Original article

New aspects of Neoproterozoic-Cambrian transition in the Corumbá region (state of Mato Grosso do Sul, Brazil)

*Nouvelles perspectives sur la transition Néoptérozoïque-Cambrien dans la région de Corumbá, Mato Grosso do Sul, Brésil*

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**Abstract**

This study aims to update the knowledge about the importance of the late Ediacaran fossil record and geochemical data from Corumbá, State of Mato Grosso do Sul, at the Brazilian-Bolivian border. The Corumbá graben system is located near a triple junction developed above a hot spot of two young (545–480 Ma) Brazilian provinces: the mostly Bolivian Chiquitos-Tucavaca aulacogen which cuts across the Amazon Craton/Rio Apa Block, and Paraguay Fold Belt. The Neoproterozoic sedimentary cover of South Paraguay Belt starts with the metasediments, diamicitties and iron formation of the Jacadigo Group, now related to an end-Cryogenian age. Most remarkable geochemical and paleontological data come from the overlying Corumbá group, mainly from the dolostones with stromatolites of the Bocaina Formation, and limestone with shale and silty intercalations at this group’s upper part, in the Tamengo Formation. This last unit contains a fossil assemblage correlated to late Ediacaran fauna. This fauna contains originally substrate-emergent tube-like *Corumbella wernerii*, *Cloudina luciana* and microfossils. Furthermore, the fossils from the Corumbá Group in Brazil and Paraguay represent the most important witnesses for the occurrence of late Ediacaran fossils close to the basal Cambrian boundary in South America. Therefore, the Corumbá region is significant for palaeogeographical reasons and, on the other hand, allows insights into the evolution of the oldest skeletonized metazoans. After new research results, the high degree of similarity of the geological facies evolution with other parts of the world (e.g. Yangtze Platform/Southern China, Siberia, Spain and Namibia) can be demonstrated, where the fragmentation of the Rodinia supercontinent and Neoproterozoic glaciations are also well-documented. The sharp top contact of the shallow marine Tamengo Formation with the laminated black shales (containing rare angular dropstones) of the discordantly overlying Guaiacurú Formation indicates that the latter represents a new transgressive glacially influenced marine onlap succession. A Cambrian age of the Guaiacurú Shales is not (yet) biostratigraphically verified, however, the underlying fossil record of cloudinids indicates a terminal Ediacaran age for the top of the Tamengo Formation. The microtubular cloudinids are interpreted as dysoxic analogues of recent tubeworms and are suggested to serve as first skeletonized worldwide “index fossils” to delineate the onset of a Phanerozoic-type body fossil vectorial evolutionary pathway. Based on the FAD of cloudinids as marker fossils, a revision of the Precambrian/Cambrian boundary is here advocated. This would avoid placing this important GSSP into the virtually worldwide Namtsas-Baykanskurian glacial hiatus.

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RÉSUMÉ


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1. Introduction

In South America, units of Paraguay Fold Belt, mainly those of its southern part, provide the most complete record of the late Ediacaran climatic, biogeographical and biotic evolution. The Paraguay belt is a Late Pan-African-Brasiliano age fold belt in southwestern Brazil, that comprises a southern and a northern branch with similar lithostratigraphy (Gaucher et al., 2003; Boggiani et al., 2010). In the South Paraguay Belt, around the city of Corumbá, in Western Brazil, late Neoproterozoic subhorizontal or tilted cratonic cover rocks lie above the basement of the Amazon Craton-Rio Apa Block. These strata include the Jacadigo Group, which caps inselbergs up to 1200 m high, and the carbonate-siliciclastic Corumbá Group, which crops out in the surrounding lowlands of the swampy Pantanal peneplain.

The importance of the Jacadigo and Corumbá groups rests in their paleoclimatic and biological context. Both units were deposited in a time interval of profound changes in the paleogeographic configuration due to the break-up of the supercontinent Rodinia, the formation of new shallow waters and the further amalgamation of Gondwana (Li et al., 2013). These events resulted in paleoclimatic changes represented by the alternation of glacial and non-glacial periods in a relatively short time interval, known as Snowball Earth model (Hoffman et al., 1998). At the same time that climatic changes occurred, the ocean chemistry also went through changes, including more available free oxygen (see review in Fedonkin, 2003; Ike et al., 2006; Och and Shields-Zhou, 2012; Mills and Canfield, 2014). Combinations of these factors lead to major biological innovations among multicellular eukaryotes, including the appearance of vendobionts and, later, the appearance of metazoans (e.g., Ike et al., 2008). Part of the Neoproterozoic innovations and peculiar environmental conditions are recorded in the Corumbá region, mainly in the homonymous group (Gaucher et al., 2003; Boggiani et al., 2010; Fairchild et al., 2012; Morais-Soares et al., 2013; Kerber et al., 2013), and thus deserve special attention.

