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Ediacaran-Cambrian microbialites of the Southern Amazon Craton: relation with the metazoan rise, sea-level changes, and global tectonics

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Abstract

Microbialites are the most abundant life evidence in Precambrian sedimentary rocks. They are produced by microbial interaction activity and sedimentary processes reflecting paleoenvironmental conditions. The Ediacaran-Cambrian carbonate and siliciclastic successions in the Southern Amazon Craton in Central Brazil, provide a key opportunity to understand how the metazoan life coexisted with the microbial communities. The spatial and temporal distribution of microbialites as well as morphological and paleoenvironmental changes have been assessed, reinterpreting previous works and including new data from the Araras-Alto Paraguai and Corumbá basins. The deposition was controlled by subsidence and sea-level changes that affected these basins, considered extensions of epicontinental seas during the Gondwana assembly. The stromatolites are restricted to coastal deposits and experienced thriving flourishment intervals after the Marinoan Glaciation (635 Ma). Post-glacial transgression was marked by microbial colonization in shallow platforms represented by stratiform and giant domical stromatolites in the Araras-Alto Paraguai Basin. The continuity of the transgression generated a moderately deep aragonite sea at about 622 Ma. A progressive sea-level fall caused the implantation of coastal environments under greenhouse conditions with tidal flat and sabkha settings colonized by centimetric-scale stromatolites. The sea retreat was accompanied by progressive uplift, causing a moderate inversion of the basin and erosion of the succession until ~560 Ma with the deposition of the last preserved tidal flat deposits with the occurrence of thrombolites. The subsiding Corumbá Basin was the site of microbially-induced deposition of carbonates in a shallow platform connected to an offshore setting with the proliferation of metazoan straddling the Ediacaran-Cambrian boundary. Microbial communities were restricted to lagoon deposits during the Lower Cambrian transgression in the Araras-Alto Paraguai Basin and the last phase refers to the sea retreat towards southeast, developing a fluvial system connected with the arid and evaporitic tidal flats colonized by microbialites that lasted until the upper Cambrian. Except for the post-glacial stromatolites, the columnar and domal microbialite indicate that the coastal settings dominated the Ediacaran-Cambrian transition. The preservation of microbialites in the post-glacial intervals can be associated with the Mg-Ca-CO_3 oversaturation in dolomitic platforms. The rapid calcification and ability to resist the dissolution and replacement have increased the stromatolites' preservation potential reported here, where its well-preserved occurrence in tidal flats and sabkha occurs due to intense early diagenetic silicification. The change from carbonate accumulation to siliciclastic-rich environments contributed to the demise of microbially-induced strata. In general, the scarce coexistence between coastal stromatolite and metazoan-bearing marine deposits makes it challenging to establish a competitive relationship between these organisms, as previously postulated.

KEYWORDS: stromatolite; carbonate platform; Araras Group; Corumbá Group; epicontinental sea.

INTRODUCTION

Microbialites are the first occurrences of life in several Precambrian successions (Walter 1994, Riding 2006, 2011, Allwood *et al.* 2007, Schopf *et al.* 2007, Spear and Corsetti 2013, Knoll 2015, Baumgartner *et al.* 2019). Although microbialites have a low biostratigraphic resolution, they are an excellent paleoenvironmental and paleoceanographic proxy (e.g., Burne and Moore 1987, Awramik and Sprinkle 1999, Grotzinger and Knoll 1999, Riding 2000, Pruss *et al.* 2010, Bosak *et al.* 2013, Santos *et al.* 2021). Earth's Proterozoic biosphere was dominated primarily by shallow-marine and intertidal bacterial biotas, as evidenced by a strong record of microbialites preserved in laminated carbonate rocks (Peters *et al.* 2017). During the Ediacaran-Cambrian transition, a decrease in the microbialite record is postulated, with possible causes being discussed below (Pratt 1982, Grotzinger and Knoll 1999).

The evolution of carbonate to siliciclastic rocks in continental margins from the Neoproterozoic to the Cambrian-Ordovician

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may suggest a global event of sea-level changes. The increase of siliciclastic input in the continental margins indicates a depositional control related to the regional uplift linked to the collision of continental blocks of the West Gondwana (Allen and Leather 2006, Torsvik and Cocks 2013). Ediacaran carbonate platforms were gradually replaced by siliciclastic-rich environments worldwide, reducing microbial-induced strata (Allen and Leather 2006). The Phanerozoic microbialites occur in progressively more restricted settings, accompanied by the uninterrupted life complexation (Riding and Liang 2005, Riding 2006).

The inference of competition results from comparing the timing of metazoan appearance with the onset of stromatolite decline (Pratt 1982, Grotzinger and Knoll 1999, Riding 2006). This decrease in the preservation potential of the microbial mats has been associated with geochemical shifts in the Late Ediacaran to the Early Cambrian oceans and the advent of metazoan organisms (Pratt 1982, Grotzinger 1990, Grotzinger and Knoll 1999, Gingras *et al.* 2011, Peters *et al.* 2017). It is challenging to infer stromatolite grazing or disturbance by metazoans in the Proterozoic (Walter *et al.* 1992a, Walter *et al.* 1992b, Riding 2006), nevertheless, to understand its preservation in the geologic record, it is also necessary to verify changes in carbonate factory to promote early fossilization. Furthermore, other important parameters are the influence of siliciclastic input over the carbonate platform, the environmental restrictions, and the resistance of these organisms to dissolution.

The Ediacaran-Cambrian carbonate and siliciclastic successions in the Southern Amazon Craton in Brazil exhibit specific microbialite-rich intervals that indicate significant evidence for a pre- to early Phanerozoic biosphere. Microbialites are abundant in the post-Marinoan carbonate deposits (~627 Ma) of the Southern Amazon Craton, mainly in coastal and shallow marine settings (Nogueira *et al.* 2003, Romero *et al.* 2020, Santos *et al.* 2021). These occurrences belong to the Lower Ediacaran Araras Group (~627-614 Ma) and the Cambrian Alto Paraguai Group in the Araras-Alto Paraguai Basin (Santos *et al.* 2017, Nogueira *et al.* 2019) as well as the Upper Ediacaran-lower Cambrian Corumbá Group in the Corumbá Basin (Boggiani *et al.* 2010, Amorim *et al.* 2020) (Fig. 1). The carbonate succession of the Corumbá Basin is a complementary section 300 km away from the south of the Araras Alto Paraguai basin (Fig. 1). Previous outcrop-based facies analysis of these successions allowed the establishment of a robust stratigraphic database, including the positioning of microbialite strata and valuable paleoenvironmental reconstructions. (Nogueira *et al.* 2003, Boggiani *et al.* 2010, Parry *et al.* 2017, Rudnitzki *et al.* 2017, Oliveira *et al.* 2019, Amorim *et al.* 2020, Romero *et al.* 2020, Santos *et al.* 2021). We used the key surfaces represented by Cryogenian-Ediacaran and Ediacaran-Cambrian boundaries to position the classical measured sections with occurrences of microbialites (Fig. 1). In this sense, this study analyzes the spatial and temporal distribution of microbialites and changes in morphology and the paleoenvironmental context in the entire record of both the Araras-Alto Paraguai and the Corumbá basins, reinterpreting previous works and including new data.

GEOLOGIC BACKGROUND

The carbonate and siliciclastic successions from the Southern Amazon Craton have been considered exclusively of Ediacaran age and included in a single foreland-type basin with deep offshore areas towards southeast. The establishment of both Araras-Alto Paraguai and Corumbá basins was associated with the Brasiliano/Pan-African Event, which involved the Amazon, São Francisco-Congo and Paraná continental blocks (Almeida 1964, Trompette *et al.* 1998, Trindade *et al.* 2003, Alvarenga *et al.* 2007, Nogueira *et al.* 2007, Tohver *et al.* 2010, Bandeira *et al.* 2012, McGee *et al.* 2015). Recent studies indicate that these successions were deformed by transtensional tectonics and not by collisional events as previously proposed (Cordani *et al.* 2013, Nogueira *et al.* 2019, Santos *et al.* 2020). Collisional tectonics was observed only in the rocks of the underlying Cuiabá Group (currently restricted to the Paraguai Belt), marking a suture adjacent to the craton (Nogueira *et al.* 2019, Santos *et al.* 2020).

