparable with δ¹³C profiles of post-late Cryogenian units of Southern Paraguay Belt (Nogueira et al. 2007, Alvarenga et al. 2008, Sial et al. 2016) and other cap carbonates formed after Marinoan glaciation (Kennedy 1996, James et al. 2001, Hoffman & Schrag 2002, Halverson et al. 2010).

The age of the Pimenta Bueno Formation is still uncertain. Pinto Filho et al. (1977) based on pollen assemblage affiliated to vegetal groups of the Pterophyta and Lycopodophyta, attributed Permo-Carboniferous Age to this unit. Cruz (1980) described the acritarch Synsphaeridium sp., in black shales exposed near Cacoal city, suggesting a Siluro-Devonian age. According to Bahia (2007) this fossil represents an evidence for Permo-Carboniferous Age, while for Goldberg et al. (2011) the acritarch genus can inequivocally suggest ages near to the Silurian-Devonian limit. However, the Synsphaeridium sp. is described since Neoproterozoic age deposits, providing a large age interval and compromising the use of this genus as inference of age (Vidal et al. 1994, Stanevick et al. 2005, Teysse`dre 2006). The stratigraphic relationship described here revealed the existence of an angular unconformity at the base of the Pimenta Bueno Formation with the Espigão d’Oeste Formation. In this study, we suggest the Silurian age to the Pimenta Bueno Formation, conferring especially the Llandovery Epoch, compatible with the first glacial episodes in intracratonic basins such as the Amazon, Paraná and Parnaiba basins (Caputo 1984, Assine 1996, Assine et al. 1998, Díaz-Martínez & Grahn 2007, Cuervo 2014).

The stratigraphy of sedimentary deposits exposed in the Southwesternmost Amazon Craton is redefined, and its correlation with adjacent regions is shown in Figure 10. This new proposal, modifying the current Early Paleozoic stratigraphy for the Parecis Basin, indicates, at least, two levels of glaciation exposed in the Southwesternmost Amazon Craton related to the Marinoan and Late Ordovician-Early Silurian events. Additionally, the new stratigraphic proposal better organizes the depositional events of the Pimenta Bueno sedimentation, indicating an expressive long term (post-glacial) transgression that can be used as an important stratigraphic marker with the other Paleozoic basins.

**CONCLUSIONS**

The integration of results obtained by stratigraphic studies in the Southwesternmost Amazon Craton provided a new stratigraphic framework for the PGB, sub-basin of the Parecis Basin. According to our new proposal, the sedimentary record was subdivided into three units. The Cacoal formation is the basal unit, consisting of diamicites, sandstone/
siltstone with dropstone. The Espigão d’Oeste Formation is made up of stromatolites, pinkish dolostone, dolostone-siltstone rhythmite and siltstone. The lowermost Espigão d’Oeste is the cap carbonate deposited during post-glacial transgression related to the Marinoan event (~635 Ma). The glacial diamictite-cap carbonate couplet, once considered paleozoic, is herein considered part of the basement cover of the PGB, without relation to the Paleozoic succession of the Parecis Basin.

The Pimenta Bueno Formation unconformably overlies the Precambrian basement rocks – crystalline and sedimentary – and consists of diamictites, sandstones, siltstones and pelites, which contain widely scattered small clasts. The Pimenta Bueno Formation is positioned on the Ordovician-Silurian interval and registers a glacial event synchronous with other intracratonic basins of South America, such as Amazon, Paraná and Parnaíba basins. Post-glacial transgression promotes sea level rise with development of storm-tidal flats. The presence of Skolithos, Lockeia, and Planolites is herein considered part of the Paleozoic succession of the Parecis Basin.

Finally, this new stratigraphic proposal modifies the current Early Paleozoic stratigraphy for the Parecis Basin indicating the Marinoan and Late Ordovician-Early Silurian glacial events. The record of the last Cryogenian glaciation in the State of Rondônia expands the Snowball Earth condition to the Southwesternmost Amazon Craton. This study provides new stratigraphic guide to future research in the PGB, as well as to contribute to the understanding of the late Precambrian-Early Paleozoic boundary and sedimentary history of this part of Amazonia.

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