UNIVERSITY OF BRASÍLIA – UnB
INSTITUTE OF GEOSCIENCES – IG
GRADUATE RESEARCH PROGRAM IN GEOLOGY

TAXONOMY, PALEOECOLOGY AND CHRONOBIOSTRATIGRAPHY ACROSS THE EDIACARAN-CAMBRIAN BOUNDARY: TAMENGO AND GUAICURUS FORMATIONS

Doctoral thesis N° 157

Doctoral thesis by Rodrigo Rodrigues Adôrno

Supervisor: Prof. Dermeval Aparecido Do Carmo

Brasília, May 2019

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Thesis submitted to the coordination of the graduate research program in geology, University of Brasília, in partial fulfillment of the requirements for the degree of doctor on geology.

Area of concentration: Biostratigraphy and Paleoecology

Supervisor and Chair of Committee:
Prof. Dermeval Aparecido do Carmo (IG/UnB – BR)

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DEDICATION

I dedicate this thesis to my wife, Gabriela Adôrno, and my parents, Rui Adôrno and Cirene Adôrno, for the love and support during my PhD journey. I also dedicate this thesis to Prof. Detlef. H. G. Walde, for being an outstanding professor and an inspiration to my study.

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“Every new beginning comes from some other beginning's end”

“Todo novo começo, nasce do fim de outro começo”

Lucius Annaeus Seneca

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RESUMO EXPANDIDO

Taxonomia, paleocologia e cronobioestratigrafia através do limite Ediacariano-Cambriano: formações Tamengo e Guaicurus

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RESUMO–Neste trabaho são apresentados resultados do estudo taxonômico e de distribuição estratigráfica de vinte e seis espécies de fósseis que integram a assemblagem fossilífera estudada a partir das formações Tamengo e Guaicurus em cinco seções na região de Corumbá e Ladário, a saber: Pedreiras Corcal e Laginha, Porto Sobramil, Porto Figueiras e Ecoparque Cacimba. Adicionalmente são apresentadas inferências paleoecológicas e paleoambientais com base na ocorrência desta assemblagem fóssil e na atualização da descrição litoestratigráfica destas seções. *Cloudina carinata* Cortijo et al., 2010, até então com ocorrências documentadas na Espanha e Sibéria, foi identificada a partir dos siltitos da Formação Tamengo na seção do Porto Figueiras, este registro representa a primeira ocorrência desta espécie em continente americano. A paelobiota estudada é composta por quatro espécies de organismos bentônicos sésseis: três metazoários biomineralizadores *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata*, *Corumbella werneri* Hahn et al., 1982, pelo vendotaenideo *Vendotaenia antiqua* Gnilovskaya, 1971, e pelo registro fragmentos de poríferos. O presente trabalho também aborda taxonomia e distribuição estratigráfica de quatro icnoespécies: *Gordia marina* Emmons, 1844, *Pilichnus* cf. *P. dichotomus* Uchman, 1999, *Didymaulichnus lyelli* (Rouault, 1850) e *Multina minima* Uchman, 2001 que integram a icnofauna bentônica vágil atualizada para a porção superior do Grupo Corumbá. Também é apresentado taxonomia sistemática para as duas espécies de macroalgas na Formação Guaicurus: *Eoholynia corumbensis* Gaucher et al., 2003 and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979). A diversidade de espécies es da Formação Tamengo foi complementada pela ocorrência de dezesseis espécies de microfósseis que possivelmente representavam o plâncton marinho, composta por espécimes permineralizados de *Chuaria circularis* Walcott, 1899 e pela ocorrência de outras quinze espécies de microfósseis de parede orgânica: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum*, *Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann, 1976 in (Timofeev et al., 1976), *Navifusa* sp. e Gen 1. sp. 1 (*chitinozoan like flask-shaped*). Foram identificadas significativa mudança nas condições paleoambientais de deposição entre as formações Tamengo e Guaicurus. Esta mudança parece estar relacionada com a eliminação de quase 95% da assemblagem fossilífera entre as formações Tamengo e Guaicurus durante a passagem Ediacariano-Cambriano. Dentre todas as vinte e duas espécies restritas à Formação Tamengo, houve apenas uma sobrevivente, a icnoespécie *Multina mínima*. Este desaparecimento local pode estar relacionado com a extinção global experimentada no limite Ediacariano-Cambriano, sendo aqui interpretado como um evento de extinção em massa. Adicionalmente foram feitas preparações palinológicas e análises de amostras do Ediacariano mais superior provenientes de seções de três países, com recuperação de nove espécies de microfósseis orgânicos na Formação Nomtsas, Namíbia, quatro espécies na Formação Tagatiya Guazu, Paraguai e seis espécies na Formação Dengying, China. Estes resultados ampliaram o escasso registro de espécies de microfósseis orgânicos para as seções do Ediacariano mais superior. Com base nos resultados taxonômicos e na distribuição estratigráfica das espécies, foi proposto ensaio bioestratigráfico consituido por sete biozonas: Superzona de Assemblagem *Cloudina;* inseridas nesta superzona há três biozonas distribuídas em seções do Brasil e do Paraguai, denominadas Zona diferencial inferior *Cloudina lucianoi*/*Corumbella werneri*; Zona de Amplitude *Corumbella werneri*; Zona diferencial superior *Corumbellla werneri*/*Cloudina lucianoi*; Subzona de Assemblagem *Bavlinella faveolata-Leiosphaeridia minutissima*. Esta subzona está inserida na base da Zona de Amplitude *Corumbella werneri*. A subzona *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone está inserida no topo da Zona diferencial superior *Corumbellla werneri*/*Cloudina lucianoi*. Por último a Zona de Assemblagem *Didymaulichnus lyelli/Eoholynia corumbensis* foi proposta. Esta biozona pertence ao Eo-Cambriano e está restrita, até o momento, à localidade da pedreira Laginha.

Palavras-Chave: Ediacariano-Cambriano, Grupo Corumbá, bioestratigrafia, *Cloudina*, *Corumbella*, micropaleontologia.

INTRODUÇÃO

O objetivo do presente trabalho é apresentar estudo detalhado da taxonomia, análise da distribuição estratigráfica das espécies e apresentar proposta de ensaio cronobioestratigráfico baseados na análise da assemblagem fossilífera das formações Tamengo e Guaicurus. Adicionalmente apresentam-se inferências paleoecológicas e paleoambientais com base na ocorrência das espécies e na atualização litoestratigráfica das seções estudadas na região de Corumbá e Ladário, Estado de Mato Grosso do Sul, Brasil. Considerando a escassez de dados micropaleontológicos para maioria das seções do Ediacariano mais superior, foram escolhidas seções para preparação e análise de amostras a partir de três localidades: Formação Nomtsas, Namíbia, Formação Tagatiya Guazu, Paraguai e Formação Dengying, China. Este estudo adicional visa complementar o escasso registro de espécies de microfósseis orgânicos descritas para o Ediacariano mais superior de seções consideradas importantes para correlação e comparação com as seções do Brasil. Finalmente constitui-se objetivo do presente trabalho apresentar integração e comparação dos resultados obtidos a partir da análise da assemblagem fossilífera das formações Tamengo e Guaicurus com aqueles publicados para outras seções do Ediacariano mais superior no Paraguai, Uruguai, Argentina, Namíbia, China, Rússia, Canadá, Estados Unidos e Omã, através da proposição de ensaio bioestratigráfico que siga as recomendações do código de nomenclatura estratigráfica internacional.

O horizonte cronoestratigráfico de interesse neste trabalho abrange o limite entre Neoproterozoico e o início do Fanerozoico. O Neoproterozoico é marcado por significativas mudanças paleoambientais, incluindo importantes eventos de oxidação atmosférica, seguida pela oxidação da porção mais profunda dos mares, além de também registrar eventos glaciais com capas de gelo que puderam alcançar baixas latitudes (Hoffman, 2009). As publicações científicas indicam pelo menos três eventos glaciais mais expressivos durante o Neoproterozoico: o primeiro é denominado glaciação Sturtiana (~720 Ma); o segundo, glaciação Marinoana (~635 Ma); e o terceiro, glaciação Gaskiers (~580 Ma) (Hoffman, 2009). O Ediacariano também registrou eventos de significativa mudança e extinções de biotas, especialmente nos intervalos cronoestratigráficos próximos à explosão do Cambriano. O Ediacariano é marcado pelo surgimento de um diversificado conjunto de grupos de metazoários, e o intervalo mais dramático de inovação morfológica que este grupo experimentou em sua história (Erwin, 2013; Darroch et al., 2018).

Além das mudanças paleoclimáticas, os níveis de O_2 dos mares e da atmosfera também oscilaram dramaticamente durante o Ediacariano. Há evidências de que as concentrações de O_2 variaram de cerca de 3 - 10% para mais de 100% do nível atual (Fike et al., 2006; Canfield & Teske, 1996). É discutido que a simultaneidade entre aparecimento de formas complexas de vida, ao mesmo tempo em que há evidências geoquímicas de que os níveis de oxigênio disponíveis subiram durante o Ediacariano (635 - 541Ma) poderia representar relação de causa e efeito. Esta simultaneidade tem levado diversos autores a proporem que a maior disponibilidade de oxigênio teria sido uma das principais causas do aparecimento dos animais complexos (Evans et al., 2018). A disponibilidade maior de oxigênio teria possibilitado o aparecimento e diversificação de grupos dotados de células eucarióticas e multicelulares e também a difusão de oxigênio através de tecidos complexos. A síntese de alguns dos tecidos envolve gasto metabólico de oxigênio substancial, como é caso da síntese de colágeno (Fike et al., 2006; Canfield & Teske, 1996). A natureza da relação entre inovações biológicas e as mudanças simultâneas paleoambientais e paleoclimáticas estão ainda sob debate, se causal ou meramente de simultaneidade.