The main goal of this paper is to show an overview of paleogeographic, tectonic and depositional context of the Jacadigo and Corumbá groups, along with new data acquired by the research team of the University of Brasilia, carried out with support by PETROBRAS, concerning isotopic and mineral approaches. Our guest author, Dr. Bernd-D. Erdtmann (Technical University of Berlin) reinterpreted the tube fossil Corumbella wernerit (Hahn et al., 1982) and presents the key aspects here. The paleontological record, as well as new chemical and sedimentological aspects of the Corumbá Group, are also presented and compared to the same key terminal Ediacaran units worldwide, like in South China and Namibia.

2. Geological setting

Stratigraphical, sedimentological and structural data suggest the following history for the Neoproterozoic sequences around the city of Corumbá, related to the evolution of a graben system. According to Jones (1985) and Walde (1988), the Corumbá region is located on a tectonic triple junction (R-R-R) developed above a hot
spot, where three basins met, separated by angles of about 120°. They are the North and South Paraguay Basins and the Tucavaca or Chiquitos-Tucavaca Aulacogen. The aulacogen and the Paraguay basins were formed approximately synchronously, with depositional age between 650 and 540 Ma (Babinski et al., 2013).

Just before the Ediacaran Period, extensional tectonics at the southern margin of the Amazonas Craton generated a graben system, known as Corumbá graben (Trompette et al., 1998; Fig. 1). In this context, two lithostratigraphic units were deposited: the Jacadigo and Corumbá groups (Alvarenga et al., 2009; Figs. 2 and 3). Paleogeographic reconstructions confirmed that the Corumbá graben was first filled with sediments of the Jacadigo Group, comprising in the lower part diamictites, volcanogenic material and arkose beds overlain by banded hematite-rich jasplilites with manganese ore intercalations and dropped boulders, as a result of a glacial event.

The depositional age of the upper part of the Jacadigo Group was recently proposed by Piacentini et al. (2013), based on 40Ar/39Ar dating, and pointed to a 587 ± 7 Ma. New data from Babinski et al. (2013) attested for Puga Formation (equivalent to the lower part of Jacadigo Group, the Urucum Formation) an end-Cryogenian age, although, a Gaskiers age cannot be discharged.

The Corumbá Group was deposited over the diamictites of the Puga Formation and marks the opening of a rift basin. It comprises five formations, including the Cerradinho and Cadieuus formations that outcrop in the southern State of Mato Grosso do Sul, and the Bocaina, Tamengo and Guaicurus formations marking the drift phase, and whose record can be observed over 350 km, from south to north in the State of Mato Grosso do Sul (Boggiani et al., 2010).

The only available dating for the Corumbá Group is a U-Pb zircon age of 543 ± 3 Ma, obtained from volcanic ashes of the Tamengo Formation, which positioned this unit close to the presumed transition to the Cambrian (Boggiani et al., 2010; Babinski et al., 2013). However, its relative age was established from the occurrence of Cloudina fossils, this biozone being well known for the latest Ediacaran.

Deformation and low-grade metamorphism in the region where Jacadigo and Corumbá rocks occur were documented (Trompette et al., 1998). Rocks underwent ductile and brittle deformations represented by a set of tectonic structures (mainly folds, foliations, faults, and fractures) which can be grouped in three main phases (D1-D2-D3) of a progressive and monocyclic event (Brasiliano cycle) at very low metamorphic grade. The third phase (D3) is subdivided in D3P and D3T of coeval crustal shortening superimposed upon a continental margin already thickened after D1 and (mostly) D2 deformations. The label D3P stands for the structures due to late crustal shortening associated with the final closure of the oceanic basin precursor of the southern end of the Paraguay Belt, whereas D3T stands for structures due to late crustal shortening most likely related to the closure of the aborted rift-type basin precursor of the Tucavaca Belt (D’el-Rey personal communication, 2015).

