 Integrated correlation of the Vendian to Cambrian Arroyo del Soldado and Corumbá Groups (Uruguay and Brazil): palaeogeographic, palaeoclimatic and palaeobiologic implications

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Received 30 May 2001; accepted 6 September 2002

Abstract

The Corumbá Group of SW Brazil and the Arroyo del Soldado Group (ASG) of Uruguay are correlated on the basis of litho-, bio- and chemostratigraphy. Both units represent marine sedimentation with alternating siliciclastics and carbonates developed on a stable continental shelf. In the Corumbá basin, sedimentation began in the Varangerian, represented by the glaciomarine Puga Formation. A series of sea-level fluctuations coupled with climatic changes are recorded up section. While uppermost deposits of the ASG are of lowermost Cambrian age, sedimentation ceased in the latest Vendian in the Corumbá basin. An assemblage of six species of organic-walled microfossils dominated by Bravinella faveolata and Soldadophycus bossii, three species of vendotaenids and two species of skeletal fossils (Cloudina and Titanotheca) is described from the Corumbá Group. The vendotaenid Eoholynia corumbensis sp. nov is described from siltstones of the Guaicurus Formation. An important diversity of skeletal fossils in the Corumbá, Arroyo del Soldado and Nama groups points to favourable Vendian palaeoclimatic conditions in SW-Gondwana. Preliminary carbon isotopic data show a series of alternating positive and negative excursions, corroborating the upper Vendian age indicated by fossils for both units. Previously reported strontium isotopic data are also consistent with this age. It is postulated that the Corumbá and ASGs were deposited onto the same shelf, which opened to the east. The Rio de la Plata Superterrane (Craton) extends farther to the north than previously expected, or it was already amalgamated with the Amazonian Craton by Vendian times. Collision of the platform with the Paraná Block caused closure of the basin during the Cambrian-Early Ordovician. Finally, models of Neoproterozoic glaciations based on enhanced bioproductivity driven by high nutrient availability are discussed.

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1. Introduction

The correlation of the Arroyo del Soldado Group (ASG) of Uruguay with the Corumbá and Jacadigo Groups of southwestern Brazil (Fig. 1) was first postulated by Gaucher et al. (1996: 360–361), on the basis of similar age, similar depositional environments, probable continuity in subsurface, and existence of *Bauhinella*-dominated acritarch-assemblages in these groups. This working hypothesis proved to be a powerful predictive tool, because it could explain many observations made thereafter. Gaucher and Sprechmann (1998, 1999) described a skeletal assemblage from the Yerbal Formation of the ASG containing *Cloudina*, which is a common fossil in the limestones of the Tamengo Formation of the Corumbá Group (Hahn and Pflug, 1985; Zaine and Fairchild, 1985; Boggiani et al., 1993; Boggiani, 1998; Gaucher 1999). Boggiani (1998) presented sedimentologic, carbon and strontium isotopic data for the Corumbá and ASG, considering that a correlation of both units is possible. Gaucher (1999, 2000) compares the fossil content, lithostratigraphy, chemostratigraphy and sedimentary environments of the Arroyo del Soldado, Jacadigo and Corumbá Groups. The author concludes that while the Arroyo del Soldado and Corumbá Groups are correlative and of Redkinian–Kotlinian (upper Vendian) age, the Jacadigo Group is composed of glacial deposits and BIF’s of the Rapitan-type, probably generated during the Varangerian glaciation, as also postulated by Almeida (1984), Walde (1987: 103), Alvarenga (1990) and Boggiani (1998). In this paper, we present in some detail the evidence that supports the correlation of these important Vendian to Cambrian units of South America. Newly discovered microfossils from the Corumbá Group and carbon isotopic profiles of the ASG are described as well. Finally, the paper deals with the consequences of this new data for the poorly-known palaeogeography of the Río de la Plata.

2. Geological setting

2.1. The Arroyo del Soldado Group

This lithostratigraphic unit was defined by Gaucher et al. (1996), to include thick (>5000 m) marine shelf deposits, which occur in the Nico Pérez Terrane of Uruguay. The boundaries of the Terrane also represent the boundaries of the occurrences of the ASG (Fig. 2), namely: the Sarandi del Yi-Piriápolis Shear Zone to the west, the Sierra Ballena Shear Zone to the East and the Cerro Partido Thrust to the south (Gaucher et al., 1998b; Gaucher, 1999, 2000). To the north, the occurrences of the ASG are covered by Phanerozoic sedimentary units and volcanics of the Parana Basin. The northernmost outcrops of the Group have been recognized by Gaucher et al. (1998c) and described by Gaucher (1999, 2000) in the so-called Isla Cristalina de Rivera, near the boundary with Brazil (Fig. 2). The unit lies with erosional and angular unconformity on: (1) a Mesoproterozoic metasedimentary complex informally known as Basal Group (Sprechmann et al., 1994; Gaucher et al., 1996) or Grenvillian Metamorphic Complex (Bossi et al., 1998), (2) Archean (3.4–2.7 Ga) metasedimentary units recently discovered in the vicinity of Piraraju (Campal and Schipilov, personal communication, 2000; Fig. 2); (3) Palaeoproterozoic (1784±5 Ma: Campal and Schipilov, 1995) rapakivi granites and (4) other granites of undetermined age. The basal Yerbal Formation (Gaucher et al., 1998a; Gaucher and Sprechmann, 1999; Gaucher, 2000) represents a siliciclastic, deepening-upward sequence, and is characterized by thin conglomerates and arkoses at the base, passing into green siltstones and banded siltstones at the top. Oxide-facies BIF have been recently discovered at the top of this unit near the city of Minas (Fig. 2). The Yerbal Formation is concordantly overlain with sharp contact by the Polanco Formation, which marks the development of a large carbonate ramp in the basin. The unit is characterized by bluish gray to black limestone–dolostone rhythmites, frequent carbonatic tempestites, pure calcisiltites and dolosiltites, and rare oolitic calcarenites (Gaucher, 1999, 2000). In the shallowest areas of the basin (to the west), carbonates of the Polanco Formation are concordantly overlain by conglomerates and arkoses of the Barriga Negra Formation (Fig. 4), recording a major regression (Gaucher et al., 1998a; Gaucher, 2000). This unit passes upwards into shales and siltstones of the basal Cerro Espuelitas Formation. In the deepest sections (to the E), the Polanco Formation shows a direct transition into the Cerro Espuelitas Formation (Gaucher, 1999, 2000; Fig. 4). The latter unit is made up of an alternation of dark shales, thick chert-deposits and oxide-facies BIF with up to 35 wt.% magnetite and/or hematite (Gaucher and Schipilov, 1994; Gaucher et al., 1996, 1998b; Gaucher, 1999, 2000). The Cerro Espuelitas Formation is truncated by an erosive surface that probably marks an important regression (Gaucher, 2000). The Cerros San Francisco Formation was deposited above this surface, and is characterized by very mature quartz-arenites with wave and current ripples, hummocky cross-stratification and low-angle cross bedding (Montañá and Sprechmann, 1993; Gaucher and Schipilov, 1993; Gaucher et al., 1996; Gaucher, 2000). Finally, the Cerros San Francisco Formation passes upwards into stromatolitic and oolitic limestones of the Cerro Victoria Formation, which contains ichnofossils of probable Cambrian age (Montañá and Sprechmann, 1993; Gaucher, 1999, 2000).

The ASG has been folded and intruded by granites and syenites in the Cambrian, granitoids yielding ages around 540–510 Ma (Bossi and Navarro, 1991: 342; Kawashita et al., 1999; Fig. 2). K–Ar datings of illite-rich pelites belonging to the Group yielded recrystallization ages between 532±16 and 492±14 Ma (Cingolani et al., 1990; Gaucher, 2000), well in accordance with ages obtained for intrusive granites. Considering these ages, the orogenic event that determined the deformation of the ASG can be taken as a terminal event of the Brasiliano Megacycle or, more probably, represent a separate orogeny (Paraguay Orogeny of Basei and Brito Neves, 1992). As stated by Gaucher (2000), the latter interpretation
seems more plausible because the orogeny records the collision of a typical Brasiliano-block (Cuchilla Dionisio Terrane) with a cratonized block, onto which the Arroyo del Soldado-shelf developed.

2.2. The Corumbá Group

With minor changes, the lithostratigraphical scheme proposed by Almeida (1965) has been
adopted by most authors recently dealing with the Corumbá Group (Almeida, 1984; Zaine, 1991; Boggiani et al., 1993; Boggiani, 1998; Alvarenga et al., 2000). Boggiani (1998) includes the Cadiueus Formation in the base of the Corumbá Group, after the recognition of a gradational contact between the Cadiueus and Cerradinho Formations. The group rests with angular and erosional unconformity on (1) granites and gneisses of the Basal Complex of the Rio Apa Block, sensu Corrêa et al. (1979), of undetermined age but probably reworked in the Mesoproterozoic; and (2) Mesoproterozoic (Uruaçuán) biotite gneisses, probably reworked in the Mesoproterozoic; and Correà et al. (1979), of undetermined age but (1.3–1.0 Ga).

The Corumbá Group was deposited on a stable continental margin (Almeida, 1984; 274; Zaine, 1991; Boggiani et al., 1993, 1998; Boggiani, 1998), and includes alternating siliciclastic and carbonatic units with a composite thickness of approximately 600 m (Boggiani, 1998). Following glacial and glaciomarine deposits of the Varangerian/Marinoan Puga Formation (Almeida, 1984; Alvarenga, 1990; Alvarenga and Trompette, 1992; Alvarenga et al., 2000), a siliciclastic deepening-upward sequence was deposited, represented by the Cerradinho Formation (Almeida, 1965, 1984; Boggiani, 1998). Boggiani (1998) interpreted the Cadiueus Formation as alluvial fan, synrift deposits generated during opening of the Corumbá basin. While this explanation cannot be ruled out, it must be born in mind that the underlying Puga Formation already records (glacio) marine conditions in the shelf. Furthermore, it is well known that alluvial fan deposits are very similar to glacial-outwash fans, also termed sandur deposits (Ruegg, 1977; Reineck and Singh, 1980: 202; Miall, 2000). Therefore, the Cadiueus Formation probably represents glacial-outwash fans deposited during retreat of the Varangerian ice-sheet. The Cerradinho Formation conformably passes into carbonates of the Bocaina Formation, or more rarely, directly into the Tamengo Formation (Almeida, 1965, 1984; Boggiani, 1998; Fig. 4). The Bocaina Formation is characterized by thick deposits of stromatolitic dolostones, that show a great lateral variation of facies (Boggiani et al., 1993; Boggiani, 1998), including phosphorites with up to 34% P2O5. The overlying Tamengo Formation is mainly composed of dark, organic rich limestones and marls with occasional Cloudina-event accumulations (Almeida, 1965, 1984; Zaine, 1991; Boggiani, 1998). Dark limestones and limestone–dolostone rhythms included by Almeida (1984) in the Cerradinho Formation were considered by Gaucher (2000: 107) as part of the basal Tamengo Formation. Finally, carbonates of the Tamengo Formation are concordantly overlain by gray siltstones of the Guaicurus Formation (Almeida, 1965; Boggiani, 1998), marking the end of deposition in the Corumbá basin.