Glacial-marine deposits related to the Marinoan glaciation (635 Ma) evidence the beginning of the sedimentation in the Araras-Alto Paraguai Basin. Massive and laminated diamictite and siltstone with dropstones characterize the Puga Formation (Alvarenga *et al.* 1988, Nogueira *et al.* 2019, Santos *et al.* 2020). Post-glacial cap carbonate sharply overlies the Puga Formation and represents the basal portion of the Araras Group. The cap carbonate includes the dolostone of the Mirassol d'Oeste Formation and the limestone of the Guia Formation, both underlying the dolostones of the Serra Quilombo and Nobres formations (Nogueira and Riccomini 2006, Nogueira *et al.* 2019). The upper Nobres Formation has been attributed to the not formalized Pacu Formation (Sial et al. 2016) (Fig. 1). The base of the Araras Group has Pb-Pb age-dates of 627 ± 32 Ma and 622 ± 33 Ma for the Mirassol d'Oeste and Guia formations, respectively, indicating an early Ediacaran age (Babinski *et al.* 2006, Romero *et al.* 2013). This age has been corroborated by $\delta^{13}C$ isotopic values from -5 ‰ in the cap dolostone to -2 ‰ in the upper Araras Group, comparable with global curves (Nogueira *et al.* 2019). A Cambrian age has been inferred based on the presence of the *Skolithos* trace fossil in the siliciclastic Alto Paraguai Group, which unconformably overlies the Araras Group, pointing to a ~80 Myr interval of either a non-depositional or erosional hiatus (Santos *et al.* 2017, Nogueira *et al.* 2019).

The Corumbá Basin is situated in the southernmost portion of the Amazon Craton, exposed in the Urucum Massif and the Serra do Bodoquena domain, limited to the east by the Rio Apa Block (Boggiani *et al.* 2010, Oliveira *et al.* 2019, Amorim *et al.* 2020). The basin comprises a carbonate and siliciclastic succession organized in five formations, from the base to the top: Cadiueus, Cerradinho, Bocaina, Tamengo, and Guaicurus (Alvarenga and Trompette 1993, Boggiani 1998, Walde *et al.* 2015). The carbonate rocks from the Tamengo Formation and the siliciclastic rocks from the Guaicurus Formation are of late Ediacaran and Cambrian ages based on the occurrence of the biota composed of soft-bodied metazoan (*Corumbella*), and skeletal fossils (*Cloudina*), as well as the possible vendotaenid algae *Eoholynea* (Pacheco *et al.* 2015, Becker-Kerber *et al.* 2017,

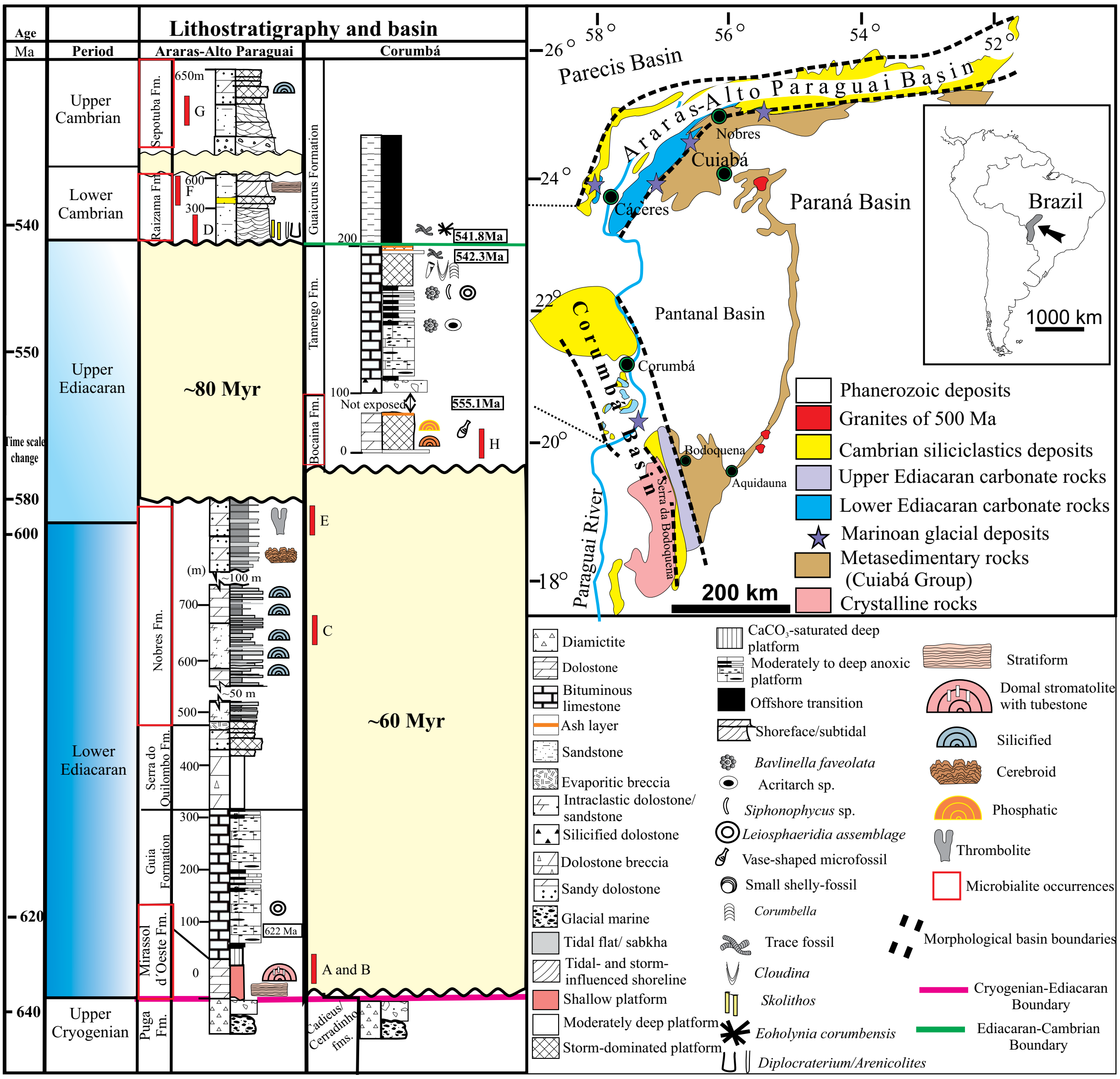

Figure 1. Location and simplified geologic map of Southern Amazon Craton. Composite lithostratigraphy and microbialite occurrences of the Ediacaran-Cambrian successions. The major gaps are found in the Lower Ediacaran in Corumbá Basin (60 Myr) and the Upper Ediacaran (80 Myr) in the Araras-Alto Paraguai Basin. Measured sections (1-7) are indicated in the composite.

Parry *et al.* 2017). Available U–Pb CA-ID-TIMS ages in ash beds indicate a 555±0.3 Ma age in the Bocaina Formation and 542 ± 0.3 Ma for the Tamengo Formation (Parry *et al.* 2017) (Fig. 1).

MICROBIALITES FROM THE ARARAS- ALTO PARAGUAI AND CORUMBÁ BASINS

Carbonate and siliciclastic rocks of the Araras-Alto Paraguai and Corumbá basins contain a variety of microbialites and structures related to microbial mats such as crinkled lamination, fenestral porosity, stratiform and domic morphology (e.g., Nogueira *et al.* 2003, Boggiani *et al.* 2010, Romero 2015, Rudnitzki *et al.* 2017, Nogueira *et al.* 2019, Romero *et al.* 2020, Santos *et al.* 2021). The microbialites are mainly distributed in the moderately deep carbonate shelf deposits and peritidal settings of the Araras and Corumbá groups, as well as the basal siliciclastic coastal sediments of the Raizama Formation (Figs. 1 and 2, Tab. 1).