O Período Ediacariano também registra uma das mais importantes inovações biológicas: o surgimento do esqueleto biomineralizado. As espécies inicialmente descritas como portadaroras desta inovação e as que foram mais bem estudadas são as espécies de *Cloudina* Germs, 1972. Além das espécies deste genero, há inumeras especies biomineralizadoras distribuídas nos gêneros *Sinotubulites* Chen, et al., 1981, *Conotubus* Zhang and Lin, 1986 in (Lin et al., 1986), *Namacalathus, Corumbella* Hahn et al., 1982 and *Gaojiashania* Yang et al., 1986 in (Lin et al., 1986).

Dentre todos os gêneros que abrigam espécies de animais biomineralizadores do Ediacariano mais superior, *Cloudina* é o possui maior distribuição geográfica, com ocorrências em diversas seções do Andar Ediacariano mais superior na Namíbia (Grant, 1990), Omã (Conway Morris et al., 1990), Sul da China (Hua et al., 2005; Cai et al., 2013; Cortijo et al., 2015a), Espanha (Cortijo et al., 2010; Cortijo et al., 2015b), Sibéria (Kontorovich et al., 2008, 2009; Zhuravlev et al., 2012; Grazhdankin et al., 2015), Canadá (Hofmann & Mountjoy, 2001), México (Sour-Tovar et al., 2007), Brasil, Argentina e Uruguai (Gaucher et al., 2003; 2005b; Warren et al., 2014; Adôrno et al., 2017), Paraguai (Warren et al., 2011; 2012; 2017; 2019) e California (Grant, 1990; Zhuravlev et al., 2012). Especies do animal biomineralizador *Sinotubulites* Chen et al., 1981 também tem distribuição geográfica ampla e têm sido descritos em seções do Ediacariano mais superior do Sul da China (Cai et al., 2015), México (McMenamin, 1985), na California e Nevada nos Estados Unidos (Signor et al., 1987), e na Espanha (Cortijo et al., 2015b). A espécie problemática *Namacalathus hermanastes* Grotzinger et al., 2000 foi originalmente descrita a partir do Grupo Nama, Namíbia (Grotzinger et al., 2000; Zhuravlev et al., 2015). Adicionalmente, esta especie também ocorre no Ediacariano mais superior no oeste do Canadá, (Hofmann & Mountjoy, 2001), Omã (Amthor et al., 2003), Sibéria (Kontorovich et al., 2008, 2009; Grazhdankin et al., 2015) e Paraguai (Warren et al., 2017).

Na América do Sul as seções da Formação Tamengo do Grupo Corumbá representam as melhores oportunidades de estudo relacionadas às mudanças climáticas e inovações biológicas experimentadas durante o Ediacariano terminal (Boggiani et al., 2010). O Grupo Corumbá é constituído da base para o topo pelas formações Cadieus, Cerradinho, Bocaina, Tamengo e Guaiucurus. Trabalhos têm sido produzidos sobre a paleontologia do Grupo Corumbá (Beurlen & Sommer, 1957; Fairchild, 1978; Hahn et al., 1982; Walde et al., 1982; Zaine & Fairchild, 1985; Zaine 1991; Hidalgo, 2002; Gaucher et al., 2003; Becker-Kerber et al., 2013; Tobias, 2014; Pacheco, 2012; Leme et al., 2008; Pacheco et al., 2011; Walde et al., 2015; Adôrno et al., 2017; Parry et al., 2017) e também sobre a estratigrafia e evolução tectono-estrutural (Barbosa, 1949; Almeida, 1964, 1965, 1984; Alvarenga & Trompette 1992; Boggiani & Alvarenga 2004; Gaucher et al. 2003; Babinski et al. 2008; Boggiani et al. 2010; Meira, 2011; Spangenberg et al., 2014; D’el-Rey et al. 2016; Sial et al., 2016) e sobre o contexto sedimentológico (Boggiani et al., 1993; Boggiani, 1998; Oliveira, 2010; Campanha et al., 2011; Fontanela, 2012; Fazio et al., 2019).

METODOLOGIA

Diversos trabalhos de campo foram realizados nas cercanias dos municípios de Corumbá e Ladário, Mato Grosso do Sul, além de um trabalho de campo na Namíbia e África do Sul e outro no Sul da China. Durante os trabalhos de campo, foram levantados seções e perfis litoestratigráficos com posicionamento das amostras de rochas coletadas de maneira sistemática, com espaçamento regular entre as coletas. As localidades estudadas do Grupo Corumbá incluem os afloramentos de cinco principais localidades: Ecoparque da

Cacimba, pedreira Corcal, a pedreira Laginha, Porto Sobramil e Porto Figueiras (atualmente denominada Marina do Gerson). Adicionalmente, foram preparadas amostras coletadas em seções das formações Dengying, China, Tagatiya Guazu, Paraguai e Nomtsas, Namíbia visando complementar o escasso registro de espécies de microfósseis orgânicos para estas seções.

Três modalidades de preparação de amostras foram empregadas durante a execução da pesquisa visando à recuperação de fósseis: 1. Invertebrados, 2. Microfósseis biomineralizadores e permineralizados, e 3. Microfósseis orgânicos (macerações palinológicas). Quanto ao estudo de ocorrência de invertebrados como *Cloudina lucianoi* e *Corumbella werneri* bem como dos icnofósseis e algas macroscópicas, o estudo consistiu inicialmente na descrição e análise direta a partir da amostra de rocha com uso de microscópico estereoscópico, da confecção de seções polidas e lâminas delgadas para estudo com auxílio de microscópico estereoscópico, microscópio petrográfico, e em casos específicos de microscopia eletrônica de varredura (MEV).

Para a preparação química e concentração dos componentes orgânicos particulados (macerações palinolígicas) utilizou-se a metodologia própria desenvolvida no Laboratório de Micropaleontologia. A preparação consiste em atacar as amostras por 2 h com ácido clorídrico 37%. Em seguida as amostras devem ser neutralizadas para então serem atacadas com ácido fluorídrico 47% por 12h. Novamente as amostras devem ser neutralizadas por meio de diversas lavagens com água destilada até que o pH esteja próximo de 7. Uma nova digestão com ácido clorídrico pode ser feita visando consumo de fluorita, encerrando a preparação com neutralização com água destilada. Para a montagem da lâmina palinológica permanente utiliza-se o sobrenadante, e Entelan como meio de montagem padrão e fixação da lamínula.

Uma extensa consulta bibliográfica foi realizada para se determinar quais seções seriam selecionadas para estudos de comparação com os resultados obtidos a partir das seções das formações Tamengo e Guaicurus. A consulta bibliográfica permitiu incluir, além das cinco seções estudadas do Grupo Corumbá, onze seções adicionais distribuídas no Paraguai (três seções), Uruguai, Argentina, Namíbia, China, Rússia, Canadá, Estados Unidos e Omã com uma seção cada, compondo um total de 15 seções. Todo material ilustrado encontra-se depositado nas coleções de macrofósseis sob o sufixo (MAF-), Micropaleontológicos (MP-) ou na coleção de pesquisa (CP-) do Museu de Geociências, no Laboratório de Micropaleontologia da Universidade de Brasília UnB.

RESULTADOS E DISCUSSÃO

Os principais resultados obtidos com o desenvolvimento da pesquisa foi a realização de estudo taxonômico e de distribuição estratigráfica de vinte e seis espécies de fósseis que integram a assemblagem fossilífera das formações Tamengo e Guaicurus em cinco seções na região de Corumbá e Ladário, Estado de Mato Grosso do Sul, Brasil. Adicionalmente são apresentadas inferências paleoecológicas e paleoambientais com base na ocorrência das espécies e na atualização litoestratigráfica das seções da Formação Tamengo. A biota da Formação Tamengo é composta por metazoários biomineralizadores bentônicos sésseis e por registro de atividade de metazoários bentônicos vágeis representados pelos icnofósseis. Adicionalmente, a biota da desta formação é complementada por microfósseis que compunham possivelmente o plâncton marinho desta formação. Além destes resultados, novas amostras de seções adicionais das formações Dengying, China, Tagatiya Guazu, Paraguai e Nomtsas, Namíbia foram coletadas e preparadas. O resultado da preparação e análise destas amostras complementaram o escasso registro de espécies de microfósseis orgânicos para estas seções. Finalmente foi apresentado integração e comparação dos resultados obtidos a partir da análise da biota da Formação Tamengo com aqueles publicados para outras seções selecionadas do Ediacariano mais superior no Paraguai, Uruguai, Argentina, Namíbia, China, Rússia, Canadá, Estados Unidos e Omã.