The Corumbá Group was deformed and metamorphosed in the Cambrian-lowermost Ordovician (540–490 Ma) during the Paraguay Orogeny, as defined by Basei and Brito Neves (1992). This orogenic event has been either considered as a terminal event of the Brasiliano-Pan African Megacycle (Almeida, 1984; Alvarenga and Trompette, 1993; Trompette in Alvarenga et al., 2000) or as a separate orogeny (Basei and Brito Neves, 1992: 333; Gaucher, 2000; see above). Almeida (1984) defined two main structural domains in the Paraguay Belt, based on observed tectonic style, metamorphism and lithology. The ‘Metamorphic Brazilides’ represent the most deformed and metamorphosed domain to the E, in contrast with the ‘Non-metamorphic Brazilides’, which include the less deformed regions adjacent to the craton (Almeida, 1984; Fig. 3). This scheme proved very successful in explaining the different tectonic styles that shows the Corumbá Group in the different domains, and has been adopted by most authors dealing with the Paraguay Belt (Almeida, 1984; Boggiani et al., 1993; Alvarenga and Trompette, 1993; Boggiani, 1998; Alvarenga et al., 2000).
Granitogenesis in the Paraguay Belt is mainly confined to the ‘Metamorphic Brazilides’. Post-tectonic granites such as the São Vicente Granite yielded ages of 504 ± 12 Ma (K/Ar in biotite: Almeida and Mantovani, in Boggiani, 1998: 24), giving minimum age-constraints for the Corumbá Group.

3. Lithostratigraphy and sedimentary environments

3.1. Comparative lithostratigraphy

3.1.1. Common features

The comparison of both sedimentary sequences reveals the following common features of the Arroyo del Soldado and Corumbá groups:

1. Both successions rest with erosional and angular unconformity on an Archean to Mesoproterozoic granitic–metamorphic basement that is consistently older than the Brasiliano-Pan African Orogeny (≈ 750–600 Ma: Campos Neto, 2000), a fact of great importance for palaeogeographic reconstructions of the region.

2. Both groups begin with a siliciclastic, deepening-upward sequence unconformably overlying pre-Brasiliano basement, represented by the Yerbal and Cerradinho formations. These units contain rather thin, mature, basal conglomerates and sandstones, with complete absence of volcanics, volcaniclastics and pyroclastites (Almeida, 1984; Boggiani et al., 1993; Boggiani, 1998; Gaucher et al., 1998a,b; Gaucher, 1999, 2000). These facts indicate that the basin was tectonically stable and had a low palaeorelief, suggesting that the cause of the transgression was an eustatic sea-level rise rather than extensional tectonics. At the top, the mentioned formations are composed mainly of green, chloritic and glauconitic siltstones, which contain an acritarch-assemblage strongly dominated by *Bavlinella faveolata* (Gaucher, 1999, 2000).

3. The siliciclastic transgressive units of both groups pass to the top with sharp contact into thick carbonate deposits (Polanco and Bocaina-Tamengo Formations; Fig. 4). The Polanco and Tamengo formations are made up of dark, organic-rich, clastic limestones and limestone–dolostone rhythmites (Boggiani, 1998; Gaucher, 1999, 2000). The carbonatic rhythmites are very distinctive lithologies, that have been cited only from few places around the world (Bose, 1979; Fairchild, 1980; Gaucher, 1999, 2000), and indicates that both the Arroyo del Soldado and Corumbá groups presented the special conditions necessary for their genesis. Sedimentary structures and facies indicate that the Tamengo Formation was deposited in a shallower basin than the Polanco Formation. Tempestites are frequent in both units, as documented by occurrence of graded limestone beds with hummocky cross-stratification and event-accumulations of *Cloudina* in the Corumbá Group (Zaine, 1991; Boggiani et al., 1993; Boggiani, 1998; Gaucher, 2000). These facts indicate the common occurrence of storms in both basins, probably due to a tropical setting (Seilacher and Aigner, 1991).

4. Carbonate deposits of the Tamengo and Polanco Formations are overlain by thick siliciclastic, mainly pelitic units, namely the Guaicurus and Cerro Espuelitas Formations, respectively (Boggiani, 1998; Gaucher, 2000). These units are made up mainly of siltstones and shales, with minor carbonates at the base. Thick chert and BIF deposits of the middle Cerro Espuelitas Formation are absent in the Guaicurus Formation. A possible explanation could be that only the lower portion of the Cerro Espuelitas Formation is represented in the Corumbá Group, as also suggested by the fossils that occur in the Guaicurus Formation. The chemostratigraphic data obtained so far support these ideas as well (see below).

5. Palaeocurrents measured in the Corumbá Group consistently indicate that the basin deepened to the east (Boggiani, 1990, 1998; Alvarenga, 1990; Boggiani et al., 1993) and point to a source-area in the Río Apa Block, to the west (Figs. 1 and 3). In the case of the ASG, palaeocurrents measured also indicate a shelf that deepened to the SE–E, with a palaeoshoreline roughly N–S and source areas to the west (Montaña and Sprechmann, 1993; Gaucher, 2000). Facies arrangement and thickness in both basins corroborate palaeocurrent data.
3.1.2. Differences

There are some important differences in the lithostratigraphy of the Corumbá and ASGs which need to be considered here:

(1) A clear record of glacial episodes in SW-Brazil is provided by the Jacadigo Group and by tillites of the Puga Formation (Almeida, 1984; Alvarenga, 1990; Alvarenga and Trompette, 1992; Alvarenga et al., 2000). Evidence of glaciation is so far absent in the ASG. The Puga Formation is composed of massive, polymictic diamictites including angular, faceted and striated clasts up to some decimeters in size (Almeida, 1984: 272–273; Alvarenga, 1990; Zaine, 1991; Alvarenga and Trompette, 1992; Boggiani, 1998). Intercalations of pelites and fine sandstones including decimetric dropstones also occur (Almeida, 1984; Fig. 4) and corroborate the interpretation of a glacial, most probably glaciomarine depositional environment for the unit (Alvarenga, 1990; Alvarenga and Trompette, 1992; Alvarenga et al., 2000). Taking into account that the Puga Formation is concordantly overlain by the upper Vendian Corumbá Group (Almeida, 1984; Boggiani, 1998; Alvarenga et al., 2000), these deposits represent the record of the Varangerian/Marinoan Ice Age (Hambrey and Harland, 1985; Harland, 1989; Kasting, 1992; Kaufman et al., 1997; Saylor et al., 1998; Knoll, 2000) in the Corumbá basin (Alvarenga, 1990: 34; Alvarenga and Trompette, 1992). As noted above, the Cadiueus Formation may represent glacial-outwash deposits generated during the retreat of the ice-sheet. Two main scenarios can be proposed to explain the absence of Varangerian or older glacial deposits in the ASG, namely: (a) a tropical palaeogeographic location, inside the circum-equatorial ice-free zone (Hyde et al., 2000; Runnegar, 2000), where glaciation only led to sea-level drop, leaving no glacial deposits; and (b) glaciation with complete erosion of the sedimentary record of the Varangerian in the basin. Of these scenarios, the former is preferred because there is indeed abundant evidence of a tropical setting for the ASG, but complete erosion of the record cannot be ruled out (Montañá and Sprechmann, 1993; Gaucher et al., 1996; Gaucher, 1999, 2000).

(2) Sedimentary structures indicate that the Corumbá Group was deposited in a shallower basin, leading to a greater facies-variation compared to the ASG. While the Tamengo Formation shows a quite rich facies variability (Boggiani, 1998; Boggiani et al., 1993), the Polanco Formation presents a great lateral facies-persistence (Gaucher, 1999, 2000). Composite thickness of the ASG exceeds 5000 m (Gaucher, 2000) and is
thus roughly 10 times greater than that of the Corumbá Group (600 m: Boggiani, 1998), in accordance with deposition in a deeper and more rapidly subsiding basin.

(3) The stromatolitic and oolitic dolostones of the Bocaina Formation (sensu Boggiani et al., 1993; Boggiani, 1998) do not have a counterpart in the ASG. Absence of stromatolites at the base of the Polanco Formation is due to a deeper sedimentary environment. Oolitic calcarenites have been found, however, in the Polanco Formation in the Isla Cristalina de Rivera (Gaucher, 2000; Fig. 2). Moreover, the fact that the Cerradinho Formation passes directly into non-stromatolitic carbonates of the Tamengo Formation at many localities indicates that the Bocaina Formation could be restricted to the shallowest areas of the Corumbá basin. Boggiani (1998: 64) proposed that the Bocaina Formation represents the transgression of the Vendian Sea onto a peneplained basement (Pedra Branca surface) generating a large and shallow epicontinental basin. In deeper sections like in the Serra da Bodoquena, carbonates of the Tamengo Formation rest directly on the Cerradinho Formation, closely paralleling the lithostratigraphy of the ASG (Gaucher, 2000). At Fazenda Baía das Garças (points 3–4, Fig. 3), for instance, the upper Cerradinho Formation passes directly into dark limestones and limestone/dolostone rhythmites, stromatolitic dolostones of the Bocaina Formation being completely absent at that locality (Boggiani, 1990, 1998; Zaine, 1991; Gaucher, 1999, 2000).

(4) Black phosphorites with up to 34% P₂O₅ have been reported from the Bocaina and basal Tamengo Formations (Boggiani et al., 1993; Boggiani et al., 1998). They are made up of cryptocrystalline fluorapatite and contain large amounts of organic matter ( > 5%). Such lithologies have not been found so far in the ASG, where the only traces of phosphate are relicts in the shells of Waltheria marburgensis at the top of the Yerbal Formation (Gaucher and Sprechmann, 1999; Gaucher, 2000). As known from recent examples, phosphorite deposits are mainly the consequence of upwelling of deep water at the western margins of continents under favourable wind and current regime (Baturin, 1982). Evidence of upwelling in the upper Yerbal Formation has been presented by Gaucher (1999, 2000), including acritarch assemblages indicative of basin eutrophication, occurrence of glauconitic and chamositic siltstones, banded ferruginous siltstones, and recently discovered BIF. Considering the phosphorite occurrences in the Corumbá Group restricted to rather thin beds (Fig. 4) and the mentioned evidences of upwelling in the ASG, we conclude that the occurrence of phosphatic rocks in the latter unit cannot be ruled out. Furthermore, upwelling played indeed a major role in both groups at the contact between basal siliciclastics and overlying carbonates, probably indicating a similar palaeogeography for both basins.

(5) The ASG includes thick deposits of chert and BIF in the Cerro Espuelitas Formation (Gaucher and Schipilov, 1994; Gaucher et al., 1996, 1998b; Gaucher, 1999, 2000), which are unknown in the Corumbá Group (Fig. 4). The BIF represent micro- and meso-banded, oxide-facies BIF (Beukes, 1973; James, 1983) containing up to 35 wt.% magnetite or hematite and occurring in up to three horizons with maximum thickness of 200 m. Thickness of banded, massive and ferruginous cherts of the middle Cerro Espuelitas Formation reaches 400 m (Gaucher et al., 1996, 1998b; Gaucher, 1999, 2000). The Guaicurus Formation is probably correlative to the lowermost Cerro Espuelitas Formation, where BIF and chert are absent (Gaucher 1999, 2000). As already mentioned above, BIF of the Jacadigo Group cropping out in the region of Corumbá, are considered older than both the Corumbá and ASG, being probably of Varangerian or even Sturtian age (Almeida, 1984; Walde, 1987; Zaine, 1991; Gaucher, 2000).