Fig. 2. Regional map showing the cities of Corumbá and Ladário in the State of Mato Grosso do Sul, West Brazil, and the mining areas (quarries) where the fossils studied herein were recovered.

Carte régionale localisant les villes de Corumbá et de Ladário, situées dans l'État du Mato Grosso do Sul, au Brésil et les sites où les fossiles étudiés ici ont été découverts.

3. Material and methods

Samples for mineralogical analysis were collected at the Cacimba Cliff in the city of Corumbá, State of Mato Grosso do Sul, where the Tamengo Formation outcrops. The escarpment exposes limestones and intercalated pelitic rocks, as well as the basal and top levels of mudstones. The basal level of mudstone contains a Late Ediacaran fauna represented by Corumbella werneri and...
Cloudina lucianoii. The mineral composition of the rocks was determined by X-ray diffraction (XRD), whereas structures and textural features were studied through conventional petrographic analysis. All the analyses were performed at the Laboratory of X-ray Diffraction (LDRX), Institute of Geosciences, University of Brasília. Diffraction analyzes were made on Rigaku Ultima IV diffractometer operating with copper tube and nickel filter, under 35 kV and 15 mA, scanning speed of 2°/min. The scan range was 3-80° for the total sample and 2-40° for the clay fraction. The interpretation of the diffractograms was made with the aid of the MDIJADE 9.4, with a database PDF.

Most samples for the carbon and oxygen isotope study were collected at a regular vertical interval of approximately 16 m also at the Cacimba section. Carbon and oxygen isotope ratios were obtained from ground samples after reacting with 100% H₃PO₄ at 25 °C for at least 1 hour. Isotopic composition of the released CO₂ was determined by using a Finnigan DELTA Plus Advantage mass spectrometer at the University of Brasilia. Measurements were made against PDB standards for δ¹³C and δ¹⁸O. Analytical reproducibility of δ¹³C and δ¹⁸O values, based on replicas of NBS-19 standards, was better than ±0.1‰.

The acquisition of new material for paleontological and stratigraphic research was performed along new section measurements, laboratory analyses and photos of specimens in all Corumbá Group outcrops. The classical outcrops, where studies have been focused, are the quarries of Laginha (Tamengo and Guaiacur formation) and of Corcal (Tamengo and Guaiacur formations), Porto Morrinhos (Bocaina Formation) and at Sobramil Port.
(Tamengo Formation), all of them nearby or located within the city of Corumbá. The present study shows new data from the Tamengo Formation in Cabimba section, near downtown Corumbá.

Several specimens of *Corumbella* were analyzed at the Laboratório de Micropaleontologia, Institute of Geosciences, University of Brasilia. It was performed using stereomicroscope accomplished to a photography system and petrographic microscope.

4. The Precambrian fossil record of the Corumbá region

The fossil record of the Corumbá region encompasses most of the categories of Precambrian fossils known worldwide. It includes microbialites, prokaroytic and eukaryotic microfossils, trace fossils, vendobnaeids, as well as metazoans (Gaucher et al., 2003; Morais-Soares et al., 2013).

The fossil record of the Jacadigo Group remains poorly known. Up to date, only negative epirelief linear trace fossils were recovered in thin, iron-rich mudstone layers (Fig. 4g). Other micro- and macrostructures are under investigation. On the other hand, a significant fossil record comes from the upper half of the Corumbá Group, including the phosphatized dolostones of the top of the Bocaina Formation and the limestones and siltstones of the Tamengo Formation. These fossils have been known since the 1950’s (e.g. Beurlen and Sommer, 1957) and since then, some advances have been reached concerning the paleobiology of the Corumbá Group, and, therefore, documenting the diversity at the end of the Ediacaran Period (Fairchild et al., 2012; Gaucher et al., 2003; Kerber et al., 2013; Morais, 2013).

