Sedimentology and stratigraphy of Neoproterozoic-lower Paleozoic carbonate-siliciclastic succession of the southwesternmost Amazon Craton, state of Rondônia, Brazil

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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 Meso 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

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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,

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 evolutive 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 Rondonia 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) underlain 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 redescription and redefinition, 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 1966). 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

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 dolomudstone 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 <i>Planolites</i> , <i>Lockeia</i> and <i>Skolithos</i>	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 ($\sim 120^\circ$ Az), dipping gently (3° up to 15°) towards SSW to the center of PBG. The facies/microfacies of this unit include microbial laminites (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 north-eastern 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 horizontal to irregularly-wavy microbial lamination developed immediately above the contact zone (Figs. 6A and 6B). This lamination is formed by irregular and crinkly micritic laminae dominantly composed of peloids, alternating with the thick layers of microspatic dolomite (Fig. 6C). Peloids display irregular shape, ranging from well-rounded to angular, generally poorly sorted and with sizes between 20 and $100\ \mu\text{m}$. Fenestral porosity, generally less than 1 mm, occurs partly lined following the lamination, sometimes filled with microspar and spar calcite cement (Fig. 6C).

Thinly plane-parallel laminated dolomudstone/dolopackstone (Fig. 7A) overlies the doloboundstone. Locally, dolomudstone/dolopackstone exhibits even parallel to quasi-planar lamination, changing laterally to 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 microspatic dolomite. Very fine silt to very fine sand-sized detrital terrigenous form the granulometry of rhythmic lamination, and occur concentrated in dissolution seams (Fig. 7F). The terrigenous grains include quartz, potassium feldspar, plagioclase, chert, micas and clay minerals. Siliciclastic deposits gradually increase upsection, passing gradually to expressive beds of reddish siltstone 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 laminite 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 an 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) Dolomudstone/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=15cm, 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 overlies the Marinoan cap carbonate of the Espigão d'Oeste Formation (Figs. 3 and 4). The lower portion of this unit is characterized by diamictites interbedded with sandstones, siltstones and pelites. The diamictites 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 litotypes (Fig. 8B). The clasts are commonly faceted and striated. The diamictite is recurrent in the succession and generally are interbedded with fine- to coarse-grained sandstone showing sigmoidal cross-stratification and massive bedding (Fig. 8C). Locally, metric-scale lens of massive sandstones are found interbedded with diamictites (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 diamictites and pelite with dropstone. Tabular beds and laterally continuous from dozens to hundred meters of sandstone, siltstone, rhythmite and pelitic rocks prevail. The reddish-brown 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 *Skolithos* (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 diamictites 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-retreat.

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 compactation 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 clasts of granite. (C) Massive sandstone bodies overlying purplish diamictite. (D) Detail of (C) showing the alternance of coarse- to fine-grained sandstone with diamictite beds and lenses. (E) Pebbly 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

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, Renaut & Gierlowski-Kordesch 2010). The presence of *Planolites*, *Lockeia* 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, Fairchild & 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, Fairchild & Kennedy 2007, Prave *et al.* 2016). Cap dolostones were deposited in transgressive seas over formerly glaciated continental margins during Marinoan snowball deglaciation (Creveling & Mitrovica 2014). It is formed by pink-colored, thinly-laminated dolostone that contains unusual sedimentary structures and commonly has negative $\delta^{13}\text{C}$ 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, Hoffman *et al.* 1998). In Brazil, several studies conducted in the southwestern Amazonian Craton recognized diamictite underlying post-glacial carbonate Neoproterozoic successions (Nogueira & Riccomini 2006, Alvarenga *et al.* 2008, Soares & Nogueira 2008, Soares *et al.* 2013).

The Espigão d'Oeste cap dolostones, which overlay the glacial diamictites 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 laminates and typically peloidal fabric composed of micro and macropeloids. In addition, the $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ 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 unequivocally 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, Teyssèdre 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 Parnaíba 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 PBG, 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 diamictites, sandstone/

siltstone with dropstone. The Espigão d'Oeste Formation is made up of stromatolites, pinkish dolostone, dolostone-siltstone rhythmites 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 PBG, 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 influenced shallow platform. The presence of *Planolites*, *Lockeia* and *Skolithos* corroborates the marine influence.

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 conditions to the Southwesternmost Amazon Craton. This study

provides new stratigraphic guide to future research in the PBG, as well as to contribute to the understanding of the late Precambrian-Early Paleozoic boundary and sedimentary history of this part of Amazônia.

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