Fig. 4. Composite stratigraphic columns of the Corumbá and ASGs, showing correlations between lithostratigraphic units and stratigraphic distribution of most important fossil-taxa (sources: Boggiani, 1998; Gaucher, 2000 and this work). CV, Cerro Victoria Formation; Cerros SF, Cerros San Francisco Formation; Cad, Cadieuus Formation. The Cadieuus Formation has not been drawn to avoid a more complicated representation (see text). Shaded intervals in the ASG represent periods of basin eutrophication.
Fig. 4
(6) Gaucher (2000) recognized an impressive climatic deterioration recorded at the boundary between the Polanco and Barriga Negra formations, on the basis of: (a) termination of carbonate deposition at the top of the Polanco Formation; (b) change of clay-mineral composition of siltstones; and (c) destabilization of the shallower areas of the Arroyo del Soldado shelf due to sea-level drop, leading to cannibalization of shelf deposits and local deposition of up to 1500 m of conglomerates of the Barriga Negra Formation. These conglomerates do not have a correlation in the Corumbá Group, although the basin was shallower than the Arroyo del Soldado basin. Possible explanations could be that: (1) palaeorelief was much steeper in some parts of the Arroyo del Soldado basin than in the Corumbá basin; (2) the regression left only an erosive record in the Corumbá Group; and/or (3) influence of isostatic reactivations of the Sarandí del Yí-Piria´polis lineament were also responsible for the genesis of the conglomerates, a factor absent in the Corumbá basin.

3.2. Geotectonic setting and sedimentary environments

The analysis of the preceding data indicates that the Corumbá and ASGs were deposited in similar sedimentary environments and geotectonic settings. Both units were deposited on a stable, Atlantic-type continental margin, in a predominantly marine environment (Almeida, 1984: 274; Zaine, 1991; Boggiani et al., 1993; Gaucher et al., 1996, 1998b; Boggiani, 1998; Gaucher, 1999, 2000). Evidence of tectonic stability in both basins is provided by: (a) the absence of volcanic, pyroclastic or volcanoclastic rocks; (b) textural characteristics of sandstones, which are mainly quartz-arenites and subarkoses (Pettijohn et al., 1987); (c) provenance of sandstones and conglomerates from a deeply eroded, granitic and (para)metamorphic source-area; and (d) development of extensive carbonate ramps and stromatolite buildups.

The Corumbá and ASGs were deposited in a marine sedimentary environment, as shown by microfossil assemblages, skeletal fossils, vendotaenids (see below), sedimentary structures, petrography and facies distribution. Both basins record the transgression that followed the termination of the Varangerian glaciation, as indicated by biostratigraphy and carbon isotopes. This is specially clear in the Corumbá Group, where this glacial episode is represented by the tillites of the underlying Puga formation (Almeida, 1984; Alvarenga, 1990). The glacioeustatic sea-level rise that followed the Varangerian determined the deposition of the basal units of both groups. In fact, the major control of sedimentation was provided by (glacio)eustasy and not by tectonic processes, in accordance with the proposed geotectonic setting. Evidences of drastic climatic changes coupled with eustatic sea-level oscillations are widespread in the Corumbá and ASGs. The lower portions of the basal Cerradinho and Yerbal formations were deposited under cool and/or arid conditions, as shown by sandstone composition (Boggiani, 1998: 44; Gaucher, 1999, 2000) and clay-mineral suites present (Gaucher, 1999, 2000). At the base of the Bocaina, Tamengo and Polanco Formations, climate shifted towards warm, tropical conditions, because: (a) oolites are widespread (Zaine, 1991; Boggiani, 1998; Gaucher, 2000), which are typical of tropical regions (Füchtbauer and Richter, 1988: 335); (b) abundant carbonatic tempestites in the Tamengo and Polanco Formations (Boggiani et al., 1993; Boggiani, 1998; Gaucher, 2000) indicate recurrent large storms which are more common at low latitudes (Seilacher and Aigner, 1991: 252); (c) clay-mineral and terrigenous are composed mainly of kaolinite (Gaucher, 1999, 2000) and quartz-arenite, respectively (Boggiani, 1998: 68–69; Gaucher, 1999, 2000), suggesting intense chemical weathering in the source-areas (Pettijohn et al., 1987; Heling, 1988); and finally (d) the huge amounts of carbonate deposited in both basins are also indicative of a tropical setting. Up section, climate deteriorated again, as shown by the interruption of carbonate deposition at the transition to the Guaicurus and Barriga Negra–Cerro Espuelitas formations. Gaucher (1999, 2000) showed that this climate change caused an important regression which exposed the shallower areas of the Arroyo del Soldado shelf. An associated negative δ13C-excursion in unaltered carbo-
nates (see below), also suggests that this regression could be the consequence of global cooling or even glaciation (Kaufman et al., 1997; Jacobsen and Kaufman, 1999; Knoll, 2000; Kaufman, 2000).

Upwelling was another important factor in both shelves, leading to deposition of BIF, chert and phosphorites, causing phytoplankton blooms and eutrophication of the basins (Boggiani et al., 1993; Gaucher et al., 1996; Boggiani, 1998; Gaucher, 2000; Fig. 4). This fact indicates that the palaeogeographic setting of both basins was very similar, with a combination of shoreline orientation, current and wind regime that promoted upwelling of deep, cold seawater (Baturin, 1982). Indications that the basin was stratified and had episodic periods of eutrophication related to upwelling are: (a) BIF occurring in the ASG and phosphorites in the Corumbá Group; (b) strong dominance of the low-diversity microfossil assemblages by one or two taxa, including *Bavlinella faveolata* (Gaucher, 2000; Fig. 4), as also found for other upper Vendian successions worldwide (Mansuy and Vidal, 1983; Palacios, 1989; Vidal and Nystuen, 1990; Steiner, 1994); and (c) occurrence of organic-rich horizons with up to 11% TOC suggesting high bioproductivity and enhanced preservation of organic matter.

A substantial difference observed is, that while the ASG was deposited in a typical marginal or pericontinental sea (sensu Einsele, 1992), the Corumbá Group was in part deposited in a shallower epicontinental sea over a peneplainized craton. This could explain the greater thickness of the ASG, as well as its more complete sedimentary record (Einsele, 1992: 124). The Arroyo del Soldado basin was steeper and responds to a typical marginal sea (Einsele, 1992), with great lateral facies-persistence over hundreds of kilometers and deposition of a thick sedimentary wedge.

4. Palaeontology

4.1. Previous work

The first fossils to be reported from the units considered here were calcareous tubes of the Tamengo Formation described by Beurlen and Sommer (1957) as *Aulophycus lucianoi*, and later included in the genus *Cloudina* by Zaine and Fairchild (1985) and Hahn and Pflug (1985). Hahn et al. (1982) reported the occurrence of possible Scyphozoa in the Tamengo Formation, erecting the taxon *Corumbella werneri*. The occurrence of acritarchs in the Corumbá Group was first reported by Fairchild and Sundaram (1981) and later confirmed by Zaine and Fairchild (1987), which assigned them to the species *Bavlinella faveolata* and cf. *Vandalosphaeridium* sp. The first systematic study of the palaeontology of the Corumbá Group was made by Zaine (1991), who described acritarchs, filamentous microfossils, venedotaenids, and possible metazoans of the genus *Cloudina* and *Corumbella*. Boggiani (1998) reported new occurrences of *Cloudina* and *Corumbella*, extending the known stratigraphic range of these taxa in the Corumbá Group. Gaucher (2000) describes *Eoholynia* sp. from the lower Guaicurus Formation. Finally, Fairchild et al. (2000) mentioned the occurrence of possible ichnofossils, newly discovered stromatolites, oncolites and silicified colonies of probably cyanobacterial affinities.

Palaeontologic studies began more recently in the ASG. Montaña and Sprechmann (1993) reported the occurrence of stromatolites and ichnofossils in the Cerro Victoria Formation. Gaucher and Schipilov (1994) described the first acritarchs from BIF of the Cerro Espueilitas Formation. A number of publications by Gaucher et al. (1996, 1998b) and Gaucher and Sprechmann (1998) followed, describing organic-walled microfossils from almost the entire ASG. An assemblage of five genera and species of skeletal fossils including *Cloudina riemikeae* Germs (1972) has been reported by Gaucher and Sprechmann (1999). Finally, Gaucher (2000) presented detailed palaeontologic and biostratigraphic information for the ASG, also describing fossil material from the Corumbá Group.

In the following section, new fossil material from the Corumbá Group is described and compared with the fossil assemblages of the ASG. All specimens described are deposited in the collection of the Departamento de Paleontología of the
Facultad de Ciencias (FCDP) in Montevideo (Uruguay).

4.2. Organic-walled microfossils

Organic-walled microfossils are abundant and well preserved in the ASG. Although microfossils and kerogens are also abundant in the Corumbá Group, preservation is quite poor due to carbonization attributed to a thermal event associated with generation of anorogenic basaltic dykes (Walde, 1987) or unspecified contact metamorphism. This thermal event also affected the Mn-ore paragenesis of the Jacadigo Group, as well as their oxygen isotopic composition (Trompette et al., 1998 and references therein). Therefore, the reported taxa should be taken only as a fragment of the original microbiota, because most of the organic remains are unidentifiable.

Kingdom Eubacteria Woese & Fox, 1977
Phylum Cyanobacteria Stanier et al., 1978
Classis, Ordo et Fam. indet.
Genus Barlinella (Schepeleva) Vidal, 1976

Type species: Barlinella faveolata (Schepeleva) Vidal, 1976

Barlinella faveolata (Schepeleva), Vidal, 1976
Fig. 5C–E, G–H; Fig. 6F

1974 Sphaerocongregus variabilis Moorman: pls. 1–3
1976 Barlinella faveolata Vidal: figs. 7A–C
1990 Sphaerocongregus variabilis Vidal & Nystuen: fig. 9A–B, D–E, G–L
1991 Sphaerocongregus variabilis Zaine: fig. 2A.
1992 Barlinella faveolata Schopf: pl. 54J1–J3
1996 Barlinella faveolata Gaucher et al.: figs. 7.1–7.2
2000 Barlinella faveolata Gaucher: pl. 9, pl. 18.1–18.2

Type specimen. Vidal (1976) adopted the diagnosis given by Moorman (1974) for Sphaerocongregus variabilis as the valid diagnosis for Barlinella faveolata. Vidal and Nystuen (1990) find that the type specimen illustrated by Schepeleva (1962), in Vidal, 1976) ‘is in fact the organic residue after maceration of framboidal pyrite’, and recommend the use of the junior synonym instead of Barlinella faveolata for this species. Nevertheless, German et al. (1989) had already designated a lectotype for the species from the Kotlin Formation of the former USSR. This lectotype has been also illustrated by Schopf (1992: pl. 54-J). Therefore, the valid designation of a lectotype supersedes any previous restriction of the application of the name of the genus and species Barlinella faveolata. Sphaerocongregus variabilis Moorman (1974) is thus to be considered as a junior synonym.

Material. Hundreds of specimens in thin-sections of siltstones and palynological macerations of limestones and marls. In the siltstones, the specimens are commonly permineralized with iron-oxides (Fig. 5G–H). The species often occurs in acid macerations, showing advanced carbonization which gives the vesicles a gray to black colour (Figs. 5D and 6F).

Description. The observed specimens are single spheroidal vesicles made up of hundreds of tightly packed, micron-sized microspheres, thus corresponding to the endosporangia morphotype of Moorman (1974).

Dimensions. Specimens preserved in green siltstones of the upper Cerradinho Formation range in diameter between 4.0 and 21.5 μm (mean = 9.9 μm, S.D. = 4.0 μm, N = 40). This population was measured mainly in thin sections, but specimens in palynological macerations were also considered. On the other hand, the population palynologically recovered from marls of the Tamengo Formation show larger diameters, between 16 and 45 μm (mean = 27.9 μm, S.D. = 7.8 μm, N = 13). Zaine (1991: 109) found vesicles with diameters ranging between 4 and 15 μm (mean = 7 μm, N = 20) in macerations of the same stratigraphic levels of the Tamengo Formation. This strongly suggests that the differences in mean size observed are due either to facies dependence of the populations or to preparation biases (i.e. mesh apertures of sieves used).