The protistan *Titanatoba coimbrae* (Gaucher and Sprechmann, 1999) was identified in the dolostones of the Bocaina Formation (Fig. 4d). Its biological affinity was demonstrated to be a foraminifer, and thus this record may represent one of the oldest occurrences of this group. Its importance lies in the fact that this fossil allows lithostratigraphic correlations between the Corumbá Group, the Holgart Formation (Port Nolloth Group) in Namibia, and the Yerbal Formation (Arroyo del Soldado Group) in Uruguay, as well it allows paleogeographical reconstructions for the time of the amalgamation of Gondwana at the end of the Neoproterozoic (Boggiani et al., 2010).

The fossil content of the Bocaina Formation also includes laminites, oncoids, domical and columnar stromatolites recovered in a series of outcrops distributed in the Corumbá region and almost 100 km to the south. These microfossils allowed to trace back variations in the eustatic levels and, thus, reconstruct the paleoenvironmental mosaic that was present during the deposition of the Bocaina Formation (Morais, 2013).

The Tamengo Formation records the most important fossil content of Neoproterozoic of Brazil. It includes the *Cloudina lucianoi* (Beurlen and Sommer, 1957), reassigned from *Aulophybus* by Zaine and Fairchild, 1985 and *Cloudina waldie* (Hahn and Pfug, 1985), both recovered from grainstones beds (Figs. 3 and 4e-f). The genus *Cloudina* (Gems, 1972) was suggested as an index fossil of the Late Ediacaran (Grant, 1990). According to Amthor et al. (2003), the *Cloudina* species became extinct by the end of Ediacaran. Later on, a record of *Cloudina* ex. Gr. *C. riemkae* (Gems, 1972) was reported from earliest Cambrian strata in Siberia co-occurring with *Anabarites triscularis* Voronova and Missarzhhevsky, 1969 (Zhuravlev et al., 2009). Later, occurrences of anabairid species were interpreted as uppermost Ediacaran (Zhuravlev et al., 2012; Fig. 2D) from Siberian samples. Despite this apparent controversy, it is important to point out that, if evolution of species is considered, among the seven species of the genus *Cloudina*, one might be ancestral and, so, distinct timing of appearance and extinction for different species would be expected.

*Corumbella werneri* (Hahn et al., 1982; Fig. 4a-b) also occurs in the Tamengo Formation, and has been interpreted as a cnidarian, possibly related to the Scyphozoa (Hahn et al., 1982; Walde et al., 1982; Babcock et al., 2003). Van Iten et al. (2014) interpreted this fossil as a colonarid scyphozoan, related to other non-erect Ediacaran fossils such as the vendoozan genera *Phyllozoa* (Jenkins and Gehling, 1978) or *Dickinsonia* (Sprigg, 1947). Since, in 2012, three-dimensional specimens of *Corumbella werneri* were found together with two-dimensionally preserved material in a quarry on the western edge of Corumbá, it is evident that this species does not belong to the conularids, but to cloudinids (personal comm. Steiner to Erdtmann, 2012).

A series of micro- and macrofossils of uncertain affinities (*Incertae Sedis*) were also recovered in the Cerradinho, Tamengo and Guaiacurus formations (Gaucher et al., 2003). These include the enigmatic chuarids *Chuaria circularis* (Walcott, 1899) and *Tawuia* sp. (Gaucher et al., 2003; Pacheco, 2012), and different species of leiosphaerids, as well *Myxococoides* sp. and *Soldadophycus bosi* (Gaucher et al., 1996; Gaucher et al., 2003). Cyanobacteria were recovered in palynological preparations and are represented by *Bavillina jokevola* (Schepelaeva) (Vidal, 1976); *Siphonophyces robustus* (Schopf, 1968) emended Butterfield et al. (1994) and *Eoentophytya croxfordii* (Muir, 1976) emended Butterfield et al. (1994) (Gaucher et al., 2003). Rare vendobnaeids as *Eoholynia corumbensis* (Gaucher et al., 2003; see Fig. 4c for the genus) and *Vendobnaeatia antiqua* (Gnilovskaya, 1971) were recovered from fine-grained beds of the Guaiacurus Formation. *E. corumbensis* can be easily observed in hand samples, whereas *V. antiqua* was found only in palynological dissolution.

The fossil record of the Tamengo Formation is the most remarkable when compared to the other units of the Jacadigo and Corumbá groups. As pointed out by Fairchild et al. (2012) and Morais-Soares et al. (2013), the macrofossils of this unit can help to shed light on evolutionary aspects of the early metazoans, as well as to understand the environmental changes and its implications over the biota at the end of the Ediacaran. New researches, mainly the non-destructive types, have been developed aiming to access high resolution details of skeletons and shells in order to answer such open questions (Kerber et al., 2013).