A taxonomia de *Cloudina* Germs, 1972 foi atualizada e teve sua diagnose emendada (Adôrnoet al., 2017). O material-tipo de *Cloudina lucianoi* (Beurlen e Sommer, 1957) foi redescrito e posteriormente comparado com outras espécies de *Cloudina*, em especial com o material-tipo de *Cloudina hartmanae* Germs, 1972. O estudo comparativo entre estas duas espécies foi baseado em critérios morfológicos e morfométricos objetivos, que permitiram propor que *Cloudina hartmanae* deveria ser considerada sinônimo júnior de *Cloudina lucnianoi*. Esta última espécie passou então a ocupar a posição de espécie-tipo do Gênero *Cloudina* e a ter sua distribuição geográfica ampliada para todos os continentes, revelando uma grande importância para estudos de correlação bioestratigráfica global.

A ocorrência *Cloudina carinata* Cortijo et al., 2010 foi registrada a partir de siltitos da Formação Tamengo na localidade denominada Porto Figueiras, Município de Corumbá. Esta ocorrência é o primeiro registro desta espécie no continente americano, ampliando sua distribuição geográfica, cuja ocorrência já havia sido documentada, até o presente, em seções na Espanha e na Sibéria. Além de *Cloudina carinata* foram descritas ocorrências inéditas de estruturas aciculares interpretadas como espículas de poríferos, uma câmara interpretada como possível gêmula de porífero, que juntamente com *Corumbella werneri* e *Cloudina lucianoi*, integram a assemblagem de metazoários biomineralizadores bentônicos epibiontes sésseis da Formação Tamengo.

As ocorrências de *Cloudina lucianoi* da Formação Tamengo consideradas autóctone são associadas a carbonatos interpretados como representantes de paleoambientes com baixa sedimentação siliciclástica e em condições de água raza na zona fótica. *Cloudina lucianoi* tem sido considerada como responsáveis pelas primeiras construções recifais produzidas por metazoários em diversas seções do Edicariano mais superior globalmente distribuídas (Grotzinger & Al-Rawahi, 2014; 2015; Wood, 2011; Penny et al., 2014). Por outro lado, os metazoários *Corumbella werneri* e *Cloudina carinata* ocorrem com maior frequência associados a camadas de rochas siliciclásticas, interpretadas como tendo sido depositadas em paleoambientes relativamente mais profundos, ou ainda em condições episódicas de maior aporte de sedimentos. Finas lâminas de siltito com coloração vermelha abrigam grande número de espécimes de *Corumbella werneri* e mais raramente de *Cloudina carinata*, onde também se observa ocorrências abundantes de icnofósseis *Gordia marina* e *Pilichnus cf. P. dichotomus*. A coloração vermelha destas finas camadas de siltito em meio a camadas com coloração cinza escuro, se devem a presença de óxido de ferro, podendo representar episódios de oxigenação do paleoambiente, que tornavam possíveis a colonização episódica por metazoários bentônicos sésseis e vágeis.

O presente trabalho apresenta sistemática paleontológica para as icnoespécies *Didymaulichnus lyelli* e *Multina minima* previamente registradas no topo da Formação Tamengo e base da Formação Guaricurus na seção da pedreira Laginha (Parry et al., 2017), assim como para duas novas ocorrências de *Gordia marina* Emmons, 1844 e *Pilichnus* cf. *P. dichotomus* Uchman, 1999 na Formação Tamengo, pedreira Corcal. *Multina mínima*, *Gordia marina* e *Pilichnus* cf. *P. dichotomus* integram a assemblagem icnológica atualizada para a Formação Tamengo, das quais aquela denominada *Multina minima* ocorre também na Formação Guaicurus enquanto que *Didymaulichnus lyelli* possui, até o momento, ocorrência restrita à Formação Guaicurus.

Pilichnus cf. P. dichotomus é constituído por escavações complexas e bifurcadas, representando organismos epibiontes com estratégias elabodadas de escavação. *Didymaulichnus lyelli*, é representada por escavações produzidas por organismos endobiontes vágeis. *Gordia marina* representa traços possivelmente produzidos por organismos bentônicos epibiontes vágeis. *Gordia marina* constiui-se de traços superficiais simples curvados ou em forma de laços que possivelmente estão associados a organismos epibiontes vágeis exploradores do substrato na interface água-sedimento. *Multina mínima* é representada por microtúneis que representam complexos padrões de escavações possivelmente associados a pequenos organismos vermiformes endobiontes vágeis capazes de penetrar porções constituídas por material macio e inconsolidadas do substrato.

O conteúdo micropaleontológico da Formação Tamengo é constituído por microfósseis permineralizados e orgânicos. Os microfósseis permineralizados incluem registros inéditos de vesículas identificadas como *Chuaria circularis* e uma câmara com afinidade taxonômica incerta, tentativamente atribuída a gêmula de porífero, incrustada na superfície reticular de um espécime provavelmente representante de porífero na localidade do porto Sobramil.

Quinze espécies de microfósseis orgânicos, provavelmente oriundos de organismos plantônicos, foram identificadas a partir das amostras da Formação Tamengo: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966)*, Leiosphaeridia crassa* (Naumova, 1949)*, Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann in Timofeev et al., 1976, *Navifusa* sp. and Gen1. sp. 1 (chitinozoan like flask-shaped); Cinco espécies de palinomorfos foram identificadas a partir de amostras da Formação Dengying, China: *Bavlinella faveolata, Leiosphaeridia minutissima, Leiosphaeridia crassa, Leiosphaeridia obsuleta* (Naumova, 1949) e *Ostiama microcystis*; Nove espécies da Formação Nomtsas, Namíbia: *Bavlinella faveolata, Ostiama microcystis, Leiosphaeridia crassa, Leiosphaeridia obsuleta* (Naumova, 1949), *Leiosphaeridia tenuissima, Leiosphaeridia minutissima, Soldadophycus major, Coniunctiophycus conglobatum* e *Myxococcoides siderophila*. Quatro espécies da Formação Tagatiya Guazu, Paraguai: *Ostiama microcystis, Leiosphaeridia obsuleta* (Naumova, 1949) *e Leiosphaeridia minutissima* e uma espécie indeterminada Gen. 1 sp. 1. Percebeu-se a ausência de vesículas orgânicas maiores e ornamentadas em todas as seções estudadas do Brasil (Formação Tamengo), Paraguai (Formação Tagatiya Guazu), Namíbia (Formação Nomtsas) e China (Formação Dengying), como tipicamente é descrito para sequências do Ediacariano mais superior em diversas seções globalmente distribuídas (Knoll, 1996; Vidal & Moczydlowska-Vidal, 1997; Gaucher, 2000).

É possível notar uma mudança dramática entre a assemblagem fossilífera das formações Tamengo e Guaicurus. Essa mudança é seguida por mudanças no paleoambiente deposicional. A Formação Tamengo foi depositada em contexto paleoambiental favorável à precipitação de carbonatos, que seria interrompida episodicamente por entrada de sedimentos siliciclásticos imaturos muito finos de uma área-fonte proximal. A Formação Guaicurus, por outro lado, é o resultado de um fornecimento siliciclástico ininterrupto, imaturo e muito fino, proveniente de uma área-fonte proximal. Aparentemente, entre todas as vinte e duas espécies restritas à Formação Tamengo, houve apenas uma sobrevivente, a icnospécie *Multina minima* que ocorre nessas duas formações. Possivelmente, o hábito bentônico endobionte poderia ser a estratégia para resistir às mudanças paleoambientais registradas na porção superior do Grupo Corumbá, responsável pelo evento de extinção em massa observado no limite entre a Formação Tamengo e Guaicurus, Grupo Corumbá, Ediacariano-Cambriano.

A integração das informações relativas à taxonomia e distribuição estratigráfica das espécies que integram a biota da Formação Tamengo foi apresentada na forma de um ensaio bioestratigráfico composto por sete biozonas, da base para o topo respectivamente denominadas: Superzona de Assemblagem *Cloudina* com abrangência em todas as 15 seções avaliadas. Inseridas nesta superzona, foram propostas três biozonas, distribuídas nas seções do Brasil e do Paraguai: Zona diferencial inferior *Cloudina lucianoi*/*Corumbella werneri*; Zona de Amplitude *Corumbella werneri*; Zona diferencial superior *Corumbellla werneri*/*Cloudina lucianoi*. Foi proposta uma Subzona de Assemblagem *Bavlinella faveolata-Leiosphaeridia minutissima*, inserida na base da Zona de Amplitude *Corumbella werneri*. Esta subzona tem abrangência geográfica em seções do Brasil, Argentina, Uruguai, Namibia e China. A subzona *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone está inserida no topo da Zona diferencial superior *Corumbellla* *werneri*/*Cloudina lucianoi*. Por último foi apresentado uma biozona na base da FormaçãoGuaicurus, denominada Zona de Assemblagem *Didymaulichnus lyelli/Eoholynia corumbensis*. Esta biozona pertence ao Eo-Cambriano e está restrita, até o momento, à localidade da pedreira Laginha.

CONCLUSÕES

Vinte e seis espécies foram descritas a partir das formações Tamengo e Guaicurus, porção superior do Grupo Corumbá, limte Ediacaraniano-Cambriano do Brasil. Esta assemblagem fossilífera foi agrupada em cinco categorias: metazoários biomineralizadores, vendotaenídeos, icnofósseis, microfósseis permineralizados e microfósseis de paredes orgânicas.