Lower Ediacaran (635-614 Ma)

Stromatolites are the most typical components from the 35 m-thick Puga cap carbonate (Figs. 2A and 2B) at the border of the Amazon Craton in the regions of Mirassol d`Oeste and Tangará da Serra in Mato Grosso (Romero *et al.* 2020, Soares *et al.* 2020, Santos *et al.* 2021). The stratiform morphology is found at the base of the cap carbonate overlying laminated and low-angle stratified dolostone (Fig. 3). Meter- to decameter-scale domic and irregular wavy forms exhibit tubestone structures concentrated in the axial portion (Fig. 3). Giant stromatolites are restricted in the Tangará da Serra region, exhibitting decameter-scale domal morphology, laterally continuous for hundreds of meters, being an excellent example of bioherm. Megaripple bedding and quasi-planar lamination in dolostone and limestone occur sharply at the top of the microbial mounds. Limestone with crystal fans (pseudomorphs after aragonite) covers the stromatolite-bearing beds.

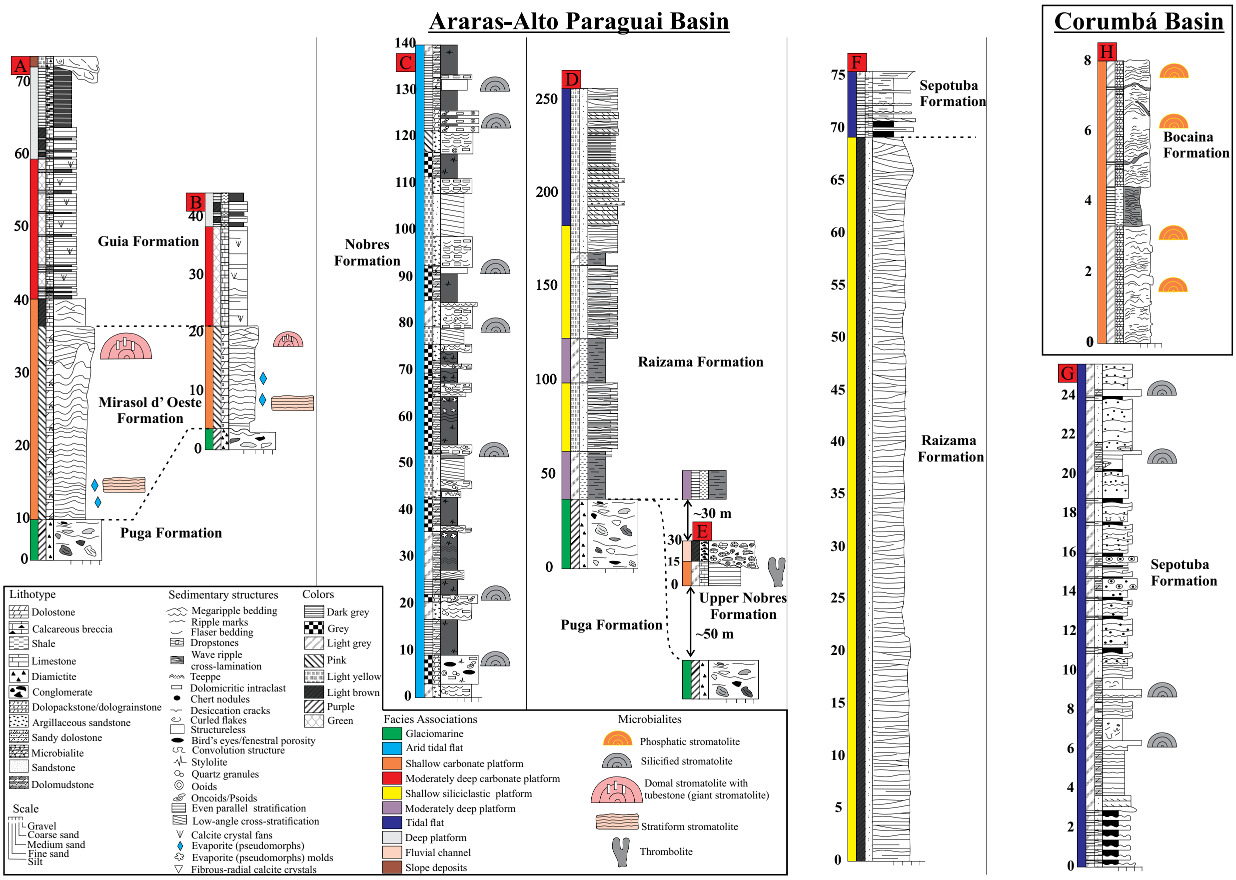

Figure 2. Ediacaran-Cambrian stratigraphic sections in the Southern Amazon Craton. The sections are indicated in Figure 1.

Table 1. Summary of microbialite occurrences through the Ediacaran–Cambrian transition in the Southern Amazon Craton.

Basin	Group	Location	Formation	Rock-type	Stromatolite				Thrombolite	References
					Columnar /Columnar-Pseudo	Domal	Stratiform	Cerebroid		
Araras/ Alto-Paraguai	Araras	Tangará da Serra region-MT	Mirassol d´Oeste	Dolomite		√	√			Soares *et al*. 2013, Santos *et al*. 2021
		Mirassol d´Oeste region-MT	Mirassol d´Oeste	Dolomite		√	√			Nogueira *et al*. 2003, Nogueira and Riccomini 2006, Font *et al*. 2010, Romero 2010, Nogueira *et al*. 2019, Romero *et al*. 2020
		Cáceres region-MT	Nobres	Chert	√	√	√	√	√	Nogueira *et al*. 2003; Nogueira and Ricomini 2006, Romero 2015, Rudnitzki *et al*. 2017, This study
	Alto-Paraguai	Glória d´Oeste region-MT	Sepotuba	Chert	√		√			Romero 2015; This study
Corumbá	Corumbá	Corumbá and Bonito region-MS	Bocaina	Dolomite	√	√	√			Boggiani *et al*. 2010, Oliveira 2010, Morais 2013, Romero *et al*. 2016
		Corumbá region-MS	Tamengo	Limestone			√			Becker-Kerber *et al*. 2017, Amorim *et al*. 2020