4.1. On Cloudina lucianoi (*Beurlen and Sommer, 1957*)

At the present, the genus *Cloudina* (Gems, 1972) has seven species:

- *Cloudina lucianoi* (Beurlen and Sommer, 1957) (Tamengo Formation, Brazil);
- *Cloudina hartmannae* (Gems, 1972) (Nama Group, Namibia);
- *Cloudina riemkae* (Gems, 1972) (Nama Group, Namibia);
- *Cloudina waldie* (Hahn and Pfug, 1985) (Tamengo Formation, Brazil);
- *Cloudina lijiagouensis* (Zhang, Li and Dong, 1982) (Yangtzé Platform, China);
- *Cloudina sinensis* (Zhang et al., 1982) (Yangtzé Platform, China);
- *Cloudina carinata* (Cortijo et al., 2010) (Spain; Table 1).

These seven species are restricted to Ediacaran strata, although early Cambrian specimens were reported in Russian successions. However, later, these Cambrian occurrences were re-interpreted as Ediacaran, as pointed below. Two of these have a worldwide distribution: *Cloudina hartmannae* and *Cloudina riemkae*.

Two species have been recognized in South America: *C. lucianoi* and *C. riemkae*. *Cloudina riemkae* was originally described from Namibia and later has been also recorded from Uruguay (Gaucher et al., 2003) and from Russia (Zhuravlev et al., 2012). *Cloudina lucianoi* has occurrences in Brazil (Beurlen and Sommer, 1957;...
Zaine and Fairchild, 1985; Gaucher et al., 2003; Boggiani et al., 2010) and in the Ediacaran Itapucumi Group of Paraguay (Warren et al., 2011).

The species Cloudina lucianoi discussed in this paper was originally described as Aulophycus lucianoi (Beurlen and Sommer, 1957), whose type-material came from the Corumbá Limestone and was sampled at the type-locality between Ladário and Corumbá cities, State of Mato Grosso do Sul, and is housed at Earth Sciences Museum (Rio de Janeiro, Brazil), which allowed access for the present study (Figs. 4F, 5).

The original paper by Beurlen and Sommer (1957) was published in a local Brazilian journal in Portuguese language. Later on, the close similarity with Cloudina was recognized by Zaine and Fairchild (1985), and a new description and diagnosis for Cloudina lucianoi was published also in Portuguese. Both diagnosis, the original one by Beurlen and Sommer (1957) and the one by Zaine

<table>
<thead>
<tr>
<th>Species of Cloudina (Germs, 1972) and their original provenance in Ediacaran system from several countries. Espèces de Cloudina (Germs, 1972) et provenance originelle dans le Système Ediacarien de différents pays.</th>
<th>BRAZIL</th>
<th>Tamengo Formation, Corumbá Group</th>
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<tr>
<td>Cloudina hartmannae (Germs, 1972)</td>
<td>NAMIBIA</td>
<td>Omkýk Member, Zaris Formation, Zaris Basin</td>
</tr>
<tr>
<td>Cloudina riemekeae (Germs, 1972)</td>
<td>NAMIBIA</td>
<td>Omkýk Member, Zaris Formation, Zaris Basin</td>
</tr>
<tr>
<td>Cloudina waldei (Hahn and Pflug, 1985)</td>
<td>BRAZIL</td>
<td>Tamengo Formation, Corumbá Group</td>
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<td>Cloudinalygosaurina (Zhang et al., 1992)</td>
<td>CHINA</td>
<td>Dengying Formation, Sinian System</td>
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<tr>
<td>Cloudinalygosaurina (Zhang et al., 2010)</td>
<td>SPAIN</td>
<td>Membrillar Member, Ibor-Navalpino Group</td>
</tr>
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</table>

Fig. 5. To the left, section with stratigraphic range and type-horizons of Corumbella werneri (Hahn et al., 1982) and Cloudina lucianoi (Beurlen and Sommer, 1957) near Sobramil port, Ladário Municipality, State of Mato Grosso do Sul, Brazil (to the left; adapted from Boggiani et al., 2010). To the right, polished sections showing specimens of C. lucianoi (A, sample 1154 and B-D, sample 1153, both housed at the National Department of Mineral Production – DNPM, Earth Sciences Museum, Rio de Janeiro) and specimen of C. werneri (D, CP-745, housed at the Museum of Geosciences, University of Brasilia), all from their type-horizon.