A fossil assemblage de Formação Tamengo consiste de vinte e três espécies. Deste total, três espécies representam organismos biomineralizadores bênticos sésseis de hábito epibionte: *Cloudina lucianoi* (Beurlen e Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010, *Corumbella werneri* Hahn et al., 1982 e uma espécie indeterminada de porífero. Uma espécie vendotaenídio epibionte séssil *Vendotaenia antiqua* Gnilovskaya, 1971 também foi aqui estudada. Duas icnospices representam atividade de organismos de hábito bentônico endobionte vágil: *Multina minima* Uchman, 2001 e *Pilichnus cf. P. dichotomus* Uchman, 1999. *Gordia marina* Emmons e *Pilichnus cf. P. dichotomus* representam animais sésseis epibiontes exploradores da interface água-sedimento. Adicionalmente, foram recuperadas dezesseis espécies provavelmente derivadas de organismos plactônicos. Quinze microfósseis de parede orgânica: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann in Timofeev et al., 1976, *Navifusa* sp. and Gen1. sp. 1 (chitinozoan like flask-shaped), e uma espécie de microfóssil permineralizado *Chuaria circularis* Walcott, 1899.

Quatro espécies representam a assemblagem bentônica para a Formação Guaicurus: *Eoholynia corumbensis* Gaucher et al., 2003, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979), *Multina minima* e *Didymaulichnus lyelli* (Rouault, 1850). Deste total, três espécies têm ocorrências restritas a essa formação: *Eoholynia corumbensis*, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) e *Didymaulichnus lyelli*. Apenas *Multina minima* possui ocorrências compartilhadas com a Formação Tamengo.

Como é possível notar, a Formação Tamengo é detentora da maior diversidade de espécies do Grupo Corumbá, Ediacariano mais superior. Um evento de desaparecimento local é conspícuo durante a passagem da Formação Tamengo para a Formaçaõ Guaicurus. Com base na datação disponível e nas mudanças dramáticas no paleoambiente e na biota, foi apresentada uma hipótese de que este desapareciemento local poderia estar relacionada à extinção em massa a nível global do limite Ediacariano-Cambriano, pouco antes da explosão do Cambriano, conforme observado em outras seções consideradas cronocorrelatas.

Aparentemente, dentre todas as vinte e duas espécies restritas à Formação Tamengo, houve apenas uma sobrevivente, a icnospécie *Multina minima* que ocorre nas duas formações estudadas. Possivelmente, o hábito bentônico endobionte poderia ser a estratégia para resistir às mudanças paleoambientais registradas e ao evento de extinção em massa experimentado na porção superior do Grupo Corumbá.

Cinco seções da Formação Tamengo tiveram descrição litoestratigráficas atualizadas: seção do Ecoparque da Cacimba, Porto Figueiras, Porto Sobramil, pedreiras Corcal e Laginha. Além do levantamento dos perfis litoestratigráficos, as ocorrências das espécies foram posicionadas em cada perfil, permitindo a proposição de ensaios bioestratigráficos.

Também foram recuperadas e identificadas cinco espécies de microfósseis orgânicos a partir de amostras da Formação Dengying, China: *Bavlinella faveolata, Leiosphaeridia minutissima, Leiosphaeridia crassa, Leiosphaeridia obsuleta* (Naumova, 1949) e *Ostiama microcystis*; Nove espécies a partir de amostras do Grupo Nama, Namíbia: *Bavlinella faveolata, Ostiama microcystis, Leiosphaeridia crassa, Leiosphaeridia obsuleta* (Naumova, 1949), *Leiosphaeridia tenuissima, Leiosphaeridia minutissima, Soldadophycus major, Coniunctiophycus conglobatum* e *Myxococcoides siderophila.* Quatro espécies na Formação Tagatiya Guazu, Paraguai: *Ostiama microcystis*, *Leiosphaeridia obsuleta* (Naumova, 1949) and *Leiosphaeridia minutissima* e Gen. 1 sp. 1. O resultado micropaleontológico para estas seções complementou o escasso registro de espécies de microfósseis orgânicos no Ediacariano mais superior.

Sete biozonas foram propostas, sendo representadas da base para o topo: Superzona de Assemblagem *Cloudina* distribuída em todas as seções avaliadas no Brasil, Paraguai, Uruguai, Argentina, Estados Unidos, Canadá, Namíbia, Omã, Russia e China. Inseridas nesta superzona, há três biozonas, distribuídas em seções do Brasil e do Paraguai, da base para o topo: 1*)* Zona diferencial inferior *Cloudina lucianoi*/*Corumbella werneri*; 2) Zona de Amplitude *Corumbella werneri*; 3) Zona diferencial superior *Corumbellla werneri*/*Cloudina lucianoi*. Com base no registro micropaleontológico foi possível propor a Subzona de Assemblagem *Bavlinella faveolata*-*Leiosphaeridia minutíssima*, inserida na base da Zona de Amplitude *Corumbella werneri*, que possui distribuição geográfica no Brasil, Argentina, Uruguai, Namíbia e China. A subzona *Vendotaenia antiqua*-*Cloudina lucianoi* Concurrent-Range Subzone está inserida no topo da Zona diferencial superior *Corumbellla werneri*/*Cloudina lucianoi*. Por último foi apresentado uma biozona na base da FormaçãoGuaicurus, denominada Zona de Assemblagem *Didymaulichnus lyelli/Eoholynia corumbensis*. Esta biozona pertence ao Eo-Cambriano e está restrita, até o momento, à localidade da pedreira Laginha.

Futuros estudos envolvendo taxonomia e distribuição estratigráfica da biota de seções que representam o Ediacariano mais superior serão de grande importância para avanços bioestratigráficos do intervalo Ediacariano mais superior. Atenção especial precisa ser dada às ocorrências de *Cloudina* sp. reportadas na Formação Sete Lagoas, Grupo Bambuí, principalmente visando o posicionamento estratigráfico e taxonômico precisos para aquelas ocorrências. Adicionalmente, estudos sobre biologia especialmente nas áreas de filogenia e morfologia comparada com metazoários, além de estudos aprofundados sobre a microbiota deste importante intervalo, devem ser encorajados.

REFERÊNCIAS BIBLIOGRÁFICAS

Todas referências bibiográficas são apresentadas no capítulo REFERENCES desta tese.

EXPANDED ABSTRACT

Taxonomy, paleoecology and chronobiostratigraphy across the Ediacaran-Cambrian boundary: Tamengo and Guaicurus formations

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ABSTRACT–This work presents results of the taxonomic study and the stratigraphic distribution of twenty-six species of Tamengo and Guaicurus formations in five sections in the Corumbá and Ladário regions: Corcal and Laginha quarries, Porto Sobramil, Porto Figueiras and Ecoparque Cacimba. In addition, paleoecological and paleoenvironmental inferences are presented based on the occurrence of this fossil assemblage and the updating of the lithostratigraphic description of the sections of upper Corumbá Group. *Cloudina carinata* Cortijo et al., 2010, had documented occurrences in Spain and Siberia, and now it is presented unprecedented occurrence in America continent, from siltstones of the Tamengo Formation at Porto Figueiras section, Brazil. The studied paelobiota is composed of three biomineralizing metazoan: *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata*, *Corumbella werneri* Hahn et al., 1982, poriferous spicules, putative sponge gemmule and sessile epibionts prokaryotic-colony *Vendotaenia antiqua* Gnilovskaya, 1971. The present work also deals with taxonomy and stratigraphic distribution of the four ichnospecies: *Gordia marina* Emmons, 1844, *Pilichnus cf. P. dichotomus* Uchman, 1999, *Didymaulichnus lyelli* (Rouault, 1850) and *Multina minima* Uchman, 2001 that integrate the updated benthic vagile ichnofauna for upper portion of Corumbá Group. Three vendotaenid species were identified: *Vendotaenia antiqua* in Tamengo Formation, and two species in Guaicurus Formation: *Eoholynia corumbensis* Gaucher et al., 2003 and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979). The species diversity of the Tamengo Formation fossil assemblage was complemented by the occurrence of sixteen microfissil species that possibly represented marine planktic, characterized by the permineralized microfossil *Chuaria circularis* Walcott, 1899 and other fifteen species of small sphaeromorphs organic-walled microfossils: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum*, *Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann, 1976 in (Timofeev et al., 1976), *Navifusa* sp. and Gen. 1 sp. 1. A dramatic changed was identified in paleoenvironmental conditions for deposition of Tamengo and Guaicurus formations. It can be clearly seen that there is a possibility of these changes contributing to the elimination of almost 95% of the paleobiota, including the extinction of the epibenthic metazoan and the disappearance of planktic organic-walled microfossil. Among all twenty-two species restricted to Tamengo Formation, there was only one survivior, the ichnospecies *Multina minima* that occurs in both of these formations. This local disappearance could be attributed to the global Ediacaran-Cambrian mass extinction. In addition, samples were prepared and analyzed from sections of three countries where organic-walled microfossils were recovered: nine species from the Nomtsas Formation, Namibia; four species from the Tagatiya Guazu Formation, Paraguay; and six species from the Dengying Formation, China. These results increased the scarce record of organic-walled microfossils species from these additional uppermost Ediacaran selected sections. Based on the taxonomic results and the stratigraphic distribution of the species identified from the Tamengo Formation in the Corcal quarry, a biostratigraphic essay consisting of seven biozones was proposed. Based on the complementation of the micropaleontological data for the three additional studied sections, and based on the paleontological record present in the bibliography for other selected sections, the Tamengo

Formation biozones could be extended covering fifteen uppermost Ediacaran sections from nine countries: Brazil (four sections), Paraguay (three sections), Uruguay, Argentina, Namibia, China, Russia, Canada, United States and Oman, one section each. The seven biozones proposed were named, from bottom to top: *Cloudina* Assemblage Superzone that is distributed in all 15 analyzed sections. Inserted in this superzone, there are three biozones: *Cloudina lucianoi/Corumbella werneri* Interval Zone; *Corumbella werneri* Range Zone; *Corumbellla werneri/Cloudina lucianoi* Interval Zone, these three biozones have geographic distribution until the present which is restricted to Brazil and Paraguay. Two subzones are proposed: *Bavlinella faveolata-Leiosphaeridia minutissima* Assemblage Subzone inserted in the base of *Corumbella werneri* Range Zone and *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone at the upper portion of the *Corumbella werneri/Cloudina lucianoi* Interval Zone. The first subzone spans across Brazil, Argentina, Uruguay, Namibia and China, the second across Brazil, Namibia, China and Siberia. Finally, *Eoholynia corumbensis* Range Zone was proposed in the base of Guaicurus Formation at Laginha quarry, lowermost Cambrian, which is restricted to Laginha quarry locality so far.

