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Tubestone microbialite association in the Ediacaran cap carbonates in the southern Paraguay Fold Belt (SW Brazil): Geobiological and stratigraphic implications for a Marinoan cap carbonate

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ABSTRACT

The restriction of tubestone structures tomicrobialitic laminites in cap carbonates associated with the Marinoan glacial event in North and South America, Namibia, Australia and Oman makes them an important stratigraphic marker for the base of the Ediacaran system. This association has been recognized in the Mirassol D'Oeste Formation (635 Ma) adjacent to the northern Paraguay Fold Belt, and are reported here in isolated outcrops at Morraria do Sul and Forte de Coimbra in the southern Paraguay Fold Belt, west-central Brazil. The tubestone-microbialite associations at all localities reveal very similar macro- and microstructures, mineralogy, textures and fabrics. The microbialites consist of microbial laminites made up of dolomicrite clustered in microclots with dolospar-filled fenestrae. Lamination is defined by alternation in the relative abundance of these two components, suggestive of simple oscillations within a relatively uniform depositional environment and paleoecological setting. In the two new localities the tubestone fillings consist mainly of massive dolomicrite, although subordinate portions with concave lamination defined by concentrated very fine siliciclastic grains also occur. The presence of both massive and laminated tube fillings indicates variation in the processes responsible for their formation. These results extend the occurrence of the post-Marinoan tubestone-microbialite association at least 600 km southward from Mirassol D'Oeste in the north and document minor variations among the localities, which is what one would expect over such a broad distribution of this feature. The results also indicate that the isolated dolostones at Morraria do Sul and Forte de Coimbra do not belong to the Bocaina Formation (Corumbá Group), with which they have previously been correlated.

1. Introduction

The tubestone strucutures are associated with Marinoan cap carbonates that marks the beginning of the Ediacaran sedimentation (ca. 635 Ma). These cap carbonates exhibit part or all of an exclusive set of unusual sedimentary features, including megaripples, megapeloids, cementstones and a peculiar tubestone-microbialite facies (Hoffman and Schrag, 2002; Allen and Hoffman, 2005; Corsetti and Grotzinger, 2005; Romero et al., 2012; Bosak et al., 2013). The term *tubestone* as used in this paper refers to finely laminated dolomitic microbial laminites (= stratiform stromatolites) cut by clearly evident abundant vertical, cylindrical to irregular tubular structures up to a few centimeters across and, in exceptional cases, more than a meter in length, that cut finely laminated dolostone and are filled by dolomicrite and dolospar, which may or may not exhibit fine lamination, distinct from the surrounding rocks.

Cloud (1968) first described such features in the Noonday

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Dolomite in Death Valley, USA, likening them to trace fossils, but later coined the term "tubestone structures" for them (Cloud et al., 1974). Since then, other origins have been suggested for such structures, including fluid escape (Cloud et al., 1974; Kennedy et al., 2001), unusual hydrodynamic processes influencing development of microbial laminites (Bosak et al., 2013), and as a rare end-member microbialite resulting from the peculiar conditions of carbonate supersaturation at the time of cap carbonate deposition (Corsetti and Grotzinger, 2005). Other authors have referred this combination to as "geoplumb stromatolites" (Hoffman, 2011) and "tubestone stromatolites" (Bosak et al., 2013).

The tubestone-microbialite association has been recognized in many cap carbonates associated with the Marinoan glaciation in the USA (Alaska and California), Namibia, Canada, Mongolia and Brazil (Cloud et al., 1974; Corsetti and Grotzinger, 2005; Hoffman et al., 2009; Hoffman, 2011; Romero et al., 2011; Bosak et al., 2013). In fact, the geological record of the tubestone-microbialite association appears to be temporally restricted to this particular post-glacial episode at circa 635 Ma. This paper discusses two occurrences of this association in the southern Paraguay Fold Belt.

In Brazil, the tubestone-microbialite association was first observed in the Mirassol D'Oeste Formation, basal unit of the Araras Group, that together with the lower part of the Guia Formation, are considered a Marinoan cap carbonate in the cratonic cover succession adjacent to northern Paraguay Fold Belt in Mato Grosso State (Nogueira, 2003; Nogueira et al., 2003; Soares et al., 2013). The Mirassol D'Oeste Formation directly overlies massive glacigenic diamictites of the Puga Formation, with pebble-sized striated clasts of varied lithologies (e.g. sandstone, granite) in a sandy argillaceous matrix. The full cap overlying the Puga Formation shows of the entire set of sedimentary structures considered as unique to post-Marinoan caps including megaripples, megapeloids, cementstones and the tubestone-microbialite association (Nogueira et al., 2003; Font et al., 2010). Other evidence coherent with the post-Marinoan interpretation for the Mirassol D'Oeste Formation includes the negative δ^{13} C isotope profiles ranging from −3.5 to −8.9‰ (Nogueira et al., 2007) and $^{87}Sr/^{86}Sr$ values of 0.7074–0.7090 similar to other post-Marinoan units worldwide (Font et al., 2006; Nogueira et al., 2007; Halverson et al., 2010).