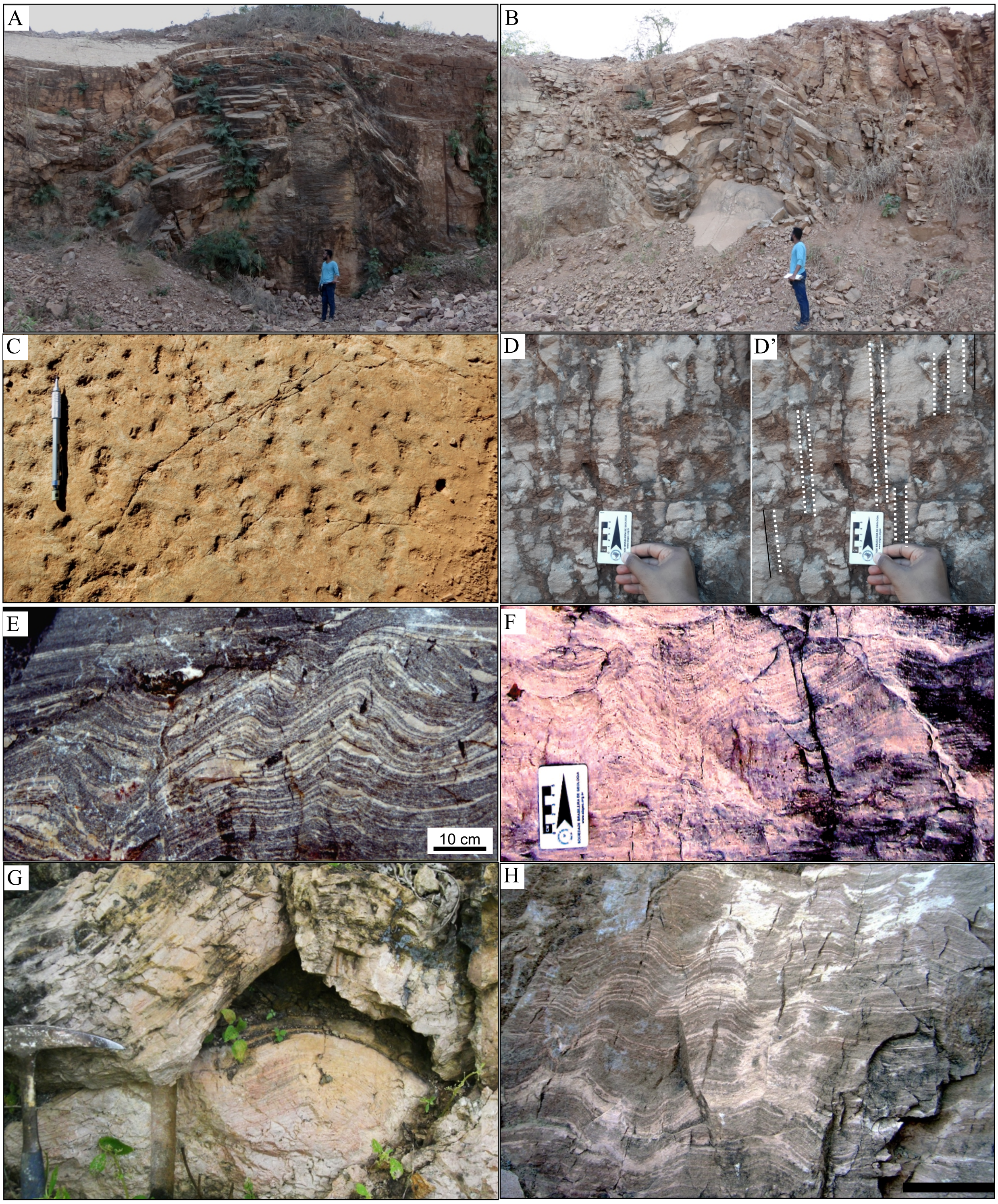

Figure 3. Puga Cap Carbonate stromatolites in the Amazon Craton. (A and B) Giant domic laterally continuous mounds. (C) Tubestone structures in plan view. (D and D') Tubestone in longitudinal view. (E) Bitumen impregnated irregularly wavy stromatolites. (F) Irregular wavy stratiform stromatolites. (G) Domal stromatolite. (H) Irregular wavy stratiform stromatolites Terconi and Calcário Tangará quarries record by Romero *et al.* (2020) and Santos *et al.* (2021).

Silicified microbialites occur at the top of the Araras Group (Nobres Formation) inside meter-scale shallowing upward cycles marking the contact between dolomudstone, laminated dolopackstone and sandstone with cross-lamination, ripple marks, and evaporite (pseudomorphs) molds. (Figs. 4A and 4B) (Rudnitzki *et al.* 2017, Nogueira *et al.* 2019). These microbialites comprise centimetric stratiform and columnar morphotypes frequently found in the Cáceres region (Figs. 1, 4C and 4D). Cerebroid morphotypes of stratiform to pseudo-columnar stromatolites overlie brecciated beds with tabular clasts (Figs. 4C, 4E, and 4F), centimeter-scale pseudo-columnar stromatolites resembling thrombolites with restricted occurrence in the Planalto da Serra region (Figs. 4G and 4H).

Upper Ediacaran (555-541 Ma)

Microbialites from the Corumbá Basin occur associated with meter-scale shallowing upward cycles composed of dolomitized carbonate in the Bocaina Formation, in the Corumbá and

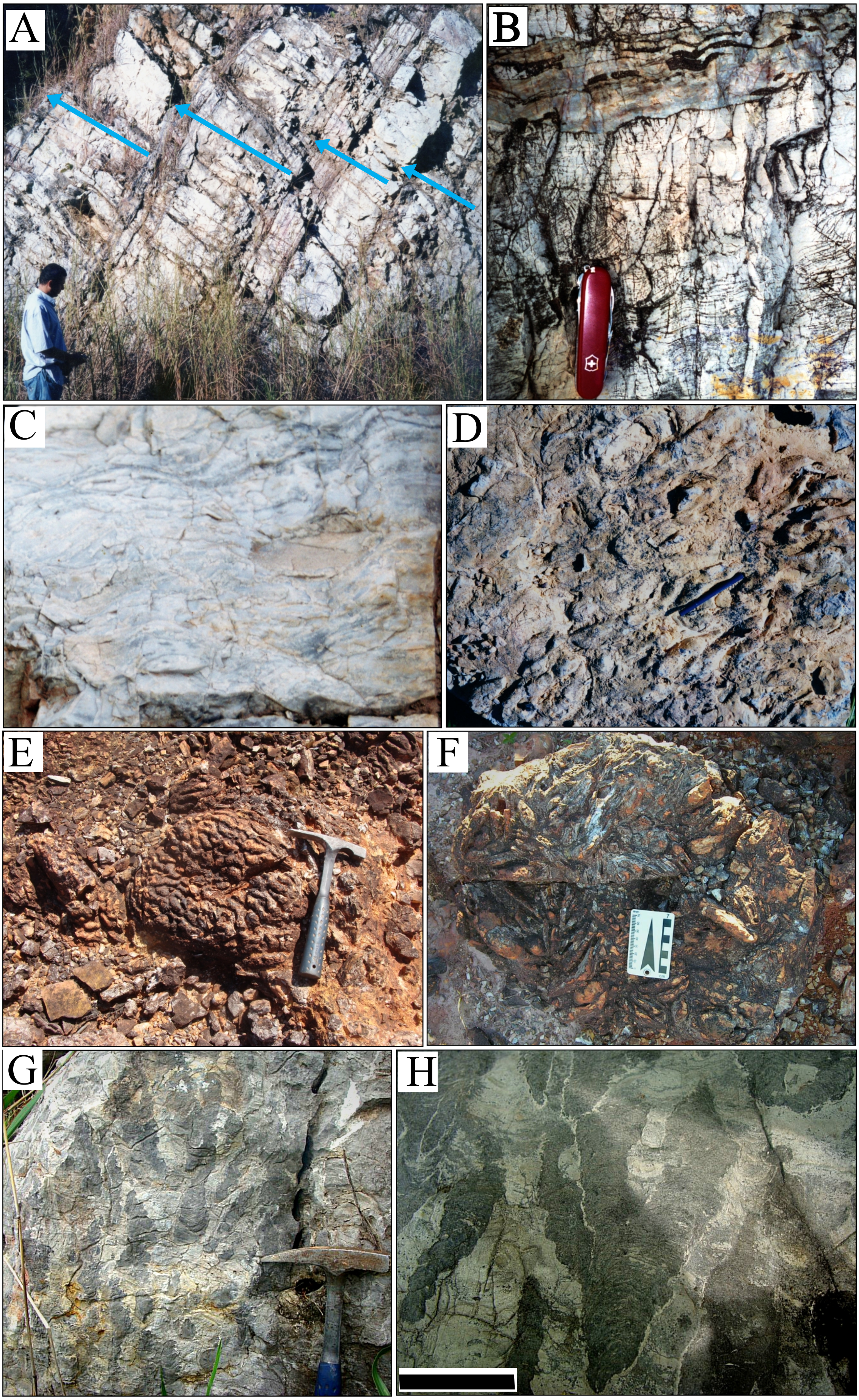

Figure 4. Lower Ediacaran stromatolites of the Upper Araras Group. (A) Shallowing upward cycles (arrows) in tidal flat deposits comprising massive and laminated dolostones. (B and C) Silicified stratiform stromatolites in the top of the shallowing upward cycles. (D) Oriented small-scale mounds in plain view (pen scale is 15 cm). (E) Plain view of the cerebroid stromatolites. (F) Carbonate elongated clast forming teepee breccia associated with the cerebroid stromatolites. (G and H) Trombolites, note the columnar morphology (scale bar is 10 cm).