Key words: Ediacaran-Cambrian, Corumbá Group, biostratigraphy, micropaleontology.

INTRODUCTION

The objective of this work is to present a detailed taxonomic study, to perform analysis of stratigraphic distribution of the species and to propose a chronobiostatigraphic framework for the biota of the Tamengo and Guaicurus formations, Ediacaran-Cambrian boundary, Brazil. In addition, paleoecological and paleoenvironmental inferences are presented based on the occurrence of the species and the lithostratigraphic update of the sections in Corumbá and Ladário regions, Mato Grosso do Sul State, Brazil. Considering the scarcity of micropaleontological data for uppermost Ediacaran sections, samples from three additional sections were prepared and analyzed from the Nomtsas Formation, Namibia, Tagatiya Guazu Formation, Paraguay and Dengying Formation, China. This additional study aims to complement the record of organic-walled microfossils species described for these three additional sections. Finally, it is the objective of this work to present an integration and comparison of the results obtained from the analysis of the Tamengo Formation fossil assemblage with those published for other uppermost Ediacaran sections from Paraguay, Uruguay, Argentina, Namibia, China, Russia, Canada, United States and Oman, by proposing a biostratigraphic essay following the recommendations of the International Stratigraphic Code.

The chronostratigraphic horizon of interest in this work covers the uppermost Ediacaran and lowermost Cambrian. The Neoproterozoic is marked by significant paleoenvironmental changes, including important atmospheric oxidation events, followed by the oxidation of the deeper portion of the seas, and also to record glacial events with ice caps that could reach low latitudes (Hoffman, 2009). Scientific publications indicate at least three most significant glacial events during the Neoproterozoic: the first is called Sturtian glaciation (~ 720 Ma); the second Marinoan glaciation (~ 635 Ma); and the third glacial event would have occurred in the Ediacarian and became known as the Gaskiers glaciation (~ 580 Ma) (Hoffman, 2009).

In addition to the paleoclimatic changes, the O_2 levels of the seas and the atmosphere also oscillated dramatically during the Ediacaran Period. There is evidence that O_2 concentrations varied from about 3 - 10% to more than 100% of the current level (Fike et al., 2006; Canfield & Teske, 1996). It is argued that the simultaneity between appearances of complex life forms, while there is geochemical evidence that the available oxygen levels rose during the Ediacaran (635 - 541Ma) could represent cause and effect relationship. This simultaneity has led several authors to propose that increased oxygen availability would have been one of the main causes of the onset of complex animals (Evans et al., 2018). The increased availability of oxygen would have enabled the emergence and diversification of groups with eukaryotic cells and multicellular and also the diffusion of oxygen through complex tissues. The synthesis of some of the tissues involves substantial metabolic expenditure of oxygen, such as the case of collagen synthesis (Fike et al., 2006; Canfield & Teske, 1996). The nature of the relationship between biological innovations and the simultaneous paleoenvironmental and paleoclimatic changes are still under debate, whether causal or merely simultaneity.

The Ediacaran Period also records one of the most important biological innovations: the emergence of the biomineralized skeleton. In addition to the species of *Cloudina* Genus, there are other numerous biomineralizing species of distributed into the genus *Sinotubulites* Chen, et al., 1981, *Conotubus* Zhang and Lin, 1986 in (Lin et al., 1986), *Namacalathus*, *Corumbella* Hahn et al., 1982 and *Gaojiashania* Yang et al., 1986 in (Lin et al., 1986). The Ediacaran also records biotic turnover and extinction closely followed by the Cambrian Explosion, marked by the appearance of a diverse array of metazoan groups, and the most dramatic interval of metazoan morphologic innovation in the history of life (Erwin, 2013; Darroch et al., 2018).

Among the biomineralizing species, *Cloudina* species are the most widely geographically distributed, with occurrences in several sections of the uppermost Ediacaran stage in Namibia (Grant, 1990), Oman (Conway Morris et al., 1990) , South China (Hua et al., 2005, Cai et al., 2013, Cortijo et al., 2015a), Spain (Cortijo et al., 2010, Cortijo et al., 2015b), Siberia (Kontorovich et al., 2008; Sour-Tovar et al., 2007), Brazil, Argentina, and Uruguay (Gaucher et al., 2006), Canada (Hofmann & Mountjoy, 2001) (Warren et al., 2014), Paraguay (Warren et al., 2011, 2012, 2017, 2019) and the USA (Grant, 1990; Zhuravlev et al., 2012). *Sinotubulites* species also have broad geographical distribution and have been described in sections of the uppermost Ediacaran of Southern China (Cai et al., 2015), Mexico (McMenamin, 1985), California and Nevada in the United States (Signor et al. 1987), and in Spain (Cortijo et al., 2015b). The problematic species *Namacalathus hermanastes*, was originally described from the Nama Group, Namibia (Grotzinger et al., 2000; Zhuravlev et al., 2015), with occurrences also recorded in Paraguay (Warren et al., 2019). In addition, this species also occurs in the uppermost Ediacaran in western Canada (Hofmann & Mountjoy, 2001), Oman (Amthor et al., 2003), Siberia (Kontorovich et al., 2008, 2009; Grazhdankin et al., 2015) and Paraguay (Warren et al., 2017).

The upper Corumbá Group sections represent the best opportunities to study the terminal Ediacaran climate changes and biological innovations in South America (Boggiani et al., 2010). The Corumbá Group is constituted from the base to the top by Cadieus, Cerradinho, Bocaina, Tamengo and Guaiucurus formations. Several works have been produced on the palaeontology of the Corumbá Group (Beurlen & Sommer, 1957; Fairchild, 1978; Hahn et al., 1982; Walde et al., 1982; Zaine & Fairchild, 1985; Zaine 1991; Hidalgo, 2002; Gaucher et al., 2003; Becker-Kerber et al., 2013; Tobias, 2014; Pacheco, 2012; Leme et al., 2008; Pacheco et al., 2011; Walde et al., 2015; Adôrno et al., 2017; Parry et al., 2017), also on the stratigraphy and tectono-structural evolution (Barbosa 1949; Almeida 1964, 1965, 1984; Alvarenga & Trompette, 1992; Boggiani & Alvarenga, 2004; Gaucher et al., 2003; Babinski et al., 2008; Boggiani et al., 2010; Meira, 2011; Spangenberg et al., 2014; D'el-Rey et al., 2016; Sial et al., 2016); and finally on the sedimentological context (Boggiani et al., 1993; Boggiani, 1998; Oliveira, 2010; Campanha et al., 2011; Fontanela, 2012; Fazio et al., 2019).

METHODOLOGY

Several fieldworks were carried out in the vicinity of the municipalities of Corumbá and Ladário, Mato Grosso do Sul, in addition to a field work in Namibia and South Africa and another in the South of China sections. During the field works in Corumbá region, lithostratigraphic logs were uptdated and samples were collected in a systematic way with positioning of each collected sample. The studied locations of the Tamengo Formation, Corumbá Group include the outcrops of five main localities: Ecoparque da Cacimba, Corcal and Laginha quarries, Porto Sobramil and Porto Figueiras. In addition, samples collected from sections of the Dengying, China, Tagatiya Guazu, Paraguay (collected and shared by Professor Lucas V. Warren) and Namtsas, Namibia formations were prepared to complement the scarce organic microfossils species register for these sections.

Three modalities of samples preparation were used aiming at the recovery of fossils: 1. Invertebrates, 2. permineralized microfossils and, 3. Organic-walled microfossils (palynologic maceration). As for the study of the occurrence of invertebrates such as *Corumbella werneri* and *Cloudina lucianoi* as well as the ichnofossils and macroscopic algae, the study initially consists of the description and direct analysis from rock using stereoscopic microscopy; polished sections were prepared as well as thin slides for study on the stereoscopic microscopy, petrographic microscope and in specific cases of scanning electron microscopy (SEM).