In successions traditionally attributed to the Corumbá Group of middle to late Ediacaran age in the southern Paraguay Fold Belt, Boggiani et al. (2010) described a possible tubestone-microbialite association at Porto Morrinhos, near Corumbá city, and Morais (2013) recently suggested the presence at Forte de Coimbra, at the margins of Paraguay river, and at Morraria do Sul in the Serra da Bodoquena,, This paper describes and compares these occurrences and examines the paleoenvironmental and stratigraphical implications of their identification as part of the unique set of sedimentological structures restricted to Marinoan cap carbonates.

The occurrence of tubestones at different localities motivated the study, once no strong evidence of Neoproterozoic post-glacial cap carbonate has been yet recognized at southern Paraguay Belt, the results would extend the paleogeographic occurrence of glaciation at the beginning of Ediacaran Period to the Southern portion of the Paraguay Belt and better constrain the time range of the Corumbá Group.

2. Geological setting

The Paraguay Fold Belt was formed when the Amazonian Craton, the Congo-São Francisco Craton (to the east), and the Rio de La Plata Craton (to the south) collided during final amalgamation of the western portion of the supercontinent Gondwana at the end of the Brasiliano/Pan-African event in the mid-Cambrian (~520 Ma) (Almeida, 1984; Alvarenga et al., 2000). The Brazilian portion of this fold belt extends in an arc opening southeastward that is initially oriented N-S in the southern portion in the state of Mato Grosso do Sul (Serra da Bodoquena, Urucum Massif and Serra do Amolar), curving northeastward in its northern portion in the state of Mato Grosso (Fig. 1a), it continues southward with outcrops in Paraguay (Warren et al., 2012). The sedimentary history is different in the northern and southern parts of this fold belt (Trompete et al., 1998; Alvarenga et al., 2000; Boggiani et al., 2010; Rudnitzki et al., 2016).

Glaciogenic diamictites of Puga Formation are overlain by a Marinoan cap carbonate in the north, represented by dolostone and limestone of the Mirassol D'Oeste and basal Guia formations, respectively, within the Araras Group (Nogueira et al., 2003; Hoffman and Macdonald, 2010). The temporal context and stratigraphic relations of the basal portion of the succession in the southern part of the fold belt, however, are still not satisfactorily constrained (Boggiani et al., 2010). In the exposures around Corumbá, it begins with the Jacadigo Group which consists of continental conglomerates, diamictites, immature sandstones and arkoses and passes conformably upward to lacustrine or marine banded iron formations (Freitas et al., 2011; Angerer et al., 2016). Angerer et al. (2016) have presented evidence for a glacial influence on the deposition of the banded iron formation. Glaciogenic diamictites have long been known in this region several tens of kilometers south of Corumbá in the isolated Morro do Puga, the type locality of the Puga Formation (Maciel, 1959; Boggiani and Coimbra, 2002). Directly above these diamictites lie reddish non-microbial calcareous laminites interpreted as a cap carbonate (Boggiani et al., 2003; Babinski et al., 2013), which do not, however, exhibit tubestone structures. Completing the section at Morro do Puga is a thick succession of poorly exposed limestone assigned to the Bocaina Formation of the Corumbá Group (Maciel, 1959; Boggiani and Coimbra, 2002; Boggiani et al., 2003; Babinski et al., 2013). This same formation also overlies the Jacadigo Group closer to Corumbá (Freitas et al., 2011) and is broadly distributed in the Serra da Bodoquena. By the same token that extensive occurrences of diamictites in the Paraguay Fold Belt have been attributed to the Puga Formation (Boggiani and Coimbra, 2002), practically all dolostones in the southern part of this fold belt have traditionally been assigned to the Bocaina Formation, including the isolated outcrops described here. However, stratigraphic relationships among all these outcrops have yet to be clearly demonstrated (Almeida, 1965; Boggiani et al., 1993, 2010), which is an important point in this paper.

The dolostones containing the tubestone-microbialite structures described here have previously been considered as part of the Bocaina Formation in the Corumbá Group (Fig. 1b) (Boggiani, 1998). The depositional age of this formation is poorly constrained, but must be younger than the Jacadigo Group and the Puga Formation and older than the overlying Tamengo Formation of confirmed latest Ediacaran age, based on the presence of the metazoan index fossil *Cloudina* Germs 1972 (Beurlen and Sommer, 1957; Zaine and Fairchild, 1985; Grant, 1990; Zaine, 1991) and a U–Pb SHRIMP age of 543 ± 3 Ma for zircon crystals from volcanic tuffs intercalated within the *Cloudina*–bearing carbonate beds (Babinski et al., 2008).

The Bocaina Formation is clearly younger than both the Jacadigo Group and the Puga Formation (Almeida, 1946; Freitas et al., 2011; Piacentini et al., 2013), and older than the overlying Tamengo Formation of the Corumbá Group, but its precise age is still unknown. $^{40}Ar/^{39}Ar$ age dating of cryptomelane in manganese ore within the Jacadigo Group indicates mild metamorphism at about 590 Ma (Piacentini et al., 2013), but says nothing as to the age to the Bocaina Formation. Age dating of detrital zircon in Puga Formation diamictites and stable isotope studies of the reddish limestones overlying the Puga Formation provide information on the maximum age of all post-Puga rocks (Corumbá Group) in the