Serra da Bodoquena region, Mato Grosso do Sul. Centimetric microbialites are found at the top of meter-scale mounds with predominantly stratiform to gently undulate geometry forming biostrome (Figs. 5A and 5B). The centimetric columnar microbialites can reach up to 50 cm (Figs. 5C and 5D). In the region of Bonito, phosphatic minerals are found associated with stromatolitic lamination.

Cambrian (541-480 Ma)

Cambrian stratiform stromatolites occur solely in the Araras- Alto Paraguai Basin (Figs. 6A and 6B), locally found in the top of 3m-thick coarsening upward cycles composed of sandstone interbedded with silex beds, at the base of Raizama Formation, exposed in the Serra do Mangaval, near the city of Cáceres. This morphotype is up to 15 cm thick, generally silicified, and alternates with terrigenous laminae. The microbialite-bearing deposits are interbedded with trough cross-bedded sandstone and rhythmic mudrock-sandstone, composing inclined heterolithic stratification.

Silicified stromatolites from the upper Alto Group were described in the region of Glória d'Oeste. These structures occur in centimeter-scale shallowing upward cycles of sandstone and rhythmite with evaporitic (pseudomophs) molds (popcorn and enterolithic laminae) (Fig. 6C). They exhibit stratiform geometry (Fig. 6B) with local pseudo-columnar portions. Some columnar stromatolites have a centimetric goblet shape (Fig. 6D).

PALEOENVIRONMENT

The paleoenvironment of the Ediacaran succession in the Southern Amazon Craton is predominantly interpreted as marine to coastal settings (Fig. 1). In contrast, microbialites cannot found in moderately to deep waters, as evidenced in the upper part of the Guia Formation, or the lower Serra do Quilombo Formation (Fig. 7). The evolution of stromatolites in the basal succession from the Araras-Alto Paraguai Basin was heavily dependent on the post-glacial sea level that influenced the deposition of cap carbonates drowned by long-term transgression responsible for the preservation of ~400 m-thick limestones (Nogueira *et al.* 2007, 2019; Fig. 7). Dolomitic stratiform stromatolite flourished directly overlying Marinoan glacial diamictite, marking the Cryogenian-Ediacaran boundary (Romero *et al.* 2020). These stromatolites represent the first occurrence of microbial mats in hypersaline, dense, stratified, and calm shallow waters preceding the glacial isostatic adjustment (GIA) (Santos *et al.* 2021). The laminae were percolated by sodium-rich sulfate-brine fluids filling interpeloidal porosity with gypsum and organominerals precipitation as a consequence of microbial metabolism (Santos *et al.* 2021).

The establishment of greenhouse conditions and GIA influence increased the accommodation space with definitive implantation of glacio-eustatic retrogradational settings and abundant nutrients, comprising an ideal scenario for developing giant microbial mounds (Santos *et al.* 2021). The continuity of long-term transgression in an ice-free sea allowed the reworking by oscillatory flow from extreme winds, generating megaripple bedded-strata (Allen and Hoffman 2005, Romero *et al.* 2020, Santos *et al.* 2021). The stromatolites are not observed in the maximum flooding associated with a siliciclastic inflow and these factors are suggested to have caused the demise of stromatolites in this succession (Romero *et al.* 2020, Santos *et al.* 2021), which was followed by the deposition of long-term transgressive lime mud in an aragonitic sea recorded by calcite crystal fans (pseudomorphs after aragonite), precipitated directly on the basin floor under the highest temperature during the climax of

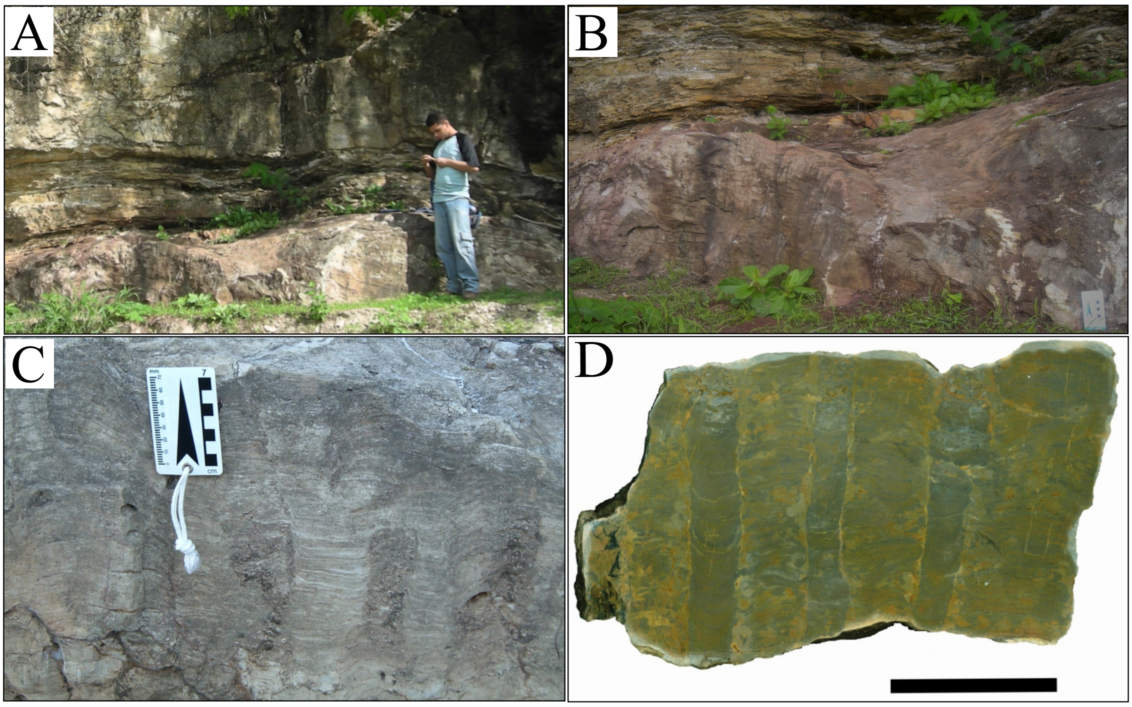

Figure 5. Upper Ediacaran stromatolites of the Corumbá Group. (A and B) domic laterally continuous mounds. (C and D) detail of stromatolitic lamination (scale bar is 10 cm).