A. Vue d’ensemble. B-C. Détails de sections transversales et longitudinales. D. Sections transversales montrant une structure de cônes emboîtés. E. Corumbella werneri (détails).
and Fairchild (1985), emphasized size variations of the exoskeleton of the species nowadays referred to *Cloudina lucianoi*. It is pointed out herein that the clear cone-in-cone characteristic for the genus is used to keep this species as a member of *Cloudina*. Generally, species of *Cloudina* have a layered cone-in-cone exoskeleton which differs from the tubular shaped skeleton species of the carbonatic algae *Autophybus* (Fenton and Fenton, 1939). *Cloudina waldiei* (Hahn and Pflug, 1985) described from the same locality of the Tamengo Formation was considered by Zaine and Fairchild (1985) as a junior synonym of *Cloudina lucianoi*, however, this inclusion of *C. waldiei* cannot be considered as final.

The type-horizon of *C. lucianoi* was originally considered as Cambrian (Beurlen and Sommer, 1957), however, Zaine and Fairchild (1985) and Walde (1988) considered this type-horizon to be part of the uppermost Neoproterozoic Tamengo Formation. Boggiani et al. (2010) and Babinski et al. (2013), based on direct radiometric dating of detrital zircons, isotope and paleontological data, confirmed that this interval has to be placed into the Ediacaran.

Originally, the type-horizon for *Cloudina lucianoi* was positioned at the uppermost portion of the Tamengo Formation (Fig. 3), located several meters above the water-pumping station at the southern banks of the Paraguay River (Beurlen and Sommer, 1957), in the locality known as Sobramil Port. As shown by Walde (1988) and Boggiani et al. (2010) in the Sobramil Port area, *Cloudina lucianoi* first occurs above the occurrences of *Corubbella werneri* (Hahn et al., 1982) and disappears close to the uppermost Tamengo Formation. Two-dimensional specimens of *Corubbella werneri* commonly occur in siliceous sediments, mainly pelites, whereas *Cloudina lucianoi* occurs in limestones. Recent geological investigations in October 2012, as well as during the Corumbá Meeting in August 2013, demonstrated the occurrence of *C. werneri* together with *Cloudina lucianoi* at the Corcal quarry at a higher stratigraphic level of the Tamengo Formation.

It is important to point out that the type-horizon for *Corubbella werneri* was also positioned in outcrop of the Tamengo Formation located at the Sobramil Port area (Fig. 5), close to the type-locality for *Cloudina lucianoi*. Both species occur in the same succession also in Itapucumi Group in Paraguay (Warren et al., 2011).

At the present date, a revision of *Cloudina lucianoi* is under investigation as well as a detailed comparison with the six other *Cloudina* species. The seven species are considered to be restricted to the Ediacaran period. Some of these species may be synonymized. Valid species may possess a distinctive skeletal structure and their first appearance (FAD) and extinction (LAD) may not have occurred at the same time. Therefore, the projected taxonomic revision, which is being conducted, may contribute to improve the Ediacaran biostратigraphy.

Warren et al. (2014) referred to undetermined species of *Cloudina* in strata of the Bambuí Group, possibly the Sete Lagoas Formation, State of Minas Gerais, Brazil. When the species identification has been completed, this new occurrence of *Cloudina* sp. in Minas Gerais may open a new perspective for biostратigraphic correlation between strata of Terminal Neoproterozoic in Brazil as well as abroad.