Distribution. The occurrence of this taxon in the Tamengo Formation was already noted by Zaine and Fairchild (1987) and Zaine (1991). Barlinella faveolata occurs in large masses in green siltstones
of the upper Cerradinho Formation in the Serra da Bodoquena (point 3, Fig. 3), and also in black, organic-rich marls of the Tamengo Formation near Corumbá (Pedreira Saladeiro/Itaú, point 9 of Fig. 3), as described by the above mentioned authors.

Remarks. *Baavinella faveolata* shows more variability and better preservation in the ASG, with occurrence of all morphotypes described by Moorman (1974), as noted by Gaucher (2000). Apart from this, the fossils of the Corumbá Group are identical to the corresponding morphotypes of the ASG. *Baavinella faveolata* is closely associated with green siltstones in the Cerradinho Formation occurring in large numbers and dominating the fossil assemblage. In this facies, *Baavinella* is

Fig. 5. Organic-walled microfossils from the Corumbá and ASGs, as observed in thin sections (C, E–H) and palynological macerations (A–B, D). (A) *Vendotaenia antiqua*, fragment from green siltstones of the upper Cerradinho Formation (point 3, Fig. 3). (B) Saucer-shaped colony of *Soldadophycus bossii* from gray siltstones of the lowermost Guacurus Formation (Pedreira Laginha, point 10 of Fig. 3). Note typical transitions between spheroids and filaments. (C) *Baavinella faveolata*, vesicle-chain occurring in green siltstones of the upper Cerradinho Formation (point 3, Fig. 3). (D–E) Solitary vesicles of *Baavinella faveolata* from the same facies and locality as C. (F) *Baavinella faveolata*, specimen FCDP 3189 from the Yerbal Formation of the ASG (near Minas de Corrales). (G–H) Solitary, hematized vesicles of *Baavinella faveolata*, occurring in green siltstones of the upper Cerradinho Formation (point 3, Fig. 3). Note loss of details due to ferrification. Scale bars represent 10 μm for all figures.
Fig. 6. Organic-walled microfossils recovered by means of palynological macerations from the Corumbá Group. (A) *Soldadophycus bossii*, carbonized, saucer-shaped colony from gray siltstones of the lowermost Guaicurus Formation at point 10 (Fig. 3). (B) *Soldadophycus bossii*, same provenance as the former. (C–D) Two filament-balls of *Siphonophycus robustum* from gray siltstones of the lowermost Guaicurus Formation at point 10 (Fig. 3). (E) *Myxococoides* sp., semicarbonized colony in dark marls of the Tamengo Formation (Pedreira Saladeiro/Itau, point 9 of Fig. 3). Note psilate, loosely aggregated spheroids (arrowed). (F) *Bawlinella faveolata*, single vesicle from the Tamengo Formation (same provenance as E). (G) *Leiosphaeridia* sp., carbonized specimen under epillumination. Recovered from gray siltstones of the lowermost Guaicurus Formation (point 10, Fig. 3). Scale bars represent 10 μm for all specimens.
typically hematized, sometimes obscuring morphologic detail (Fig. 5G–H). The same happens in the correlative Yerbal Formation and also in the Cerro Espuelitas Formation of the ASG (Gaucher, 2000). The palynofacies are in fact almost indistinguishable, probably due to eutrophic conditions fueled by high nutrient (P, Fe, N) availability in both basins.

*Bawlinella faveolata* is a long-ranging fossil, found in successions ranging from the Upper Riphean (Vidal, 1976; Samuelsson, 1997) to the Ordovician (Reitz, 1991). Well-preserved fossils clearly belonging to this taxon have been found by Salamon and Gaucher (in preparation) in Middle Devonian (Givetian) siliceous shales of the Rheinisches Schiefergebirge of Germany. Nevertheless, it is clear that the taxon reached its acme in the upper Vendian, when it was a dominating component of the biota worldwide (Moorman, 1974; Mansuy and Vidal, 1983; Knoll and Sweet, 1985; Germs et al., 1986; Palacios, 1989; Vidal and Nystuen, 1990; Gaucher, 2000).

Genus *Siphonophycus* Schopf (1968), emend Knoll et al. (1991)

Type species: *Siphonophycus kestron* Schopf, 1968

*Siphonophycus robustum* Schopf (1968), emend Knoll et al. (1991)

**Fig. 6C–D**

1968  *Eomycetopsis robusta* Schopf: pls. 82.2–3; 83.1–4
1991  *Siphonophycus robustum* Knoll et al.: figs. 10.3, 10.5
1994  *Siphonophycus robustum* Butterfield et al.: figs. 26A, G
1994  *Siphonophycus robustum* Hofmann and Jackson: fig. 11.5

Type specimen: Specimen of plate 83.1 (a, b) of Schopf (1968)

**Material.** Three mat fragments and one complete filament ball in macerations of gray siltstones of the base of the Guaicurus Formation at Pedreira Laginha, near Corumbá (point 10, Fig. 3).

**Description.** Psilate, unbranched, nonseptate filaments 0.8–3.0 μm in diameter (mean = 1.8 μm, S.D. = 0.5 μm, N = 21). The entangled filaments occur either as irregular mat-fragments or as filament balls (Fig. 6C–D).

Remarks. The species of the genus *Siphonophycus* are distinguished on the basis of trichome-size (Knoll et al., 1991; Butterfield et al., 1994). The material from the Guaicurus Formation has a size distribution intermediate between *S. septatum* (Schopf) Knoll et al. (1991) and *S. robustum*. The latter is characterized by filament diameters in the range of 2–4 μm (Knoll et al., 1991; Butterfield et al., 1994; Hofmann and Jackson, 1994). Nevertheless, the habit of the filament-aggregates described here is identical to *S. robustum*. Butterfield et al. (1994: fig. 26G) report the occurrence of *S. robustum*-balls similar to modern *Nostoc*-balls in the Svanbergfjellet Formation of Spitsbergen, which closely resemble our material. Moreover, they find that the species is the most common shale-facies microbial mat-builder, as is the case in the Guaicurus Formation. Therefore, we assign the material to *S. robustum* (Schopf) Knoll et al. (1991).

Incertae sedis

Group *Acritarcha* Evitt, 1963

Genus *Leiosphaeridia* Eisenack (1958), emend Downie & Sarjeant (1963)

Type species: *Leiosphaeridia baltica* Eisenack (1958)

*Leiosphaeridia tenuissima* Eisenack (1958)

**Fig. 6C–D**

1958  *Leiosphaeridia tenuissima* Eisenack: pl. 1.2–1.3
1994  *Leiosphaeridia tenuissima* Butterfield et al.: fig. 16I
1994  *Leiosphaeridia tenuissima* Hofmann and Jackson: fig. 12E
1998  *Leiosphaeridia tenuissima* Gaucher et al.: fig. 4.6
2000  *Leiosphaeridia tenuissima* Gaucher: pl. 11.5

**Material.** Two well-preserved specimens in macerations of siltstones of the lowermost Guaicurus Formation at Pedreira Laginha (point 10, Fig. 3).

**Description.** Thin-walled, compressed, psilate spheroidal vesicles with common folds. Diameter ranging from 70 to 120 μm (only two specimens). The individuals are partially carbonized, showing a light gray colour.

**Remarks.** These are the largest acritarchs of the Corumbá microbiota, as is also the case in the ASG (Gaucher, 2000). Absence of larger acritarchs is typical of uppermost Vendian successions
Leiosphaeridia sp.
Fig. 6G

Material. Two complete specimens and some fragments recovered by acid maceration from siltstones of the lowermost Guaicurus Formation at Pedreira Laginha (point 10, Fig. 3).

Description. Compressed ellipsoidal vesicles with rectilinear or curvilinear folds, 72–150 μm in maximum diameter. Wall probably thick, and opaque due to advanced carbonization. Irregular sculpture of wall probably due to degradation of an originally psilate wall.

Remarks. Due to the opacity of the vesicles, no reliable estimation of wall-thickness could be made. Nevertheless, the specimens are quite different in their degree of carbonization, type of folds and superficial features to those described here under Leiosphaeridia tenuissima from the same locality. These facts suggest that the species is thick-walled, unlike L. minutissima. If this point is confirmed, then the specimens could be assigned to Leiosphaeridia jacutica (Timofeev) Mikhaylova and Yankauskas (Hofmann and Jackson, 1994), but more material is needed.

Incertae sedis
Genus Soldadophycus Gaucher et al. (1996)

Type species: Soldadophycus bossii Gaucher et al. (1996)

Soldadophycus bossii Gaucher et al. (1996) Fig. 5B, Fig. 6A–B

1989 Tipo B Palacios, pl. V; figs. 1–4
1996 Soldadophycus bossii Gaucher et al.: figs. 6.1–6.5; fig. 6.7
1998 Soldadophycus bossii Gaucher and Sprechmann: p. 184
2000 Soldadophycus bossii Gaucher: pls. 14–15; 17.4

Type specimen. Holotype: specimen FCDP 3188, figured by Gaucher et al. (1996: fig. 6.1). Paratype of saucer-shaped colonies is the specimen FCDP 3207b (fig. 6.2 of Gaucher et al., 1996).

Material. Twelve colonies and colony-fragments in palynological macerations of marls, siltstones and limestones of the upper Cerradinho, Tamengo and lower Guaicurus formations. Fossil sites for each of the mentioned units are the locality of Baía das Garças (point 3, Fig. 3), Pedreira Saladeiro/Itau (point 9, Fig. 3) and Pedreira Laginha (point 10, Fig. 3), respectively. The species occurs more frequently in the Cerradinho and Guaicurus formations.

Dimensions. Diameter of the spheroidal cells ranging between 2.6 and 8.2 μm (mean = 4.9 μm, S.D. = 1.6 μm, N = 41). Maximum width of filaments varying between 1.7 and 3.5 μm (mean = 2.3 μm; S.D. = 0.6 μm; N = 7). Diameter of saucer-shaped colonies varying between 57 and 65 μm. A single vase or bottle-shaped colony occurs, with a diameter of 90 and 160 μm long. These values are completely within the cell and colony sizes typical for the species (Gaucher et al., 1996; Gaucher, 2000: 78).

Description. Soldadophycus bossii is characterized by the co-occurrence of psilate, spheroidal cells and septate, branched filaments (Gaucher et al., 1996). Nevertheless, some colony-types are made up only of spheroidal cells. In the Corumbá Group, the saucer-shaped colonies dominate (Figs. 5B and 6A–B), but subspheroidal and vase-shaped colonies also occur. The typical transitions from spheroids into filaments and vice versa were also observed (Fig. 5B). Unlike in the ASG, the fossils are always carbonized, showing gray to black (opaque) colours.

Remarks. As in the ASG, Soldadophycus occurs in the Corumbá Group in relatively large numbers only in the siliciclastic units bracketing carbonate deposits (Cerradinho and Guaicurus formations). In the Tamengo Formation they are an accessory element of the microbiota, as in the case of the Polanco Formation (Gaucher, 2000).

Genus Myxococcoides Schopf (1968)

Type species: Myxococcoides minor Schopf (1968)
**Myxococcoides** sp.

Fig. 6.E

2000 *Myxococcoides* sp. Gaucher: p. 105

**Material.** Three fairly well preserved colonies in palynological macerations of marls of the Tamengo Formation (Pedreira Saladeiro/Itau´, point 9 of Fig. 3) and green siltstones of the Cerradinho Formation (point 3, Fig. 3).

**Description.** Spheroidal to ellipsoidal, colonial microfossils. Walls thin, psilate, and rather hyaline despite advanced carbonization. Cells loosely aggregated into irregular colonies of up to 50 μm in maximum dimension. Maximum diameter of cells ranging between 4.5 and 8.0 μm (mean = 6.3 μm, S.D. = 1.1 μm; N = 10).