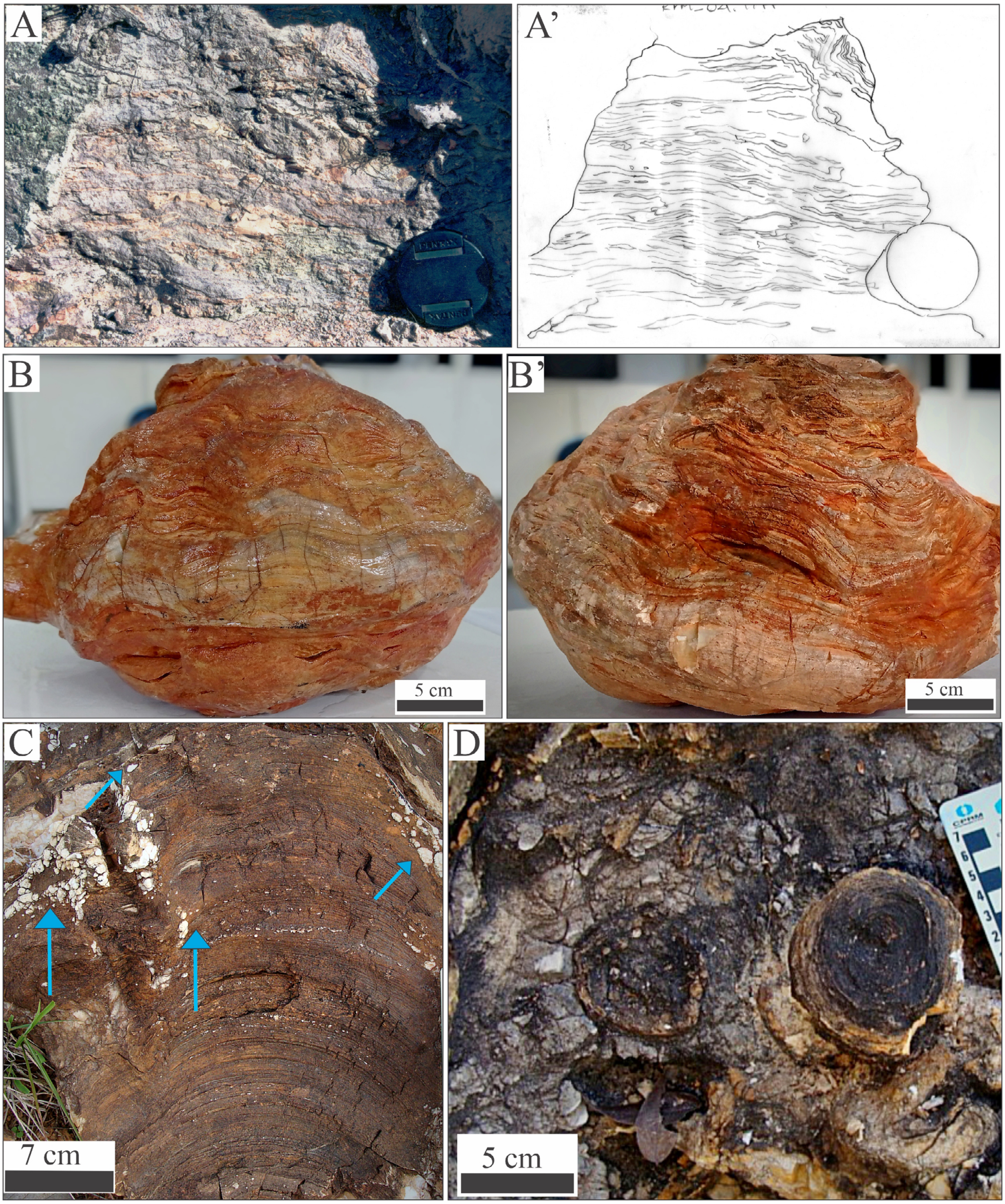

Figure 6. Cambrian stromatolites of the Alto Paraguai Group. (A and A') Stratiform stromatolites from the Raizama Formation (scale-lens cap is 8 cm). (B and B') representative sample of stratiform stromatolite. (C) Popcorn evaporite pseudomorphs (arrows) associated with domical stromatolite. (D) Goblet shape domical stromatolites in plain view.

greenhouse conditions (Nogueira *et al.* 2003, 2019, Soares *et al.* 2020). This microbial interval exhibits δ^{13}C around −5‰ passing to −4‰ for anoxic, deep-platform limestone succession, hindering colonization of microbial communities. The deep-water limestones keep the δ^{13}C values around −2‰ for more than 350 m-thick upsection, suggesting the return of carbon productivity in Neoproterozoic seawaters, which is comparable with other cratons worldwide (Fig. 7) (Nogueira *et al.* 2019).

The continuous disappearance of anoxic and deep waters conditions related to the long-term transgression was evidenced by the progressive shallowing-up sea waters. Afterward, evidence of a warm climate is recorded in the dolomitized arid tidal flat successions from the upper Araras Group (Nogueira *et al.* 2019). The δ^{13}C values ranging from −2.5‰ to +0.3‰ confirm a change of Neoproterozoic seawater conditions (Fig. 7). Domal stromatolites occur at the top of Araras Group, marking the limit between subtidal-intertidal deposits, forming

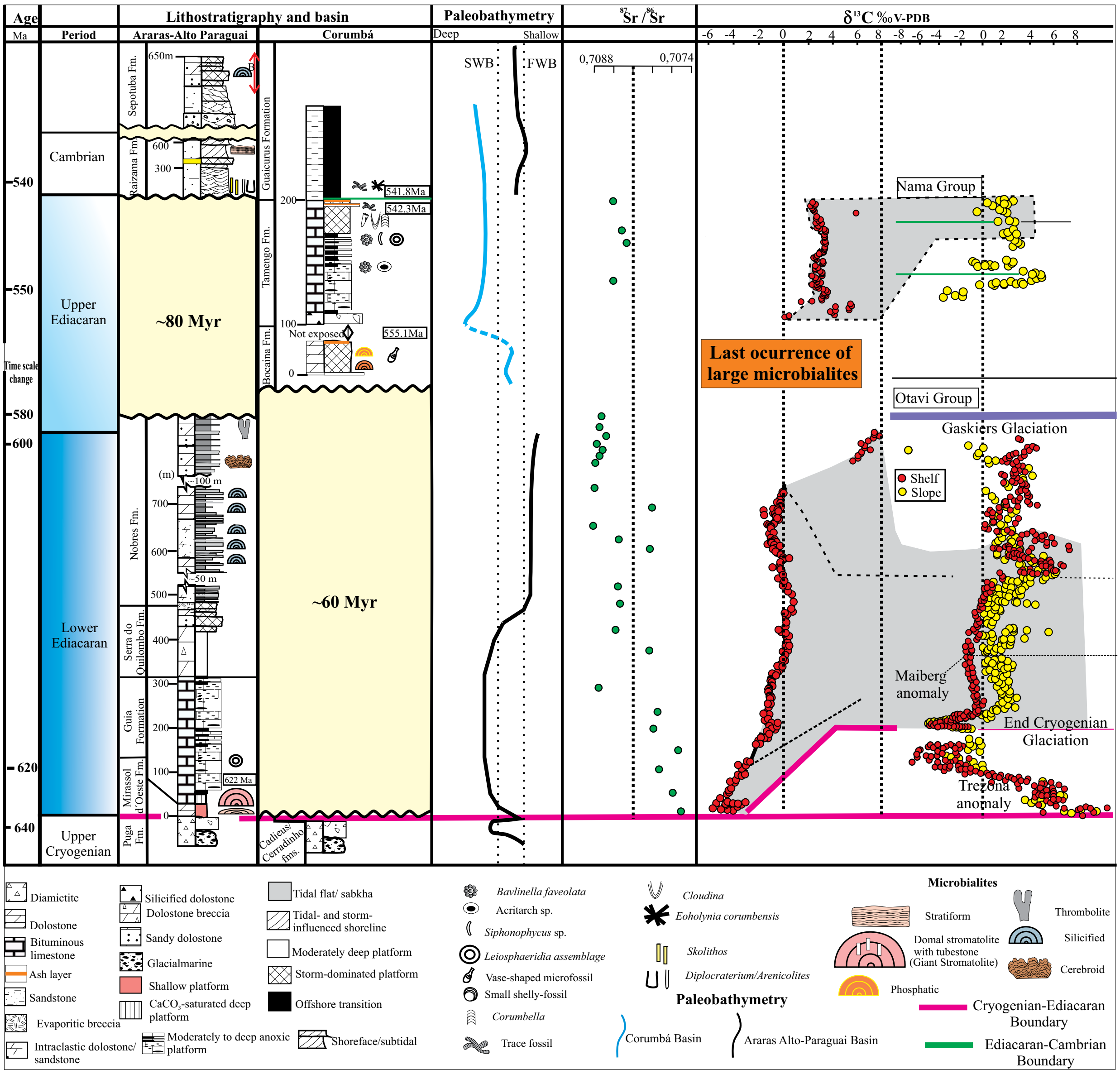

Figure 7. Sea-level curve, carbon isotope, and $^{87}Sr/^{86}Sr$ chemostratigraphy and lithostratigraphy of Ediacaran-Cambrian of the Southern Amazon Craton (Modified of Nogueira *et al.* 2019, Sial *et al.* 2016) compared to composite $\delta^{13}C$ curve of Otavi Group in Namibia (Halverson *et al.* 2005, Macdonald *et al.* 2009). In this context, the Araras Group does not trespass the lower Ediacaran. Mid- to late Ediacaran and Cambrian deposits are recorded in Corumbá Group. Cambrian deposits also occur in the Araras-Alto Paraguai Basin. Carbon data in the upper Nobres Formation has been attributed to the not formalized Pacu Formation (Sial et al. 2016).

meter-scale shallowing to brining-upward cycles of arid tidal flat and sabkha (Nogueira and Riccomini 2006, Nogueira *et al.* 2007, Rudnitzki *et al.* 2017). The presence of desiccation cracks, rip-up clasts, and tepee features compose a brecciated substrate where microbial mats grew, forming cerebroid morphology, indicative of subaerial exposure in tidal flat (Fig. 4G). We considered these $\delta^{13}C$ values to be less altered as carbon depletion can be associated with meteoric waters commonly related to the peritidal setting. The slightly negative $\delta^{13}C$ values around -2.0‰ and 0‰ near to the Cambrian deposits associated with $^{87}Sr/^{86}Sr$ values between 0.7074 and 0.7089 are compatible with the Ediacaran- post-Marinoan- carbonates calibrated with $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ curves, from the Otavi Group of Namíbia (Nogueira *et al.* 2019, see Fig. 7 for the locality and stratigraphic position of this data).