4.2. On biological affinities of *Corubbella werneri* (Hahn et al., 1982)

Since its discovery, the systematic position of *Corubbella werneri* (Hahn et al., 1982) has been controversial with regard to its phylogenetic relations and its mode of fossilization as well as its original mode of life (Babcock et al., 2005). Based on several similar morphological traits, *C. werneri* was compared to *Stephanoscyphus*, a “bundled” colony of recent multibranched cnidarian coronoid polyps, by Hahn et al. (1982) and (with modifications) by Babcock et al. (2005). Despite some morphological similarities of *Stephanoscyphus* with *C. werneri*, a phylogenetic and taxonomic relationship appears to be unlikely. Basically, two major reconstruction models have been proposed for *C. werneri* so far:

- an erect or semi-erect tubular life mode (Hahn et al., 1982; Babcock et al., 2005) with a phylogenetic-taxonomic assignment to coronoid scyphozoans and a systematic association of *C. werneri* to conulariid scyphozoans by Babcock et al. (2005), Pacheco (2012), and Van Ilen et al. (2014);
- a sea bottom attached semi-tubular life mode with a probable “open” phylogenetic relationship to other non-erect Ediacaran fossils such as the vendozoan genera *Phyllozoan* or *Dickinsonia* (Zaine and Fairchild, 1985; Erdtmann, 2004).

However, *Phyllozoan* is only known as an imprint without any test or shell. Both systematic assignments as colunariids and as Vendozoans are now rejected resulting from the current analysis of 3-D preserved material.

A distal tetragonal “crown” was postulated originally by Hahn et al. (1982), then by Babcock et al. (2005) and by Pacheco et al. (2011) to have existed and later was also refuged by Pacheco (2012) (Fig. 4B). No “head-crown” or parts of it, however, were observed by the present authors. A conulariid phylogenetic and thus taxonomic relationship cannot be verified herein because all materials collected by these authors do not substantiate any tetragonal cross-sectional diameter, but instead, an original (pre-compression) consistently circular transverse cross-section of these tuboid forms. As already proposed by Cai et al. (2014), the general morphology of cloudinids suggests a functional ecological relationship of these fossils to Recent pogonophoran “tube worms”, what would place them as an analogous in terms of functional biology, in terms of an extremely low oxygen-dependent strategy, with sessile bottom-dwelling group of fossils.

5. Results and discussion

5.1. On new observations on mineralogical and chemical aspects of the Corumbá Group

The *Corubbella*-bearing massive silstone contains euhedral and corroded crystals of quartz. It overlays a meter of silstone and shale planar laminae and is recovered by rhythmite, which presents, under microscope, some microbial mats, cracked laminae, and thin sections of prismatic calcite interpreted as pseudomorphs over gypsum crystals. All the rocks present fractures commonly filled by calcite or gypsum. The mineralogical analysis determined by XRD (Fig. 6c4), pointed for all pelitic whole rocks to be constituted mainly by quartz, muscovite, smectite and chlorite. Calcite and gypsum are major constituents in some layers. Smectite and illite are the main constituents of the clay fraction, whereas chlorite is a minor constituent, and quartz is scarce, except in the layers containing gypsum, where it is a main constituent in both whole rock and clay fraction. Dark gray calcarenites, strongly recrystallized, are comprised by calcite, whereas quartz and smectite are minor or trace constituents. The basal level of the limestone is a fossiliferous grainstone with bioclasts of *Cloudina*, which can be seen in thin sections (Figs. 6c1 to c3).

The isotopic results obtained for the Cacimba Section show a range from −11.9‰ to −9‰ for δ18O and −8‰ to +6‰ for δ13C (Fig. 6b).

The basal level of mudstone with microbial mats, cracked laminae, and calice pseudomorphs over gypsum crystals indicates episodic events of fine detrital deposition under shallow to
intertidal marine conditions. Smectite as a major constituent of the whole rock and clay fraction suggests a deposition of thin sediments containing significant amounts of unstable material, such as volcanic ash. This assumption is supported by the presence of chlorite.

In the studied section, **Corumbella** was found only at the basal level of the Tamengo Formation at the Cacimba outcrop and may be associated with episodic events of burial, or even water quality changes driven by the interaction with the volcanic material.

These basal limestones are mainly bioclastic beds in which **Cloudina** is a common constituent. Narrow, high and symmetrical peaks of illite and chlorite characterize a late diagenesis, but the important amount of smectite may have been preserved thanks to a potassium deficit, or telodiagenesis.