For the chemical preparation and concentration of the particulate organic components (organic-walled microfossils), the own methodology developed in the Laboratory of Micropaleontology was used. The preparation consists of attacking the samples for 2h with 37% hydrochloric acid. The samples were neutralized and treated with 47% hydrofluoric acid for 12h. Again the samples were neutralized by several washes with distilled water until the pH was close to 7. A further hydrochloric acid digestion can be done for fluorite consumption. For the assembly of the permanent palynological slides, the supernatant organic-matter content was used, and Entelan was used as the standard mounting medium covered with cover slip glass.

An extensive literature survey was conducted to determine which sections would be selected for comparison studies with the results obtained from the sections studied in the Tamengo Formation. The bibliographic consultation allowed to include, in addition to the five studied sections, eleven additional sections distributed in Paraguay (three sections), Uruguay, Argentina, Namibia, China, Russia, Canada, the United States and Oman with one section each. All illustrated material are housed in the collections of macroscopic fossils under the suffix (MAF-), Micropaleontological collection (MP-) or in the research collection (CP-) of the Museum of Geosciences, at the Laboratory of Micropaleontology of the University of Brasilia-UnB.

RESULTS AND DISCUSSION

Twenty-six described species integrate the fossil assemblage of the Tamengo and Guaicurus formations, and were clustered six categories: biomineralizing metazoan, biomineralizing microfossils, vendotaenids, ichnofossils, organic-permineralized microfossils and organic-walled microfossils.

Tamengo Formation fossil assemblage consists of twenty-three species. From the total of twenty-three species, three represent benthic biomineralizing epibiont of sessile habit: *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010, *Corumbella werneri* Hahn et al., 1982 and an indeterminate species of poriferous. Three ichnospecies represent activity of vagile organisms of benthic habit: *Multina minima* Uchman, 2001, *Gordia marina* Emmons, 1844 and *Pilichnus cf. P. dichotomus* Uchman, 1999. *Multina minima* represents endobiot organisms while *Gordia marina* and *Pilichnus cf. P. dichotomus* represent epibiont vagile explorers of water-sediment interface. Additionally, sixteen species probably derived from plankticic organisms were recovered. Fifteen species of small sphaeromorphs organic-walled microfossils that possibly represented marine planktic: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann in Timofeev et al., 1976, *Navifusa* sp. and Gen1. sp. 1 and one species of permineralized microfossils *Chuaria circularis* Walcott, 1899. The sessile epibionts prokaryotic-colony *Vendotaenia* *antiqua* was previously reported in Cerradinho and Bocaina formations, and herein the occurrences are expanded to Tamengo Formation.

Four species represent the benthic fossil assemblage for Guaicurus Formation: *Eoholynia corumbensis* Gaucher et al., 2003, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979), *Multina minima* and *Didymaulichnus lyelli* (Rouault, 1850). From the total, three species have occurrences restricted to this formation: *Eoholynia corumbensis*, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) and *Didymaulichnus lyelli*, only *Multina minima* has shared occurrences with Tamengo Formation. It is worthy of note that, Tamengo Formation yielded the greatest biodiversity.

It is possible to note a dramatic change in the fossil assemblage from Tamengo to Guaicurus formations. This change in the fossil assemblage are followed by changes in the depositional paleoenvironment. The Tamengo Formation was deposited in a favorable paleoenvironment for deposition of carbonates, which was episodically interrupted by immature siliciclastic supply from very fine-grained rocks of a nearby source area. The Guaicurus Formation, on the other hand, is a result of an uninterrupted immature siliciclastic supply from a nearby source area, composed of very fine-grained rocks (Fazio et al., 2019). Apparently, 95% of the twenty-three species of Tamengo Formation disappeared, only the ichnospecies *Multina minima* have occurences in both of these formations. Possibly, the benthic endobiont habit could be the strategy to resist the paleonvironmental changes recorded in the upper Corumbá Group.

This disappearance recorded during the passage of Tamengo to Guaicurus formation could be related to the Ediacaran-Cambrian global mass extinction event, just before the Cambrian Explosion as observed globally (Darroch et al., 2018). This inference is reinforced by the dating of ash beds at the upper portion of Tamengo Formation at Corcal quarry section presented in Parry et al. (2017) as 541.85 ± 0.75 Ma. Considering this age for the top of Tamengo Formation, an early Cambrian age would be expected for Guaicurus Formation. Furthermore, it is worth mentioning that all occurrences of organic-walled from Tamengo have small size (majority between 5 - 70µ diameter), and that no organic-walled microfossil was found in the Guaicurus Formation. The small size organic-walled microfossil in Tamengo Formation, tending toward complete absence in the Guaicurus Formation could also reinforce the hypothesis of a local disappearance during the passage of Tamengo to Guaicurus, and could also be related to the Ediacaran-Cambrian extinction as already mentioned.

In addition to these results, new samples of additional sections of the Dengying, China, Tagatiya Guazu, Paraguay and Nomtsas, Namibia formations were collected and prepared. The results of the preparation and analysis of these samples complemented the scarce register of organic-walled microfossil species for these uppermost Ediacaran sections. The absence of larger and ornate organic vesicles was observed in all studied sections of Brazil (Tamengo Formation), Paraguay (Tagatiya Guazu Formation), Namibia (Formation Nomtsas) and China (Dengying Formation), as is typically described for sequences of the most uppermost Ediacaran sections globally distributed (Knoll, 1996; Vidal & Moczydlowska-Vidal, 1997; Gaucher, 2000).

The taxonomy of *Cloudina* Germs, 1972 was updated and had its diagnosis emended (Adôrnoet al., 2017). The type-material of *Cloudina lucianoi* was redescribed and later compared to other *Cloudina* species, especially *Cloudina hartmanae* Germs, 1972. The comparative study between these two species was based on objective morphological and morphometric criteria, which allowed to propose that *Cloudina hartmanae* Germs, 1972 should be considered a junior synonym of *Cloudina lucnianoi* (Beurlen & Sommer, 1957). The latter species then occupied the position of type-species of the *Cloudina* Genus and has its geographical distribution extended to all continents, revealing a great importance for studies of global biostratigraphic correlation.

The occurrence *Cloudina carinata* Cortijo et al., 2010 was recorded from siltstones of the Tamengo Formation in the locality called Porto Figueiras, Municipality of Corumbá.

It is the first record of this species in the American continent, expanding its geographic distribution, whose occurrence has been documented in sections from Spain and Siberia.

The occurrences of *Cloudina lucianoi* considered autochthonous in the Tamengo Formation are associated with carbonate rock interpreted as representing paleoenvironments with low siliciclastic input and in shallow water conditions in the photic zone. Moreover, *Cloudina lucianoi* has been considered as being responsible for the first reef constructions produced by metazoans in several uppermost Edicarian sections (Grotzinger & Al-Rawahi, 2014, Wood, et al., 2011; Penny et al., 2014). On the other hand, the metazoan *Corumbella werneri* and *Cloudina carinata* are most frequently associated with layers of siliciclastic rocks of the Tamengo Formation, interpreted as having been deposited in relatively deeper paleoenvironments and/or in a condition of higher siliciclastc supply. Fine reddish-colored siltstones layers present large numbers of *Corumbella werneri,* ichnofossils *Gordia marina* and *Pilichnus cf. P. dichotomus* specimens and more rarely *Cloudina carinata*. The redish coloration of these thin layers of siltstone interbeded between layers with dark gray color are due to the presence of iron oxide, which may represent episodes of oxygenation of the paleoenvironment, which made possible the episodic colonization by sessile and vagile benthic metazoans.

The current work presents the taxonomy for the ichnoespecies *Didymaulichnus lyelli* and *Multina minima* Uchman, 2001 previously documented in the top of the Tamengo Formation and at the base of the Guaricurus Formation in the Laginha quarry section (Parry et al., 2017). Two other new occurrences identified as *Gordia marina* Emmons, 1844 and *Pilichnus cf. P. dichotomus* Uchman, 1999 are herein presented. *Didymaulichnus lyelli* occurs only in Guaicurus Formation. *Multina minima*, *Gordia marina* and *Pilichnus cf. P. dichotomus* integrate the updated ichnology assembly for the Tamengo Formation, of which *Multina minima* also occurs in the Guaicurus Formation.

Pilichnus cf. P. dichotomus consists of complex and bifurcated excavations, representing epibiont organisms with elaborate excavation strategies. *Didymaulichnus lyelli*, is represented by excavations produced by vagile endobiont organisms. *Gordia marina* represents tracks possibly produced by vagile epibiont worms. This species consists of simple curved or loop-like surficial tracks that are possibly associated with substrate exploratory, vagile epibiont organisms at the water-sediment interface. *Multina minima* is represented by complex patterns microtunnels that represent excavations possibly associated with small, endobiont worm that are able to penetrate portions made up of soft and unconsolidated sediment.

The integration of the information regarding taxonomy and stratigraphic distribution of the species was presented as a biostratigraphic essay composed of seven biozones, from the base to the top, respectively named: *Cloudina* Assemblage Superzone that is distributed in all 15 analyzed sections. Inserted in this superzone, there are three biozones, distributed in sections of Brazil and Paraguay: *Cloudina lucianoi/Corumbella werneri* Interval Zone; *Corumbella werneri* Range Zone; and *Corumbellla werneri/Cloudina lucianoi* Interval Zone (Adôrno et al., 2016b; Adôrno et al., 2017). It was possible to propose two subzones: *Bavlinella faveolata - Leiosphaeridia minutissima* Assemblage Subzone inserted in the base of *Corumbella werneri* Range Zone and *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone at the upper portion of the *Corumbella werneri/Cloudina lucianoi* Interval Zone. The first subzone spans across Brazil, Argentina, Uruguay, Namibia and China, the second across Brazil, Namibia, China and Siberia. Finally, *Eoholynia corumbensis* Range Zone was proposed in the base of Guaicurus Formation at Laginha quarry, lowermost Cambrian. The geographic distribution of this biozone is restricted to Laginha quarry locality so far.