**Remarks.** The microfossils described here under *Myxococcoides* sp. resemble *M. siderophila* Gaucher (2000) in size, loose arrangement of cells in irregular-shaped colonies and wall thickness. Moreover, *M. siderophila* is a common component of the Arroyo del Soldado microbiota. Nevertheless, due to the advanced carbonization of the material studied, an assignment to that taxon would be premature.

4.3. Vendotaenids

**Class Vendophyceae** Gnilovskaya (1986)

**Order Eoholyniales** Gnilovskaya (1986)

**Family Eoholyniaceae** Gnilovskaya (1986)

**Genus Eoholynia** Gnilovskaya (1975)

**Type species:** *Eoholynia mosquensis* Gnilovskaya (1975)

_Eoholynia corumbensis_ sp. nov.

Fig. 7 A–H

2000 *Eoholynia* sp. Gaucher: pl. 17.7

**Type specimen.** Holotype: specimen FC DP 3615 (Fig. 7C–D). Paratypes of an individual with multiple basal branches is the specimen FC DP 3222 (Fig. 7E, also figured by Gaucher, 2000: pl. 17.7). As paratype of terminal sporangium, we designate the specimen FC DP 3616 (Fig. 7H).

**Derivation of name.** After the town of Corumbá, near which the fossils were discovered.

**Material.** Twenty five complete specimens plus innumerable fragments preserved as carbonaceous impressions in bedding surfaces of gray siltstones, lowermost Guaicurus Formation.

**Type locality.** The material described here was collected in the Pedreira Laginha, located along road BR-262, 16 km south of Corumbá (point 10, Fig. 3). The fossils were found in situ in gray siltstones with frequent slumps, 5–10 m above the contact with the Tamengo Formation (see stratigraphic column in Gaucher, 2000: text—fig. 39).

**Diagnosis.** A species of *Eoholynia* characterized by a cord- or ribbon-like thallus composed of 3–5 main branches, 0.05–0.6 mm wide (mean = 0.24 mm, S.D. = 0.15 mm, N = 34; Fig. 9). Main branches develop secondary branches of several orders, mostly dichotomously. Spherical bodies are frequently (but not always) attached to the surface of the main branch, and also to the ends of the lateral branches (here interpreted as terminal sporangia). Size of spherical bodies ranging between 0.3 and 1.2 mm (mean = 0.54 mm, S.D. = 0.26 mm, N = 11). Height of complete specimens 3–18 mm, mostly around 8 mm.

**Discussion.** *Eoholynia corumbensis* differs from *Eoholynia mosquensis* Gnilovskaya (1975) mainly in its considerably larger size. While *E. mosquensis* is characterized by main branches 0.1–0.15 mm wide (Gnilovskaya, 1979, 1985), *E. corumbensis* reaches 0.6 mm (Fig. 9), thus four times wider than the largest specimens of the former species. Side branches of *E. corumbensis* are also much wider and not so intensely tapering as that of *E. mosquensis*. Finally, in the case of *E. corumbensis*, diameter of spherical bodies interpreted here as sporangia is up to 10 times larger than that reported for *E. mosquensis* (50–100 μm: Gnilovskaya, 1979, 1985; Fig. 11). Considering the above mentioned differences, we find that the erection of a new species of the genus *Eoholynia* is well justified.

**Remarks.** As already noted by Gnilovskaya (1979, 1985) and Hofmann (1994), *Eoholynia* represents the remains of eucaryotic algae, prob-
ably Phaeophyta or Rhodophyta. *Miaohephyton bifurcatum* Steiner (1994), a morphologically similar species, has been placed by Xiao et al. (1998) among the brown algae (Phaeophyta). Nevertheless, the demonstration of the palaeobiologic affinities of the species needs a more detailed study that would be out of the scope of this paper. *E. corumbensis* was probably benthic, as also suggested for *E. mosquensis* (Gnilovskaya, 1985; Burzin, 1996). The accumulations found in siltstones of the Guaicurus Formation are parautochthonous, as is the case of most Russian

Fig. 7. *Eoholynia corumbensis* sp. nov. and *Tawuia* sp. from bedding surfaces of gray siltstones of the lowermost Guaicurus Formation at Pedreira Laginha (point 10, Fig. 3). (A–H) *Eoholynia corumbensis* sp. nov. (A) Complete and straight thallus (FCDP 3613) with multiple branches. (B) Specimen FCDP 3614 with three basal branches and curious levogire arrangement. (C–D) Holotype FCDP 3615, with main branch covered with spherical bodies (sporangia). Terminal sporangia are present at the end of the main branch and at two secondary branches. (E) Paratype FCDP 3222 with intensely branching thallus. (F) Straight thallus-fragment. (G) Terminal sporangium. (H) Specimen FCDP 3616, paratype of terminal sporangium. (I–J) *Tawuia* sp. (I) Slightly curved specimen FCDP 3617. (J) Straight specimen with numerous superimposed *Eoholynia*-thalli. Scale bars represent 1 mm for all figures.
occurrences (Burzin, 1996). Regarding the stratigraphic distribution and evolution of the genus *Eoholynia*, the Brazilian material is clearly younger than *E. mosquensis* from the Redkino Series (lower Valdaian) of the East European Platform, because: (1) the lower Guaicurus Formation concordantly overlies limestones of the uppermost Tamengo Formation with $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of 0.7086 and $\delta^{13}\text{C}$ of up to +5‰ PDB (Boggiani, 1998; Fig. 12), which can be correlated with upper Valdaian sections worldwide (Jacobsen and Kaufman, 1999; Walter et al., 2000); and (2) Gnilovskaya (1979, 1985) finds that *Eoholynia* is typical of lower Valdaian rocks of the East European Platform, which are overlain by *Vendotaenia*-bearing rocks of the Kotlin Horizon (upper Valdaian). As will be discussed later, *Vendotaenia* occurs immediately below *Eoholynia* in the Cerradinho Group (Zaine, 1991). In accordance with our data, Hofmann (1992, 1994) reports younger occurrences of *Eoholynia*, probably reaching the Lower Cambrian.

It is worth noting that the larger size of *E. corumbensis* compared with *E. mosquensis* could reflect an evolutionary trend among the *Eoholyniaceae*. Older representatives of the family like the Riphean genus *Ulophyton* are even smaller than *E. mosquensis* (Gnilovskaya, 1979; Hofmann, 1994), while younger representatives are mostly larger (e.g. Steiner, 1994).

Order Vendotaeniales Gnilovskaya (1986)
Family Vendotaeniaceae Gnilovskaya (1986)
Genus *Vendotaenia* Gnilovskaya (1971)

Type species: *Vendotaenia antiqua* Gnilovskaya (1971)

*Vendotaenia antiqua* Gnilovskaya (1971)

Fig. 5A

1971 *Vendotaenia antiqua* Gnilovskaya: pl. XI.6-8
1979 *Tyrasotaenia podolica* Gnilovskaya
1985 *Vendotaenia antiqua* Gnilovskaya
1985 *Tyrasotaenia podolica* Gnilovskaya
1991 *Tyrasotaenia* sp. Zaine: fig. 5.6, pl. 10
1994 *Vendotaenia antiqua* Steiner: fig. 41k, l; fig. 45a-c; fig. 47

*Type specimen.* Specimen IGGD AN SSSR, No. 6931/20 from the Kotlin Horizon in St. Petersburg, figured by Gnilovskaya (1971: pl. XI.8).

*Material.* Zaine (1991) mentions the occurrence of 25 measured specimens of *Tyrasotaenia* sp. (synonymized by Steiner, 1994 with *Vendotaenia*) in marls of the Tamengo Formation. Our material includes five fragments recovered by means of palynological macerations from siltstones of the Cerradinho Formation and phosphorites of the Bocaina Formation (Fig. 5A).

*Description.* The material recovered from the Cerradinho and Bocaina formations consists of
fragments of ribbonlike thalli, with typical longitudinal-fibrous structure due to compaction folds. No cellular structure is present. Width of the fragments reaches 0.12 mm. The fossils are carbonized and degraded to some extent, showing gray to black colour.

Remarks. The fossils described by Zaine (1991) as *Tyrasotaenia* sp. can be confidently assigned to *Vendotaenia antiqua*. Steiner (1994) placed *Tyrasotaenia* in synonymy with *Vendotaenia*. Moreover, size and morphology of the specimens illustrated by Zaine (1991) are well in accordance with the diagnosis of *Vendotaenia antiqua* (Gnilovskaya, 1971, 1979, 1985; Steiner, 1994). The fragmentary material recovered in this work from the Cerradinho and Bocaina formations closely resembles the microstructure of *Vendotaenia antiqua* (Gnilovskaya, 1985:pls. 32.3, 33.5, 34.3–4; Vidal, 1989: fig. 1C, E). Therefore, we assume that they are conspecific with the vendotaenids of the Tamengo Formation. It is worth noting that the microstructure of *Eoholynia* from the Guaicurus Formation is very different to that of *Vendotaenia*. While the former represents eucaryotic, red or
brown algae, the latter are probably abandoned sheaths of sulfide-oxidizing organotrophic bacteria related to the Beggiaatoaceae (Vidal, 1989), although other interpretations cannot be ruled out (Gnilovskaya, 1985).

Class Chuariaphyceae Gnilovskaya & Ishchenko, in Hofmann (1994)
Order Chuariales Gnilovskaya (1986)
Family Tawuiaceae Ishchenko, in Hofmann (1994)
Genus Tawuiia Gnilovskaya (1975)
Type species: *Tawuia dalensis* Hofmann (1979, in Steiner, 1994)

*Tawuia* sp.

Fig. 7I–J

**Material.** Five carbonaceous compressions in bedding surfaces of gray siltstones of the Guaicurus Formation at Pedreira Laginha (point 10, Fig. 3), co-occurring with *Eoholynia corumbensis*.

**Description.** Sausage-shaped carbonaceous compressions, straight or 'C'-shaped, with more or less rounded ends. Width of compressions: 1.0–2.0 mm and length ranging between 5 and 12 mm.

**Remarks.** Most of the specimens observed are either straight or slightly curved. Only one speci-
men shows the more typical C-shape. Steiner (1994: pl. 2) illustrates many specimens from the Liulaobei Formation and Shilu Group of China similar to those occuring in the Guaicurus Formation. The material described here fits well within the size-range of Tawuia dalensis from those units. Nonetheless, we leave these fossils in open nomenclature until more material is available.

4.4. Skeletal fossils

Phylum indet
Classis et ordo indet
Family Cloudinidae Hahn & Pflug (1985)
Genus Cloudina Germs (1972)

Type species. Cloudina hartmannae Germs (1972)

Cloudina lucianoi (Beurlen & Sommer) Zaine & Fairchild (1985)
FIG. 10A–K

1957 Aulophycus lucianoi n. sp. Beurlen & Sommer: pl. 1–VI
1985 Cloudina lucianoi Zaine & Fairchild: p. 130
1985 Cloudina waldei Hahn & Pflug: fig. 7, pl. 1, pl. 2.3–2.4
1987 Cloudina lucianoi Zaine & Fairchild: figs. 1–7
1990 Cloudina lucianoi Grant: fig. 10E
1991 Cloudina lucianoi Zaine: figs. 5.2–5.3, pls. 3–6
1998 Cloudina lucianoi Boggiani: fig. 4.33
1999 Cloudina lucianoi Gaucher & Sprechmann: p. 66
2000 Cloudina lucianoi Gaucher: pl. 21.1–21.3

Type specimen. Specimen No. 1149 of the palaeobotanic collection of the Divisão de Geologia e Mineralogia (DNPM, Rio de Janeiro), figured by Beurlen and Sommer (1957: pl. II.b).

Material. Forty-five well-preserved specimens in thin-sections of calcareous tempestites of the Tamengo Formation at Pedreira Corcal (point 8, FIG. 3), and many others in polished slabs of these samples.