Isolated limestone with thrombolites exposed in the Eastern Araras-Alto Paraguai Basin (Fig. 6) was positioned at the top of the Araras Group (Sial *et al.* 2016). The $\delta^{13}C$ values around +6.6‰ to +8.9‰ are more enriched than the Araras Group exposed in the western and central part of the Araras-Alto Paraguai Basin. These positive values are comparable with those found in the basal Otavi Group of Namíbia (Fig. 7) and indicate a continuity of tidal sedimentation conditions before the Gaskier glaciation and preserved from the Cambrian incision event. The constant $^{87}Sr/^{86}Sr$ ratios between 0.7087 and 0.7088 (Fig. 7) confirm this stratigraphic position compared with the Sr data for the Araras Group (cf. Nogueira *et al.* 2007).

The domal and columnar stromatolites of the Bocaina Formation (Corumbá Group) present $\delta^{13}C$ positive values (Fig. 7). They are the massive colonization of microbial communities in tidal flat settings (Boggiani 1998, Gaucher *et al.* 2003, Oliveira *et al.* 2019). In contrast, only fragments of microbial mats are found in the distal deposits of the Upper Ediacaran Tamengo Formation (Amorim *et al.* 2020) or covering the *Cloudina* body fossil, apparently in situ (Becker-Kerber *et al.* 2017). This rare occurrence in the storm-influenced moderately deep ramp with high energy zones was an inappropriate site for the microbial communities colonization (Amorim *et al.* 2020). Thus, despite the occurrence of some isolated outcrops with microbialites that can be associated with the Marinoan cap carbonate (Romero *et al.* 2016), the upper part of the Corumbá Group has a continuous record from the Late Ediacaran until the Cambrian transition with the local occurrence of phosphatized stromatolites (Fig. 7). Phosphorus is one of the essential elements in all life forms, and the abundance of phosphorites in the Proterozoic-Phanerozoic transition is related to the significant phosphogenic events. Phosphorus has increased progressively in the oceans since the Sturtian. They had a relatively short-lived peak at around the upper Ediacaran-Cambrian boundary, particularly during the Tommotian, followed by an overall decrease during the Cambrian (Harland *et al.* 1990). Many fossil and recent phosphorites are associated with upwelling-dominated deep anoxic oceanic environments, and the upwelling transported this element to the shallow-water photic zone (Cook and Shergold 1984, Cook 1992). In shallow waters, phosphorus is retained in bottom sediments and recycled as microbial biomass of benthic secondary producers (Soudry 2000). The proliferation of microbial communities was the primary mechanism in the phosphorus trapping, enabling increasing biological storage of this element in the uppermost bottom sediments.

The Lower Ediacaran Araras Group was uplifted during the middle and upper Ediacaran and later truncated by the Cambrian Unconformity (Santos *et al.* 2017, Nogueira *et al.* 2019, Santos *et al.* 2020). The Cambrian deposition in the Araras- Alto Paraguai basin was dominated by siliciclastic fluvial, coastal, and marine environments. Stratiform microbial mats were restricted and developed mainly in lagoon settings in the Raizama Formation (Fig. 6A). In constract, the Guaicurus Formation in the Corumbá Basin, a contemporaneous unit of the Raizama unit, was deposited under anoxic and deep waters conditions that hinder the flourishment of microbial mats.

The microbialites are generally stratiform and domal in the Araras-Alto Paraguai basin. This similarity in morphology denotes that the paleoenvironmental did not change dramatically, and the high preservation potential degree is related to the fast pre-lithification of carbonates. Our observations indicate that Ediacaran-Cambrian stromatolite-bearing successions were deposited predominantly in coastal environments, including shallow waters or intertidal areas with rapid cementation that increase the potential preservation degree. The preservation of microbialites in the post-glacial intervals was triggered by the Mg-Ca-CO_3 oversaturation, an anomalous process in post-Marinoan dolomitic platforms (Nogueira *et al.* 2019, Romero *et al.* 2020, Santos *et al.* 2021). The rapid calcification and the resistance to the dissolution and substitution increased the preservation potential observed by well-preserved domic mounds. The intense eogenetic silicification likely increased the preservation of stromatolites in tidal flats and sabkha deposits. The kinetic precipitation velocity of insoluble salts contributed primarily to the fast cementation and increased potential preservation. Carbonate and eogenetic silica are not poorly preserved in these mounds since they were modified and replaced by later silica.

At the end of the Neoproterozoic a narrowing abundance of these structures in carbonate settings occurred, which are linked to the advent of grazing and burrowing metazoan organisms or decrease in the carbonate saturation of seawater not favoring the microbial mats precipitation and preservation (Grotzinger *et al.* 1990, Grotzinger and Knoll 1999, Riding and Liang 2005, Warren *et al.* 2013). Despite being confident that paleontological stratigraphic data have sustained this hypothesis, the stromatolite-bearing successions are generally discontinuous, truncated by unconformities and lacking a more detailed paleoenvironmental interpretation to elucidate the factors responsible for the reduction of the preservation potential degree. The observation in large scale of several successions worldwide has revealed that many intervals devoid or with low frequency of stromatolites coexisting with the metazoan fossils may indicate mainly hydrodynamic and paleoenvironmental control (Grotzinger *et al.* 2005, Gingras *et al.* 2011). In the studied successions, even the intervals with microbialites coexisting with the metazoan fossils in the Tamengo Formation (Becker-Kerber *et al.* 2017), do not support evidence of direct competition between them. The authors suggested that the Cloudinas and microbialites shared the same space, similarly to the interaction between microbialites and metazoan in modern stromatolites, where the metazoans shaped the framework of the microbialites (e.g., Ricardi-Branco *et al.* 2018). Also, if erosional events are not considered, the microbial colonization was relatively continuous and reflected solely on its preservation in coastal and shallow waters deposits.

BASIN EVOLUTION AND STROMATOLITE COLONIZATION

The coastal and marine settings developed on the Southern Amazon Craton were an extension of epicontinental seas linked to the assembly of the Gondwana (Hoffman 1991, Li *et al.* 2008, Shields-Zhou and Och 2016, Spence *et al.* 2016). Sea-level rise and fall events were associated with basin tectonics combined with the emergence of orogenic belts in the Western Gondwana (Cordani *et al.* 2013, Santosh *et al.* 2014). The Araras-Alto Paraguai and the Corumbá basins were installed over metasedimentary rocks of the Cuiabá Group, comprising the Cryogenian fold-thrust Paraguai Belt and tectonic segments that record the primordial phase of the Gondwana (cf. Santos *et al.* 2020). The flooding conditions led to the formation of several coastal environments flanking epicontinental seas, influencing the geochemistry, biologic, biogeographic factors, and oceanic circulation (Torsvik and Cocks 2013, Zhang *et al.* 2015, Babcock *et al.* 2015).

The Marinoan glaciation affected the Gondwana (~635 Ma), and the retreat of glaciers led to the flooding of all cratonic margins, favoring microbial colonization in shallow dolomitic platforms represented by stratiform and giant stromatolites in deposits at the base of Araras-Alto Paraguai Basin (Fig. 8A).