CONCLUSIONS

Twenty-six species were described from Tamengo and Guaicurus formations. This fossil assemblage were clustered six categories: biomineralizing metazoan, biomineralizing microfossils, vendotaenids, ichnofossils, organic-permineralized microfossils and organic-walled microfossils.

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It is worthy of note that, Tamengo Formation yielded the greatest diversity of species for terminal Ediacaran Corumbá Group. One event of local disappearance was proposed, and based on the dating available and in the dramatic changes in the paleoenvironment and biota, a hypothesis of this local disappearance which can be related to the global Ediacaran-Cambrian extinction, just before the Cambrian explosion was presented.

Five sections of the upper Corumbá Group had updated lithostratigraphic description: Ecoparque da Cacimba, Porto Sobramil, Corcal and Laginha quarries and Porto Figueiras. In addition to the updates of the lithostratigraphic logs, the occurrences of the species were positioned in each log, allowing the proposition of biostratigraphic essay.

Additionally, five species of organic-walled microfossils were recovered and identified from samples of the Dengying Formation, China: *Bavlinella faveolata*, *Leiosphaeridia minutissima*, *Leiosphaeridia crassa*, *Leiosphaeridia obsuleta* (Naumova, 1949) and *Ostiama microcystis*; Nine species from samples from Nama Group, Namibia: *Bavlinella faveolata*, *Ostiama microcystis*, *Leiosphaeridia crassa*, *Leiosphaeridia obsuleta* (Naumova, 1949), *Leiosphaeridia tenuissima*, *Leiosphaeridia minutissima*, *Soldadophycus major*, *Coniunctiophycus conglobatum* and *Myxococcoides siderophila*. Four species in the Tagatiya Guazu Formation, Paraguay: *Ostiama microcystis*, *Leiosphaeridia obsuleta* (Naumova, 1949) and *Leiosphaeridia minutissima* and Gen.1 sp. 1. The micropaleontological result for these sections complemented the scarce record of species of organic-walled microfossils from the uppermost Ediacaran.

Seven biozones were proposed, from bottom to top: *Cloudina* Assemblage Superzone that is distributed in all 15 analyzed sections in Brazil, Paraguay, Uruguay, Argentina, United States, Canada, Namibia, Oman, Russia and China. Inserted in this superzone, there are three biozones, distributed in sections of Brazil and Paraguay: *Cloudina lucianoi/Corumbella werneri* Interval Zone; *Corumbella werneri* Range Zone; *Corumbellla werneri/Cloudina lucianoi* Interval Zone (Adôrno et al., 2016b; Adôrno et al., 2017). It was possible to propose two subzones: *Bavlinella faveolata - Leiosphaeridia* *minutissima* Assemblage Subzone inserted in the base of *Corumbella werneri* Range Zone and *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone at the upper portion of the *Corumbella werneri/Cloudina lucianoi* Interval Zone. The first subzone spass across Brazil, Argentina, Uruguay, Namibia and China, the second across Brazil, Namibia, China and Siberia. Finally, *Eoholynia corumbensis* Range Zone was proposed in the base of Guaicurus Formation at Laginha quarry, lowermost Cambrian. The geographic distribution of this biozone is restricted to Laginha quarry locality so far.

Future studies involving taxonomy and stratigraphic distribution of the uppermost Ediacaran fossil assemblage would be of great importance for advances in the biostratigraphy. Special attention must be given to the occurrences of *Cloudina* sp. reported in the Sete Lagoas Formation, Bambuí Group, mainly aiming at stratigraphic positioning and precise taxonomic positioning for those occurrences. In addition, studies on biology especially in the areas of phylogeny and morphology compared with metazoa, in addition to in-depth studies on the microbiota of this important interval, should be encouraged.

BIBLIOGRAPHIC REFERENCES

All citations in this expanded abstract are included in the chapter REFERENCES.

TAXONOMY, PALEOECOLOGY AND CHRONOBIOSTRATIGRAPHY ACROSS THE EDIACARAN- CAMBRIAN BOUNDARY: TAMENGO AND GUAICURUS FORMATIONS

Doctoral thesis by
Rodrigo Rodrigues Adôrno

CHAPTER – 1: INTRODUCTION

The objective of this work is to present a detailed study of the taxonomy, analysis of the stratigraphic distribution of the species and to propose a chronobiostatigraphic essay for the analyzed fossil assemblage of the Tamengo and Guaicurus formations. In addition, paleoecological and paleoenvironmental inferences are presented based on the occurrence of the species and the lithostratigraphic update of the sections of the Tamengo Formation in the region of Corumbá, Mato Grosso do Sul State, Brazil. Considering the scarcity of micropaleontological data for most uppermost Ediacaran sections, samples from three localities were prepared and analyzed from Nomtsas Formation, Namibia; Tagatiya Guazu Formation, Paraguay and Dengying Formation, China. This additional study aims to complement the record of species described in the bibiography, through the systematic description of new occurrences of organic-walled microfossils for these three additional sections. Finally, it is the objective of this work to present an integration and comparison of the results obtained from the analysis of the Tamengo Formation fossil assemblage with those published for other uppermost Ediacaran sections from Paraguay, Uruguay, Argentina, Namibia, China, Russia, Canada, United States and Oman, by proposing a biostratigraphic essay following the recommendations of the International Stratigraphic Code.

The Neoproterozoic is marked by significant paleoenvironmental changes, including important atmospheric oxidation events, followed by the oxidation of the deeper portion of the seas, and also to record glacial events with ice caps that could reach low latitudes (Hoffman, 2009). Scientific publications indicate at least three most significant glacial events during the Neoproterozoic: the first is called Sturtian glaciation (~ 720 Ma);

the second Marinoan glaciation (~ 635 Ma); and the third glacial event would have occurred in the Ediacarian and became known as the Gaskiers glaciation (~ 580 Ma) (Hoffman, 2009).

In addition to the paleoclimatic changes, the O_2 levels of the seas and the atmosphere also oscillated dramatically during the Ediacaran Period. There is evidence that O_2 concentrations varied from about 3 - 10% to more than 100% of the current level (Fike et al., 2006; Canfield & Teske, 1996). It is argued that the simultaneity between appearances of complex life forms, while there is geochemical evidence that the available oxygen levels rose during the Ediacaran (635 - 541Ma) could represent cause and effect relationship. This simultaneity has led several authors to propose that increased oxygen availability would have been one of the main causes of the onset of complex animals (Evans et al., 2018). The increased availability of oxygen would have enabled the emergence and diversification of groups with eukaryotic and multicellular cells and also the diffusion of oxygen through complex tissues. The synthesis of some of the tissues involves substantial metabolic expenditure of oxygen, such as the case of collagen synthesis (Fike et al., 2006; Canfield & Teske, 1996). The nature of the relationship between biological innovations and the simultaneous paleoenvironmental and paleoclimatic changes are still under debate, whether causal or merely simultaneity.

Ediacaran Period records one of the most innovative biological adaptations, the advent of the biomineralized skeleton. The first Ediacaran fossils described as having biomineralized skeletons and certainly the best studied are the *Cloudina* species. Among the biomineralizings of uppermost Ediacaran stage (TES), *Cloudina* is the most widespread, occurring in uppermost Ediacaran successions in Namibia (Grant, 1990), Oman (Conway Morris et al., 1990), South China (Hua et al., 2005; Cai et al., 2013; Cortijo et al., 2015a), Spain (Cortijo et al., 2010; Cortijo et al., 2015b), Siberia (Kontorovich et al., 2008; Zhuravlev et al., 2012; Grazhdankin et al., 2015), Canada (Hofmann and Mountjoy, 2001), Mexico (Sour-Tovar et al., 2007), Brazil and Uruguay (Gaucher et al., 2003; Warren et al., 2014; Adôrno et al., 2017), Paraguay (Warren et al., 2011) and eastern California Grant (1990) and Zhuravlev et al. (2012) (Table 1. 1Table **1. 1.** Occurrences of *Cloudina* species and their localities. (Font: <www.gbif.org>).

Table 1. 1. Occurrences of *Cloudina* species and their localities. (Font: <www.gbif.org>).