Dimensions. Maximum diameter of fossils studied ranging within 0.5–3.5 mm (mean = 1.35 mm, S.D. = 0.64 mm, N = 32), well in accordance with earlier reports by Zaine (1991, 0.2–3.8 mm) and Hahn and Pflug (1985, 2.5–3.1 mm). However, size-frequency distribution of studied tafocenosis (FIG. 9) varies according with competence of palaeocurrents. Length of tubes reaches 11 mm, but Zaine (1991) describes specimens up to 15 mm in length.

Description. Calcareous fossils consisting of straight or curved tubes open at one end. Tubes are vertically and eccentrically stacked one into another giving cone-in-cone structures. Axes of stacked tubes are often not parallel to each other. A basal peduncle and robust spines are present in some individuals. Pedunculate specimens have commonly two open ends (FIG. 7G, J–K). Juxtaposed specimens also occur (FIG. 7F). Shell probably calcitic, but an important amount of organic matter in the shell and incomplete mineralization is suggested by the flexibility observed in some individuals, as noted by Grant (1990) for Cloudina from the Nama Group.

Discussion. Zaine (1991) considers that the name Cloudina lucianoi (Beurlen and Sommer) Zaine and Fairchild (1985) has priority over Cloudina waldei Hahn and Pflug (1985) because 'according to article 10.f of the International Code of Zoological Nomenclature (1985), for an organism not as first classified as an animal but later so classified, the original name is available if valid under the code that it was published. In this case the genus Aulophycus must be abandoned, but the specific name lucianoi is still valid' (translation from Zaine, 1991: 80). For these reasons, we consider here C. lucianoi (Beurlen and Sommer) Zaine and Fairchild (1985) as the valid name of this species (see Ride et al., 1985). Therefore, C. waldei Hahn and Pflug (1985) is to be considered as a junior synonym of C. lucianoi, contrary to the opinion of Conway Morris et al. (1990: 248).

The fossils represent benthic organisms which lived in an upright position. Seilacher (1999) interpret this organisms as (bio)mat-stickers rather than sediment stickers, mainly because of their small size compared with other well-known sediment stickers such as rugose corals. The interpretation of such a lifestyle for Cloudina, allowed Seilacher (1999) to explain the anatomy of these fossils in terms of functional morphology. Thus, stacked cones of varying lengths can be explained as organisms living in sedimentary environments with different sedimentation rates, while common kinks in the shell represent occasional perturba-
tions. Therefore, the two forms (\( \alpha \) and \( \beta \)) of \( C. \) \textit{riemkeae} described by Germs (1972) probably represent two different ecophenotypes: forma \( \alpha \) represents specimens growing under low sedimentation rate, while forma \( \beta \) grew under faster accumulating sediment. The same is true for \( C. \) \textit{lucianoi}, which also shows specimens made up of stacked cones of different lengths. \( C. \) \textit{lucianoi} presents other morphological variations, including the presence of robust spines in 15% of the observed individuals and 18% of pedunculate specimens. As already mentioned by Hahn and Pflug (1985: 425), \( C. \) \textit{lucianoi} is larger than \( C. \) \textit{riemkeae} (diameter 0.3–1.5 mm; Fig. 9) but smaller than \( \text{Cloudina hartmannae} \), (diameter 2.5–6.5 mm: Germs, 1972).

\begin{itemize}
  \item Remarks. There are no substantial differences between \( C. \) \textit{lucianoi} of the Corumba` Group and \( C. \) \textit{riemkeae} from the ASG other than their size-frequency distribution (Gaucher and Sprechmann, 1999; Gaucher, 2000; Fig. 9) and preservation. While specimens of \( C. \) \textit{riemkeae} of the ASG are completely hematized and preserved in life position (autochthonous accumulation), \( C. \) \textit{lucianoi} of the Corumba` Group is preserved in tempestites (parautochthonous accumulation) with its original, slightly recrystallized calcareous shell. Therefore, it can be expected that \( C. \) \textit{lucianoi} from autochthonous accumulations would show a wider size-frequency distribution than observed in our material.

- Order Foraminiferida Eichwald (1830)
- Suborder Textulariina Delage & Hérouard (1896)
- Family Sacamminidae Brady (1884)
- Subfamily Sacammininae Brady (1884)
- Genus \textit{Titanotheca} Gaucher & Sprechmann (1999)

\begin{itemize}
  \item Type species. \textit{Titanotheca coimbrae} Gaucher & Sprechmann (1999)

\end{itemize}

\begin{itemize}
  \item \textit{Titanotheca coimbrae} Gaucher & Sprechmann (1999)

\end{itemize}

\begin{itemize}
  \item Figs. 8.A–D

\end{itemize}

\textbf{Type specimen.} Holotype: specimen figured by Gaucher and Sprechmann (1999: pl. 5, figs. 1–2) with catalogue number FC DP 2947.

\textbf{Material.} Five complete specimens and many fragments in thin-sections and acid macerates of black phosphorites of the Bocaina Formation at Fazenda Ressaca (point 6, Fig. 3).

\textbf{Description.} Spheroidal to vase-shaped fossils with walls composed of a single layer of agglutinated rutile grains. Test is composed of one or two chambers divided by a septum (Fig. 8C), and has an open (apertural) end. Agglutinated rutile grains are well sorted but vary considerably among different specimens. While in the case of specimens figured in Fig. 8A–C long axes of rutile crystals (3–4 \( \mu \)m) are approximately 6% of maximum diameter of the test, specimen shown in Fig. 8D is composed of relatively larger crystals, with long axes up to 14% of its maximum diameter (25 \( \mu \)m). Maximum diameter of specimens ranging within 50–175 \( \mu \)m. Largest specimen observed is 0.55 mm long (Fig. 8D).

\textbf{Remarks.} On the basis of the agglutinated nature of the wall, the simple shape of the fossils, presence of perforated septa dividing the chambers and small size, Gaucher and Sprechmann (1999) assigned this genus to the Foraminiferida (suborder Textulariina), representing the oldest foraminifers currently known. The mode of life of \textit{Titanotheca} is inferred to have been free epi-benthic, on the basis of the shape and robustness of the test wall (Gaucher and Sprechmann, 1999; Gaucher, 2000). The specimens recovered from the Bocaina Formation of the Corumba` Group are the only occurrence known to date other than the type material from the ASG Group. The species has a high fossilization potential and is quite abundant in organic-rich facies such as the phosphorites of the Bocaina Formation. If the taxon is confirmed to be restricted to the upper Vendian (Valdaian) as it seems, it may eventually become a useful index fossil for that period.
5. Biostratigraphy

The palaeontologic data presented above for the Corumbá Group allows some important biostratigraphic correlations. First of all, the six genera of organic-walled microfossils described from the Corumbá Group are also present in the ASG (Gaucher, 2000). These genera are represented by six species, three of which also occur in the ASG. The shared species, *Bavelinella faveolata*, *Soldadophycus bossii* and *Leiosphaeridia tenuissima*, are the most abundant and dominate the microbiota in both units. While in the ASG 19 species of organic-walled microfossils have been described to date (Gaucher, 2000), the diversity in the Corumbá Group is considerably lower. However, there is a substantial preservational bias due to advanced carbonization and degradation of fossils in the latter unit. Most of the organic remains that were found in macerations of the Corumbá Group could not be identified, for carbonization and corrosion greatly obscures taxonomic-relevant details. The assemblages of the Corumbá and ASGs belong to the upper Vendian depauperate assemblage found in many successions worldwide (Chauvel and Schopf, 1978; Mansuy and Vidal, 1983; Volkova, 1985; Knoll and Sweet, 1985, 1987; Germs et al., 1986; Palacios, 1989; Zaine, 1991; Vidal et al., 1994; Gaucher et al., 1996). This microbiota would match the Kotlin-Rovno assemblage of *Vidal and Moczydlowska-Vidal* (1997), which is characterized by low diversity, abundance of *Bavelinella faveolata*, rarity or absence of acanthomorphs and absence of large sphaeromorphs (Vidal and Knoll, 1983; Volkova, 1985; Knoll, 1996a; Vidal and Moczydlowska-Vidal, 1997). More recently, another biostratigraphic scheme has been proposed (Knoll, 2000 and Walter et al., 2000), which recognizes three informal biozones according to the Varangerian/Marinoan glacials and the base of the Cambrian. The period immediately above the Varangerian is characterized by a simple leiosphere palynoflora (Walter et al., 2000: 383), followed by a complex acanthomorph palynoflora described from many sites worldwide (Knoll, 2000, and references therein). In the uppermost Vendian (Kotlin-Rovno assemblage of *Vidal and Moczydlowska-Vidal, 1997*), plankton diversity decreased dramatically, leading again to a depauperate assemblage dominated by small sphaeromorphs. Although no acanthomorphic acritarchs at all were found either in the Corumbá or ASG, the latter unit could be divided into three informal zones according to organic-walled microfossils. Gaucher (2000) recognized two similar low-diversity assemblages (*Bavelinella-Soldadophycus* assemblage) in the Yerbal and Cerro Espuelitas Formations divided by a more diverse assemblage occurring in the Polanco Formation (*Leiosphaeridia-Lophosphaeridium* assemblage). These assemblages correlate chemosтратigraphically quite well with those proposed by Knoll (2000) and Walter et al. (2000), the more diverse assemblage occurring worldwide at a positive δ13C peak with 87Sr/86Sr values of 0.7079, just as in the case of the Polanco Formation (Fig. 12). Gaucher (2000) proposed that this alternation could be determined by different palaeoclimatic conditions. Skeletal fossils strongly indicate an upper Vendian age for most of both units studied. *Cloudina*, for instance, has been proposed by Grant (1990) as an index fossil of this period, occurring in many successions worldwide (Germs, 1972; Palacios, 1989; Conway Morris et al., 1990; Zaine, 1991; Bengtson and Yue Zhao, 1992; Vidal et al., 1994; Boggiani, 1998; Gaucher et al., 1999; Gaucher, 2000; Hagadorn and Waggoner, 2000; Corsetti and Hagadorn, 2000; Grotzinger et al., 2000). Therefore, the Corumbá Group is almost entirely upper Vendian in age, for *Cloudina* occurs even at the top of the Tamengo Formation (Boggiani, 1998). In the case of the ASG, *Cloudina* indicates that the Yerbal Formation was deposited in the upper Vendian and not before (i.e. in the Varangerian). On the other hand, *Titanotheca* seems to be restricted to the lower parts of both groups (Yerbal and Bocaina formations), co-occurring in the ASG with *Cloudina*. This might imply that the stratigraphic range of *Titanotheca* is even more restricted than *Cloudina*, but more work is needed to prove this point.