Concerning the isotopic data, in a general view, the section shows a consistent trend for the values of $\delta^{18}$O, with less negative values toward the top. However, when we analyze the results in terms of absolute values for $\delta^{18}$O, it is noteworthy that most of the values are between $-10\%$ and $-11\%$, suggesting that its primary signature has changed. In fact, such values of $\delta^{18}$O found for the most part of the section suggest that the oxygen isotope signature reflects a diagenetic modification. For the carbon isotope, the record shows coherent and phased changes corresponding to the stratigraphic variations (Fig. 6b). In the studied section, the $\delta^{13}$C profile shows a wide variation from very positive values ($+6\%$ vs. PDB standard) to very negative values (up to $-8\%$) towards the top.

In previous works (Boggiani et al., 2010; Spangenberg et al., 2014), $\delta^{13}$C values vary from negative values (up to $-2\%$) at the base of the Tamengo Formation and become positive towards the top. The $\delta^{13}$C values as negatives as $-8\%$ for this succession have never been reported before. The sediments exposed at the Cacimba Section correspond to the upper part of the Tamengo Formation. That section is characterized by the co-occurrence of Corumbella and **Cloudina** in the lower portion of the outcrop, where $\delta^{13}$C values are positive. The negative excursion with $\delta^{13}$C values up to $-8\%$ is placed at the top of the section, where no fossils were collected due to the steep grade of this Cacimba Cliff section. However, an occurrence of **Corumbella-Cloudina** can be predicted at the higher level of the Tamengo Formation also at the Cacimba section because of a corval main occurrence of these fossils at the nearby Corcal section and at Sobramil Port. This negative excursion is apparently in agreement with the late Ediacaran carbon cycle at the Precambrian-Cambrian boundary (e.g. Narbonne et al., 1994; Amthor et al., 2003; Ishikawa et al., 2008).

5.2. On new consideration of palaeontology

The significance of the tuboid fauna of the Tamengo Formation in the Corumbá region is highlighted by two important aspects:

- paleoecologically, **Corumbella werneri** together with **Cloudina lucianoii** documents a shallow marine sea bottom suspension
feeding biota (see Cai et al., 2014), which indicates a high degree of oxygen depletion (see Spangenberg et al., 2014); 
• stratigraphically, this fauna correlates well with a very similar biota along the northern edge of the Yangtze Platform in China and probably with hypomymous fossils in Namibia, North America, Spain, Siberia and other parts of the world.

This makes this cloudinid assemblage a first true global “Index Fossil Assemblage” and a strong contender for global correlatability of the Phanerozoic. Keeping in mind that the occurrence of a “tubid or cloudinid assemblage” worldwide initiates a regressive (probably a bipolar glacially induced) trend, concomitant with hydroospheric oxygen depletion, this cloudinid group of fossils, regardless of their phylogenetic status, would present a suitable marker for the beginning of the Phanerozoic Eon. Considering that on the South China Plate as well as in many other sections worldwide, an eustatic (glacigenic) hiatus, possibly several hiati, exists at the currently defined Precambrian-Cambrian boundary a potential redefinition of this boundary at this lower (now terminal Ediacaran) level might be suggested.

6. Final remarks

Isotope signal of Camibamba section presented herein suggests a latest Ediacaran deposition, in a context of volcanic activity, what can lead to exceptional fossil preservation. These new data significantly document the still discussed Neoproterozoic-Cambrian transition in South America. Moreover, no section worldwide documents a depositionally and biostratigraphically uninterrupted succession across the Ediacaran-Cambrian boundary except (perhaps) the Fortune Head section of eastern Newfoundland (Brazier et al., 1994; Landing, 1994; Babcock et al., 2014). This section currently contains the GSSP for the lower boundary of the Cambrian System, including a biological document composed exclusively by trace fossils. These trace fossils (or any behaviorally mediated palaeoecological signals) do not document a vectorial evolutionary trend and cannot be regarded to mark any inter-systemic boundary according to the IUGS Code. Babcock et al. (2014) encourage search for an alternative stratigraphic horizon, but do not advocate any alternative for the Ediacaran-Cambrian boundary should be considered to be placed at a level below the glacigenically induced Nomtsas-Baykonurian hiati (Chumakov, 2009; Germs and Gaucher, 2012). Such terminal Ediacaran sections for a new potential Cambrian GSSP are observed in Brazil and are also documented worldwide.

It is here proposed to adopt a new Cambian GSSP within a continuous section marked by the first occurrence of a widespread, taxonomically well-defined cloudinid species.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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