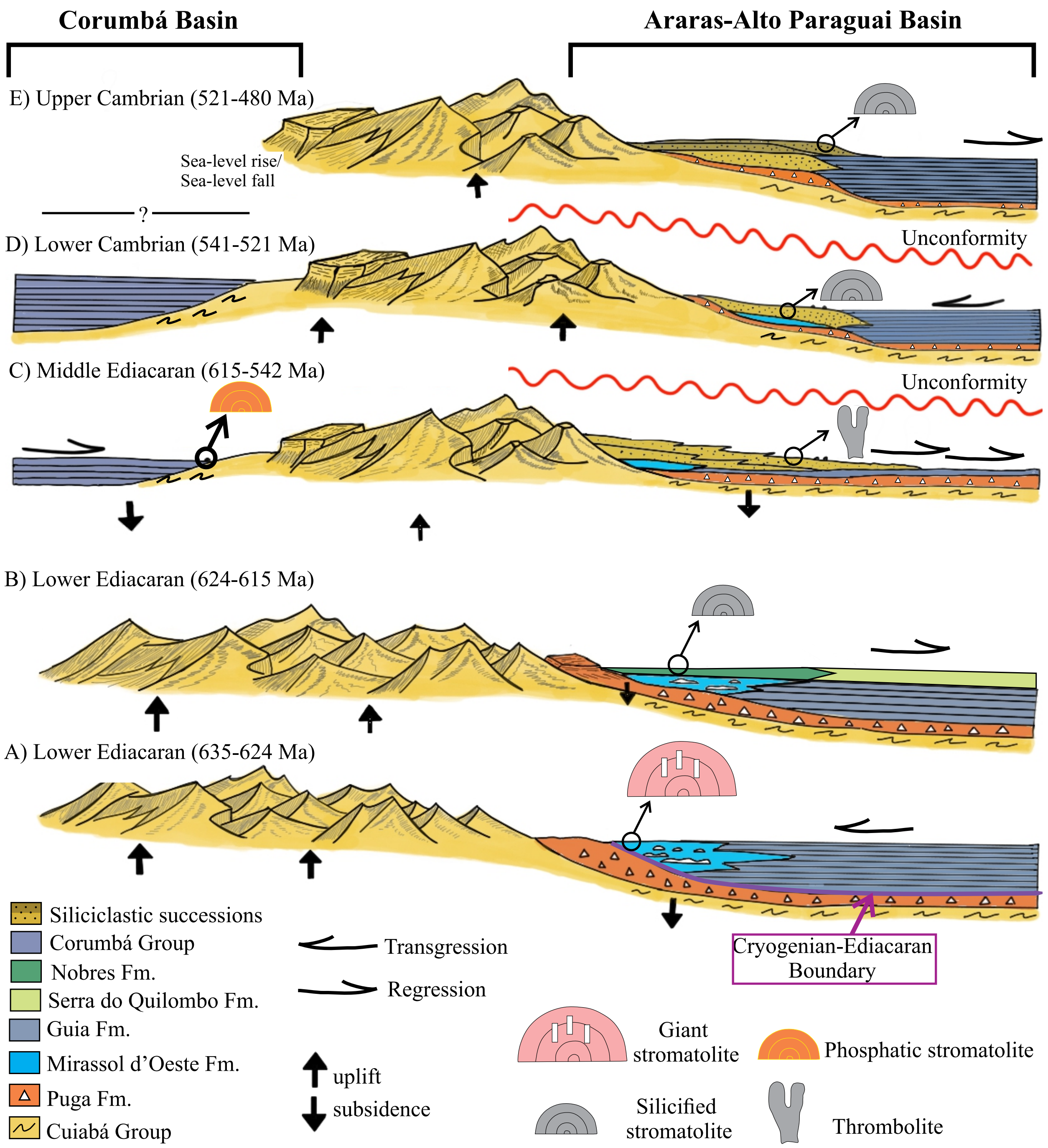

Figure 8. Basin evolution in the Southern Amazon Craton and stromatolites colonization. (A) Post-glacial transgression and microbial development in the shallow dolomitic platform. (B) Sea-level fall and implantation of tidal flat and sabkha. (C) Maximum sea-level fall with progradation of tidal flat to the central part of the epicontinental sea. (D) Sea-level rise and uplift of the Amazon Craton with the migration of the continental depositional system to NE and SW. E) Sea-level fall and implantation of tidal flat and sabkha with fluvial progradation towards SE.

During this phase, the southernmost portion of the craton was uplifted due to the collision of tectonic blocks. The continuous transgression allowed the precipitation of micrite in an aragonite sea, forming a moderately deep platform. The continuous sea-level fall led the progradation of coastal environments concomitantly with greenhouse conditions. The sea retreat caused partial exposition of post-Marinoan carbonates and culminated in the implantation of tidal flat and sabkha settings with flourishment of small-scale microbial mounds, marking the limit between the intertidal and subtidal zones (Fig. 8B). The progressive uplift caused a moderate inversion of the basin and erosion of the succession until ~615 Ma (Fig. 8C). Isolated tidal flat persisted until the mid-Ediacaran (~560 Ma). Afterwards, the Corumbá Basin was established with the deposition of microbially-induced carbonates in the Bocaina Formation, forming mounds in shallow water platforms connected to the offshore setting (Fig. 8C).

The uplift and erosion of the Araras-Alto Paraguai Basin lasted until the Cambrian and represented a gap of ~80 Myr (Nogueira *et al.* 2019). The Middle Ediacaran-Lower Cambrian unconformity is recorded solely in the Araras-Alto Paraguai Basin and represents an essential surface for regional correlation. This surface can be partially correlated with the Great Unconformity, a gap in Earth's stratigraphic record associated with the erosion produced by the Neoproterozoic glaciations (Powell *et al.* 1875, Peters and Gaines 2012, Keller *et al.* 2018). In the Araras-Paraguai basin, the unique record of glaciation is represented by the Marinoan diamictite, which underlies the Araras Group. The putative occurrence of Gaskier glaciation in this region is poorly defined (Alvarenga *et al.* 2007, McGee *et al.* 2014). Thus, we considered that the Middle Ediacaran-Lower Cambrian unconformity is related to the local uplift and linked to the regional collision of continental blocks during the assembly of the Gondwana. In contrast, the maximum marine invasion occurs in the Corumbá Basin (Fig. 8D). In the Lower Cambrian (541-521 Ma), the sedimentation in the Araras-Alto Paraguai Basin was resumed with sea-level rise deposition in coastal and marine settings with rich-microbial mats lagoons (Fig. 8D). In the Upper Cambrian, the sea-level fall caused the implantation of tidal flats and microbial mats developed, the last record in the Araras-Paraguai Basin (Fig. 8E).

CONCLUSION

The Ediacaran-Cambrian carbonate and siliciclastic successions, exposed in the Southern Amazon Craton (central-western Brazil), host various microbialite types. Each type occurs in a specific paleoenvironment related to tectonic and sea-level changes. This work provides an essential window of opportunity to evaluate the preservation potential of microbialites through the geologic record, the role of carbonate factory and siliciclastic input in fossilization, helping to understand the environmental restrictions and their resistance to the diagenesis. Coastal and marine environments affected by basin subsidence and sea-level changes controlled the microbial colonization after the Marinoan glaciation (635 Ma). These conditions were responsible for the morphology and size of these biogenic structures. Centimeter-scale stratiform and dome-like stromatolites were most frequent than giant domes, and during the Cambrian, the microbial communities colonized more restricted environments. The preservation of post-Marinoan stromatolites is associated with the Mg-Ca-CO3 oversaturated waters that caused fast calcification. In the restricted, evaporitic environments, meteoric waters with silica in its solution promoted the early fossilization of stromatolites. The early fossilization has caused resistance to dissolution and substitution during burial diagenesis. In general, the poorly documented coexistence of coastal microbial mats and metazoan-bearing marine deposits impairs the understanding of the competitive relationship between these organisms, as previously postulated.

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