Vendotaenids from the Guaicurus Formation also give important biostratigraphic information. Gnilovskaya (1979, 1985) finds that *E. mosquensis* is typical of lower Valdaian rocks of the East
Fig. 12. Chemostratigraphy of the Corumbá and ASGs, compared with well studied sections from the Witvlei-Nama groups and the Windermere Supergroup (Narbonne et al., 1994; Grotzinger et al., 1995; Kaufman et al., 1997; Saylor et al., 1998). Negative (N) and positive (P) δ13C-excursions were numbered starting from the first post-Varangerian/Marinoan deposits. Total thickness represents approximately 2500 m for the Witvlei-Nama groups (Saylor et al., 1998) and 5000 m for the Windermere Supergroup (Kaufman et al., 1997). CSF: Cerros San Francisco Formation, CV: Cerro Victoria Formation, Blaube: Blaubeker Formation, Bläss.: Blässkrans Formation, Buschmannsk.: Buschmannsklippe Formation.
European Platform, which are overlain by Vendotaenia-bearing rocks of the Kotlin Horizon (upper Valdaian). As already noted above, E. corumbensis of the Guaiacurus Formation postdates Vendotaenia-bearing marls of the Tamengo Formation, and is thus younger than E. mosquensis. On the other hand Vendotaenia antiqua is considered to be restricted to the upper Vendian and occurs in many successions worldwide. Some examples are the East European Platform (Gnilovskaya, 1979, 1985; Burzin, 1996), China (Steiner, 1994 and references therein) and Namibia (Germ et al., 1986). The association of Vendotaenia with Ta-wisia is known from the Dengying Formation of China (Steiner, 1994), of uppermost Vendian age. Finally, it has been suggested that Corumbella wernerii Hahn et al. (1982) from the Corumbá Group (Tamengo Formation) could be a representative of the Ediacara fauna (Zaine, 1991Walde, 1987: 103) or even belong to the sabellidids (Fairchild et al., 2000). In either case, these fossils would indicate an upper Vendian (Ediacaran, Valdaian) age for the Tamengo Formation. However, an alternative interpretation of Corumbella as scyphozoans (Cnidaria) cannot be ruled out (Hahn et al., 1982; Hagadorn and Waggoner, 2000), though it seems rather improbable (Zaine, 1991).

Summing up, there is quite a lot of biostratigraphic information that points unequivocally to an upper Vendian (Valdaian) age for both groups. Furthermore, the striking similarity of the biotas that lived in both basins suggests that they had an ample connection or were even part of the same shelf. It is worth noting that not only the more widespread planktonic genera and species are shared, but also representatives of the benthos like Cloudina and Titanotheca.

6. Chemostratigraphy

The first stable isotope analyses for the Corumbá Group were reported by Zaine (1991), but the data were unfortunately not ordered against their stratigraphic position, and are of very limited value for correlation. Boggiani (1998) reports detailed carbon, oxygen and strontium isotope analyses for the Corumbá and ASGs, among other Neoproterozoic-Cambrian units of South America. Gaucher (1999, 2000) presents a curve of δ13C variations in carbonates of the ASG, based on the data reported by Boggiani (1998). Finally, Kawa-shita et al. (1999) report δ13C, δ18O and 87Sr/86Sr data for four samples from the base of the Polanco Formation of the ASG. The stratigraphic relevance of these determinations have been discussed by Gaucher et al. (1999). We present here new δ13C and δ18O determinations for 13 samples of the upper Yerbal Formation and lowermost Barriga Negra Formation of the ASG. The database includes, for the Corumbá Group, 37 δ13C and δ18O determinations, while in the case of the ASG, δ13C and δ18O was determined for 30 samples. Raw data are given in Table 1, while synthetic δ13C curves for the Corumbá and ASGs are shown in Fig. 12. Furthermore, preliminary data of a high-resolution chemostratigraphic survey of the Polanco Formation (Gaucher et al., 2002) were also considered. As for Sr-isotopes, a series of 20 87Sr/86Sr determinations for carbonates of the Corumbá Group was carried out by Zaine (1991). Boggiani (1998) presents 6 87Sr/86Sr analyses for the Tamengo Formation. Finally, Kawa-shita et al. (1999) report the only 87Sr/86Sr data available for the ASG, consisting of four determinations in little altered samples (Mn/Sr ~ 0.1; δ18O PDB ~ −11‰) of the lowermost Polanco Formation.

6.1. Corumbá Group

<table>
<thead>
<tr>
<th>Locality</th>
<th>Sample</th>
<th>δ¹⁸O_{SMOW}‰</th>
<th>δ¹³C_{PDB}‰</th>
<th>δ¹³C_{PDB}‰</th>
<th>Precision (δ¹⁸O)</th>
<th>Precision (δ¹³C)</th>
<th>Remarks</th>
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<td>+24.986</td>
<td>−5.695</td>
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<td>−</td>
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<td>−10.288</td>
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<td>PRJ 13P</td>
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Data from localities PYE 31-32 and CCU 4 are from Kawashita et al. (1999). Analysis from localities CPA 27-28, PRJ 13-14 and ILL 2, 4 were reported by Boggiani (1998). Other localities: this work.
limestones of the lower Tamengo Formation record a negative $\delta^{13}C$ excursion ($-2.5$ to $-3.3\%_\text{oo}$ PDB) associated with *Corumbella* - and *Cloudina*-bearing strata (Boggiani, 1998). The negative peaks of the middle Sheepbed Formation (Windermere Supergroup) and the upper Witveli-lower Nama Group (N2; Fig. 12) resemble values obtained for the lower Tamengo Formation (Narbonne et al., 1994, 1997; Saylor et al., 1998). Moreover, this negative peak is globally associated with the first occurrence of relatively diverse Ediacaran fossils and *Cloudina* (Narbonne et al., 1994; 1284; Saylor et al., 1998: 1233), as in the Corumbá Group. Up section in the Tamengo Formation, a positive $\delta^{13}C$ excursion of up to $+5.8\%_\text{oo}$ PDB is recorded in *Cloudina*-rich beds, which has been correlated by Boggiani et al. (1996, 1997), with the younger Ediacaran (upper Vendian) positive excursion (P2, Fig. 12) recorded worldwide. Uppermost Tamengo limestones show also positive $\delta^{13}C$ values, and are thus older than the Gamettrail-Zaris negative excursion N3 (Fig. 12). This important negative excursion is probably represented in the lower Guaiacurus Formation, but no isotopic data for this unit are available. Alternatively, it could be correlated to the small $\delta^{13}C$-negative peak in the uppermost Tamengo Formation, with $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.7086 (Boggiani, 1998).

### 6.2. Arroyo del Soldado Group

Varangerian–Marinoan deposits are not known from the ASG. Since the lower Yerbal Formation is devoid of carbonates, the post-Varanger negative excursion (N1, Fig. 12) is not recorded in the ASG. Pink dolostones of the upper Yerbal Formation show positive $\delta^{13}C$ values of up to $+2.2\%_\text{oo}$ PDB (Table 1, Fig. 12), which continue into the lowermost Polanco Formation, reaching $+2.9\%_\text{oo}$ PDB (Kawashita et al., 1999). This peak corresponds to the positive $\delta^{13}C$-peak of the lower Sheepbed Formation (Narbonne et al., 1994; Kaufman et al., 1997) and middle Witveli Group (Saylor et al., 1998), because: (a) it is upper Vendian (post-Varangerian) in age, as demonstrated by *C. riemkeae* occurring in the uppermost Yerbal Formation; and (b) it includes limestones with $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.7078 (Kawashita et al., 1999), similar to those encountered in the lower Sheepbed Formation (Windermere Supergroup) and in the Buschmannsklippe Formation of the Witveli Group (Narbonne et al., 1994; Kaufman et al., 1997; Walter et al., 2000: 376). Although the remarkably thick, pure and little altered carbonates of the overlying Polanco Formation represent the desideratum for the determination of a precise $\delta^{13}C$ curve, reconnaissance studies carried out by Boggiani (1998) and Gaucher (2000) and the authors yielded ambiguous results. The stratotype of the Formation, located in the Tapes Grande Syncline (Gaucher, 2000) has shown exclusively negative values throughout the section (sites CPA 27 to CPA 30* of Table 1). Nevertheless, other sections in the Isla Patrulla Block and Pirarajá region (sites CCU 4, PYE 31–32 and PRJ 13–14 of Table 1; Gaucher et al., 2002) show that the lower and upper Polanco Formation records positive $\delta^{13}C$ excursions, and that carbonates there experienced little diagenetic overprint (Mn/Sr mostly within 0.05 and 0.5; $\delta^{18}O$ between $-6$ and $-11\%_\text{oo}$). Differences in the carbon isotopic composition could respond to an enhanced metamorphic overprint at the stratotype, or more probably, to a very characteristic, deeper sedimentary environment in which primary dolomite precipitation (Vasconcelos and McKenzie, 1997; Burns et al., 2000) due to bacterial sulphate reduction took place (Gaucher, 2000: 32). In such disaerobic environments, recycling of organic matter by bacteria yields isotopically light CO$_2$, which is then incorporated into carbonates, resulting in $^{13}C$-depletion (Strauss et al., 1992; Kaufman and Knoll, 1995: 30; Hoefs, 1997: 122). Calver (2000) proposed that $^{13}C$-depletion of deep-water, upper Vendian carbonates of the Adelaide Rift Complex (Australia) responds to water stratification, which also played a key role in the ASG (Gaucher, 2000). The sections in which positive values have been recorded are characterized by lower palaeobathymetry, above storm-weather wave-base, and also by less dolomite precipitation. In modern marine environments, shallow seawater is enriched in $^{13}C$ by approximately 1%oo PDB relative to deep water (Hoefs, 1997: 121). Ongoing
research with detailed sampling of sections up to 800 m thick is intended to solve this problem. All things considered, it is reasonably well established that two positive δ13C excursions are recorded in the lowermost Polanco (P1, Fig. 12) and upper Polanco Formation (P2), separated by an abrupt negative excursion to −3.5‰ PDB (N2). The transition from the Polanco Formation into the Cerro Espuelitas Formation or the lowermost Barriga Negra Formation is marked by a shift to negative values of −1.7‰ PDB (lowermost Barriga Negra Formation) or −3.6‰ PDB (lower Cerro Espuelitas Formation). This negative peak is tentatively correlated to 13C-depleted carbonates of the N3 excursion (Fig. 12) recorded in the Gametrail Formation (Windermere Supergroup; Kaufman et al., 1997) and uppermost Zaris Formation (Nama Group; Grotzinger et al., 1995; Saylor et al., 1998). No carbonates are known from the upper Cerro Espuelitas or Cerros San Francisco Formation, the youngest record being stromatolitic and oolitic limestones of the Cerro Victoria Formation (Montañá and Sprechmann, 1993; Gaucher, 2000). Three analyses reported by Boggiani (1998) suggest the presence of a further negative δ13C excursion. Taking into account the lowermost Cambrian age proposed for this unit on the basis of trace fossils (Montañá and Sprechmann, 1993; Gaucher, 2000), the mentioned negative peak could match the negative δ13C excursion of the Proterozoic-Cambrian boundary N4 (Fig. 12) recorded worldwide (Kaufman et al., 1997; Saylor et al., 1998; Knoll, 2000; Corsetti and Hagadorn, 2000), but more data are needed to confirm this.

Summing up, there is a reasonably good correlation between the δ13C curves obtained for the Corumbá and ASGs with the global curve of the upper Vendian, thus supporting other lines of evidence such as biostratigraphy and geochronology. The available 87Sr/86Sr data for the Corumbá and ASGs also corroborate an upper Vendian age for these units (Kaufman et al., 1993; Gorkov et al., 1995; Kaufman et al., 1997; Knoll, 2000; Walter et al., 2000). Sedimentation began already in the Varangerian in the Corumbá basin (Puga Formation), unlike the ASG, which begins with post-glacial eustatic sea-level rise. On the other hand, δ13C-data suggest that deposition of the ASG probably continued into the lowermost Cambrian, unlike the Corumbá Group. We are confident that high-resolution carbon chemostratigraphy will allow to refine these correlations (Gaucher et al., 2002).

7. Discussion

7.1. Palaeogeography

All lines of evidence presented above indicate that: (1) the Arroyo del Soldado and Corumbá groups are coeval; (2) broadly the same climatic and eustatic sea-level changes are recorded in both units; and (3) both basins had either an ample connection or were part of the same shelf. Furthermore, the units studied here were clearly deposited in a passive, Atlantic-type continental margin (Almeida, 1984; Zaine, 1991; Boggiani et al., 1993; Gaucher et al., 1996, 1998a,b; Boggiani, 1998; Gaucher, 1999, 2000). In both groups, the platform deepened to the east, with granitic-metamorphic source areas located to the west (Boggiani, 1990, 1998; Boggiani et al., 1993; Montañá and Sprechmann, 1993; Gaucher, 2000). Considering the above mentioned facts, the only plausible explanation is that the Corumbá and ASGs were deposited onto the same shelf. This hypothesis is supported by the same tectonic vergence to the W-NW and same structural style (Almeida, 1984: 269; Boggiani et al., 1993; Gaucher et al., 1996, 1998a,b; Boggiani, 1998; Gaucher 1999, 2000). Considering the above mentioned facts, the only plausible explanation is that the Corumbá and ASGs were deposited onto the same shelf. This hypothesis is supported by the same tectonic vergence to the W-NW and same structural style (Almeida, 1984: 269; Boggiani et al., 1993; Gaucher et al., 1996, 1998a,b; Boggiani, 1998; Gaucher 1999, 2000). In both groups, the platform deepened to the east, with granitic-metamorphic source areas located to the west (Boggiani, 1990, 1998; Boggiani et al., 1993; Montañá and Sprechmann, 1993; Gaucher, 2000). In both groups, the platform deepened to the east, with granitic-metamorphic source areas located to the west (Boggiani, 1990, 1998; Boggiani et al., 1993; Montañá and Sprechmann, 1993; Gaucher, 2000). Considering the above mentioned facts, the only plausible explanation is that the Corumbá and ASGs were deposited onto the same shelf. This hypothesis is supported by the same tectonic vergence to the W-NW and same structural style (Almeida, 1984: 269; Boggiani et al., 1993; Gaucher et al., 1996, 1998a,b; Boggiani, 1998; Gaucher 1999, 2000). In both groups, the platform deepened to the east, with granitic-metamorphic source areas located to the west (Boggiani, 1990, 1998; Boggiani et al., 1993; Montañá and Sprechmann, 1993; Gaucher, 2000).
The possibility that the Río de la Plata Superterrane (Craton) could extend to the north to latitudes around 20°S has been already suggested by Ramos (1988). While studying a basement window in southern Paraguay (Fig. 13), Meinhold (1998) and Meinhold et al. (2000) also postulated the continuity of the Río de la Plata Craton to the north. Ramos (1988) suggested that the collision of the Río de la Plata Craton with the ensialic Alto Paraguay Terrane, located to the east, resulted in deformation of the Paraguay belt. The Alto Paraguay Terrane of Ramos (1988) is roughly equivalent to the Paraná (Continental) Block of Soares (1988, Fig. 13), and has been considered in the palaeogeographic reconstructions of Unrug (1996). The study of this crustal block is hindered by the sedimentary cover of the Paraná Basin (Figs. 1 and 13), but some data has been obtained by interpretation of gravimetric and magneto-meteric surveys, as well as datings of basement.

Fig. 13. Major cratonic areas in SE-South America, showing extension of the Corumbá-Arroyo del Soldado palaeoshelf. Major lineaments and boundary of post-Cambrian cover were modified from Almeida et al. (1973). Probable boundaries of the Paraná Block according with Soares (1988). Western boundary of the Río de la Plata Superterrane taken from Ramos (1988). Position of the hypothetical Mesoproterozoic suture between the Amazonian Craton and the Río de la Plata Superterrane is not known due to extensive volcanosedimentary cover of the Paraná Basin. DFB, Dom Feliciano Belt; RB, Ribeira Belt.
rocks from oil exploration drilling (Ramos, 1988; Soares, 1988). It follows from this discussion that the collision of the Río de la Plata Superterrane with the Paraná Block (Alto Paraguay Terrane) in the Cambrian is responsible for the closure and deformation of the Arroyo del Soldado-Corumbá shelf. The deformed sedimentary cover marks the suture between this two continental blocks (Fig. 13). A similar palaeogeographic reconstruction has been recently presented by Teixeira (2000), while studying upper Vendian–Cambrian ('Eocambrian') sedimentary successions from SE-Brazil. The author suggested that closure of the Brazilides ocean between the Amazonian-Río de la Plata cratons and the Paraná Block-São Francisco Craton resulted in deformation of the Corumbá shelf in the Cambrian. Brito Neves et al. (1999) and Campos Neto (2000) proposed a slightly different palaeogeographic scheme for the region.

7.2. Palaeoclimatology

Drastic climatic changes took place during deposition of the Corumbá and ASGs (Section 3.2). Climate shifted quite rapidly between ‘greenhouse’ and ‘icehouse’ effects, as known from sedimentary successions of this age worldwide (Kasting, 1992; Kirschvink, 1992). Gaucher (2000) proposed that these changes were driven mainly by palaeoceanographic factors that strongly altered bioproductivity. Kaufman (2000) arrived to a similar model through other lines of evidence. The model proposed by Gaucher (2000) includes the following sequence of events:

(1) In the Upper Riphean, enhanced hydrothermal activity (Knoll, 1994) related to the rifting of Rodinia (Hoffman, 1991; Dalziel, 1995; Unrug, 1996) pump large quantities of iron, silica, and other nutrients into the ocean. These accumulate in the deep ocean, generating an enormous reservoir, leading to ocean stratification.

(2) Due to a favourable wind and current regime, enhanced upwelling takes place. Upwelling zones represent only 0.1% of the present ocean surface (Baturin, 1982), but this need not be constant through geologic time. Enhanced upwelling of nutrient-rich waters stored in the deep-ocean reservoir trigger massive phytoplankton blooms (Palacios, 1989; Vidal and Nystuen, 1990), deposition of BIF and phosphorites. The ocean becomes largely eutrophic, and large amounts of organic matter accumulate on the shelves. Sulphate-reducing bacteria find optimal conditions in the anoxic lower water-layer, leading to anomalous sulphate consumption and shift in $\delta^{34}$S towards extremely positive values (Walter et al., 2000; Kaufman, 2000).

(3) Drawdown of CO$_2$ by blooming phytoplankton-populations reduces greenhouse effect and triggers glaciation (Kaufman et al., 1997; Kaufman, 2000) and eustatic sea-level fall. Concomitantly, large amounts of oxygen would be released into the atmosphere, accounting for the proposed Neoproterozoic oxygen-increase (Holland, 1994; Canfield and Teske, 1996).

(4) During snowball earth, silicate weathering, carbonate deposition and bioproductivity are greatly reduced, allowing for accumulation of atmospheric CO$_2$.

(5) Restored greenhouse effect leads to global warming, ice melting and sea-level rise. Consumption of nutrients stored in deep waters, a reduction of hydrothermal activity after the Varangerian (as shown by $^{87}$Sr/$^{86}$Sr relations: Knoll, 1994; Jacobsen and Kaufman, 1999; Walter et al., 2000) and better water mixing seem to be the cause for the final disruption of the system in the Early Cambrian.

7.3. Palaeobiology

As already proposed by Grant (1990) and Gaucher and Sprechmann (1999), the fact that shelly fossils were so widespread and relatively diverse in the upper Vendian suggests that biomineralization and agglutination were not simply a local phenomenon by latest Proterozoic times. Grotzinger et al. (2000) describe the calcareous fossil *Namacalathus hermanastes* from reefs of the Nama Group, adding one more species to the known diversity of Precambrian shelly fossils. They further report the occurrence of undetermined, tube-shaped, calcareous fossils from the same reefs. The Nama Group of Namibia and the ASG of Uruguay are thus the units which contain the most diverse shelly assemblages reported to
date (Germs, 1972; Gaucher and Sprechmann, 1999; Gaucher, 2000; Grotzinger et al., 2000). This suggests that favourable palaeogeographic and consequently palaeoclimatic conditions in that regions (see above) stimulated the diversification of mineralized fossils. Considering that both basins were probably located at either sides of the same ocean (Unrug, 1996; Teixeira, 2000), it is probable that the ‘oasis’ generated in that way represents in fact the cradle of many different lineages, which could evolve despite the inhospitable conditions elsewhere. Furthermore, the diversity of types of biomineralization and agglutination found in the upper Vendian is surprising, suggesting that the advent of skeletons must have occurred much earlier than currently accepted.

8. Conclusions

The Arroyo del Soldado and Corumbá groups are roughly coeval, and were deposited onto the same passive continental margin, developed on the Río de la Plata Suppertime. Thus, this continental block probably extends farther to the north than previously expected, or, alternatively, it was already amalgamated to the Amazonian Craton by Vendian times. Closure of the basin is related to the collision of the platform with the Paraná Block (Alto Paraguay Terrane) during the Cambrian-Early Ordovician. Broadly the same climatic and eustatic sea-level changes are recorded in both units. Climate shifted quite rapidly between ‘greenhouse’ and ‘icehouse’ effects, with the consequent lithological variations. Varangerian/Marinoan glaciogenic deposits are not known from the Arroyo del Soldado basin, but are represented in the Corumbá basin by the Puga Formation. This suggests that the ASG was deposited in a lower palaeolatitude, inside the circum-equatorial (<25°), ice-free region predicted by recent computer simulations of Neoproterozoic glaciations. New data obtained further support recent models of Neoproterozoic climate change and glaciations proposed independently by Gaucher (2000) and Kaufman (2000). These models are based on enhanced bioproductivity driven by high nutrient availability in the largely stratified Neoproterozoic oceans. Newly discovered fossils are described from the Corumbá Group, with a total of six species of organic-walled microfossils, three species of vendotaenids and two species of skeletal fossils including Cloudina and Titanotheca. The vendotaenid Eoholynia corumbensis sp. nov is described from siltstones of the Guaicurus Formation. The biota preserved in the Corumbá Group correlates well with that represented in the ASG. An upper Vendian (Valdaian) age is confirmed for both units, using biostratigraphic, as well as carbon and strontium isotopic data. While uppermost deposits of the ASG are of lowermost Cambrian age, sedimentation ceased already in the uppermost Vendian in the Corumbá basin. Nevertheless, continuing research in the poorly known, uppermost units of the Corumbá Group (Guaicurus Formation) might reveal the Proterozoic/Cambrian transition as well. Finally, an important diversity of skeletal fossils in the Corumbá, Arroyo del Soldado and Nama groups points to favourable palaeoclimatic conditions in the region occupied by the ocean that extended between the Río de la Plata and Kalahari cratons. It is here proposed that this favourable conditions generated an ‘oasis’, in which skeletal fossils and metazoa could evolve despite the inhospitable conditions elsewhere.

Acknowledgements

This study is the product of fruitful cooperation between Brazilian and Uruguayan researchers. The authors are indebted to many individuals who collaborated in many respects. Deep gratitude is due to the late Armando Marcio Coimbra (1949–1998), who actively participated of field work and contributed with stimulating ideas, but could not see the completion of this publication. Ana Lucia Desenzi Gesicki (Campo Grande) and Silvana Martinez (Montevideo) are thanked for valuable help during field work in Brazil and Uruguay, respectively. Antonio Luiz Teixeira (Sao Paulo) is thanked for providing literature and for valuable comments. Our sincere appreciation goes to Prof. Malcom Walter and an anon-
yrous reviewer for their useful comments and suggestions. Field work in Uruguay has been financed by research project 1040 of the Consejo Nacional de Investigación Científica y Tecnológica (CONICYT), Uruguay. Analyses and publication expenses were financed by research projects C-32 and C-39 of the Comisión Sectorial de Investigación Científica (CIC, Uruguay) and project CONICYT 6007. C.G. is indebted to the German Academic Exchange Service (DAAD) for a generous research grant (1995–1999) and further financial support in many respects. This paper is a contribution to projects IGCP 450 (Proterozoic sediment-hosted base metal deposits of western Gondwana) and IGCP 419 (Foreland basins of the Neoproterozoic belts in central to southern Africa and South America).

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