Species	**Country**	**Locality**	**Latit grau dec**	**Long grau dec**
***Cloudina* sp.**	Mongolia	ridge above Khunker Gorge	46.72892	95.99601
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	Paraguay	2 outcrops, 10 km apart, E of the Paraguay River, Rio Apa Block Warren et al., 2011	-22.7667	-57.48333
***Cloudina* sp.**	Mexico	FCIP 01/625, near Rancho Fatima.	30.11667	-111.9833
***Cloudina carinata* Cortijo et al., 2010**	SPAIN	lower reaches of the Estena River on the Membrillar property, NE Badajoz	39.36167	-4.837778
***Cloudina carinata* Cortijo et al., 2010**	Brazil	Porto Figueiras Section Corumbá Municipality, Mato Grosso do Sul State, Brazil	-18.998937°	-57.62873°
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	Russia	borehole Vostok 3 at the Northern Vezdekhodnyi Horst between western Lisitsa trough and RosOmãkha trough	59.4	85.66666
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***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	Canada	Jasper National Park of Canadá	53.03333	-118.7333
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	SPECIFIC LOCATION: Shuimoshan, Xingshan County, Hubei, China. LAT/LONG: estimated based on Xingshan, China.	31.30833	110.8039
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	SPECIFIC LOCATION: Lijiagou/Kuanchuanpu, Ningqiang County, Shaanxi, China. LAT/LONG: estimated based on Ningqiang, China.	32.94222	106.2264
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	Hanzhong, Shaanxi	32.98333	106.2667
***Cloudina* sp.**	USA	Nopah Range. SE 1/4, SE 1/4, SW 1/4, sec. 11, T20N, R8E, Tecopa Pass 7.5' quadrangle. Talus slope exposed on North-trending Ridge about 2.4km(1.5mi)NNE of Noonday Mine, Inyo County, California.	35.842	-116.089
***Cloudina* sp.**	USA	Montgomery Mountains. SW 1/4, NW 1/4, SW 1/4, sec. 11, T185, R52E, Mt. Schader 7.5"" quadrangle. Talus slope on E side of an unnamed wash. 3.4km(2.1mi)SW of ghost town of Johnie, Nye County, Nevada.	36.4	-116.1035
***Cloudina* sp.**	USA	Spring Mountains SW 1/4, sec. 34, T18S, R54E, Horse Springs 7.5"" quadrangle. Talus slope immediately NE of Santa Clara Spring, just W of the approximate border between Nye and Clark Counties, Nevada.	36.34	-115.902
***Cloudina* sp.**	Namibia	Latitude and longitude coordinates are general for the country of Namíbia.	-22	17
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	Oman	The formation outcrops throughout the Salt Basin Birba Area. Specimens from the Birba North-1 borehole at a subsurface depth of about 4500 m.	18	55.31667

***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	Exposure in a stream section about 300m to the west of the hamlet of Xuanjiangping and about 2.8km south of the village of Kuanchuanpu	36.85	109.31
***Cloudina* sp.**	Antarctica	Specimens collected near the top of Taylor Nunatak on the east side of the Skackleton Glacier, central Transantarctic Mountains.	-84.7333	-176.1667
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	Lijiagou/Kuanchuanpu [Dengying Fm]	32.9422	106.226
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	Shuimoshan [Dengying Fm]	31.3083	110.804
***Cloudina* sp.**	Brazil	Corumba-Ladario, Brazil	-19	-57.62
***Cloudina* sp.**	Oman	Thrombolites, Mukhaizna-11 well	18.75	54.5
***Cloudina* sp.**	Namibia	Thrombolite Reef, Schwarzrand Subgroup	-28.58	18
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	Canada	Ediacaran, Lijiagou, Bed 8, Kuanchuanpu, Shaanxi	32.98	106.27
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	China	*Cloudina* of the Gaojiashan Fm., Shaanxi Province - Conway Morris et. al 1990	36.85	109.31
***Cloudina lucianoi* (Beurlen & Sommer, 1957)**	Oman	*Cloudina* of the Ara Formation, Omãn - Conway Morris et. al 1990	18	55.32
***Cloudina* sp.**	Namibia	Zaris Formation, Kubis Subgroup, Nama Group, Namíbia - Germs 1995	-25	17
***Cloudina* sp.**	Namibia	Nomtsas Formation, Schwarzrand Subgroup, Nama Group, Namíbia - Germs 1995	-22	17
***Cloudina* sp.**	Namibia	Urusis Formation, Schwarzrnad Subgroup, Nama Group, Namíbia - Germs 1995	-22	17
***Cloudina* sp.**	Antarctica	Taylor Formation, Antártica - Yochelson et. al. 1977	-84.73	-176.17
***Cloudina* sp.**	USA	LACMNH loc. 17132, Wood Canyon Fm., Inyo County, CA - Hagadorn and Waggoner 2000	38.08	-120.3
***Cloudina* sp.**	USA	LACMNH loc. 17130, Wood Canyon Fm., Nye County, NV - Hagadorn and Waggoner 2000	36.57	-116.15
***Cloudina* sp.**	USA	LACMNH loc. 17131, Wood Canyon Fm., Nye County, NV - Hagadorn and Waggoner 2000	37	-115.68
***Cloudina* sp.**	Namibia	Late Precambrian Dabis Formation, Germs 1995	-22	17
***Cloudina* sp.**	Brazil	Quarry in the Januaria City, Late Precambrian Sete Lagoas Formation, Warren, et al 2014	-15.4	-44.4
***Cloudina riemkeae*? Germs (1972)**	Argentina	Loma Negra Formation, Sierras Bayas Group, Argentina (Gaucher et al., 2005)	-37.851	-58.261
***Cloudina* sp.**	Uruguay	Yerbal Formation, Arroyo del Soldado Group, Uruguay (Gaucher et al., 2003)	-34	-55

Sinotubulites, also has a wide geographic distribution and has been recovered from uppermost Ediacaran strata in South China (Cai et al., 2015), Mexico (McMenamin, 1985), eastern California and Nevada (Signor et al., 1987), and Spain (Cortijo et al., 2015b), *Conotubus* Zhang and Lin, 1986 in (Lin et al., 1986) and *Gaojiashania* Yang et al., 1986 in (Lin et al., 1986) in South China. The colonial *Namacalathus* was first described from Namibia (Grotzinger et al., 2000; Zhuravlev et al., 2015) also occurring in uppermost Ediacaran strata in western Canada (Hofmann and Mountjoy, 2001), Oman (Amthor et al., 2003), Siberia (Kontorovich et al., 2008; Grazhdankin et al., 2015) and Paraguay (Warren et al., 2017) (Figure 1. 1).

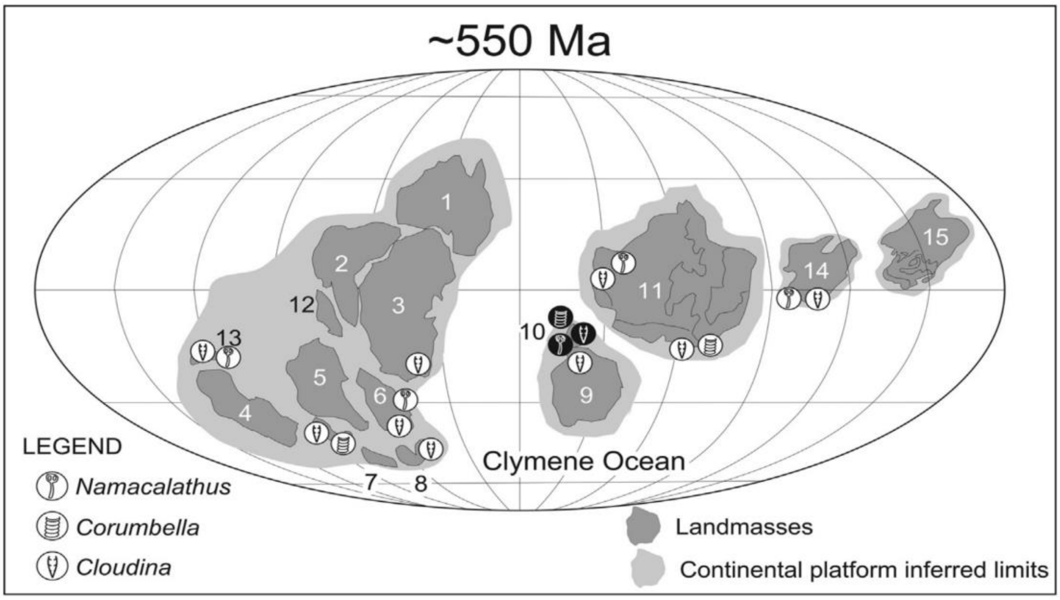


Figure 1. 1. Paleogeographic reconstruction and occurrence of *Cloudina*, *Corumbella* and *Namacalathus*. 1 – Australia, 2 – India, 3 – Antarctica, 4 – West Africa, 5 – Congo-São Francisco, 6 – Kalahari, 7 – Paraná, 8 – Rio de la Plata, 9 – Amazonia, 10 – Rio Apa, 11 – Laurentia, 12 – Madagascar, 13 – Arabia-Nubia, 14 – Siberia, 15 – Baltica (Warren et al. 2017).

Cloudina species have been considered as potential guide fossils for the Ediacaran/Cambrian boundary (Grant, 1990). The *Cloudina* genus was regarded as the oldest representative of the first aparison of the biomineralized skeleton (Brasier, 1979; Conway Morris, 1987, 1989; Conway Morris et al., 1990). Although new findings of tubular fossils such as *Ramitubus increscens* Liu et al., 2008, *Ramitubus decrescens* Liu et al., 2008, *Sinocyclocyclicus guizhouensis* Xue et al., 1992, *Quadratitubus orbigoniatus* Xue et al., 1992, and *Crassitubus costatus* Liu et al., 2008 were recovered from the Doushantuo Formation (635.2 ± 0.6 Ma and 551.1 ± 0.7 Ma) (Condon et al. 2005). These older biomineralizings skeletons are attributed to calcifying metazoan, allowing to admit that the emergence of the biomineralized skeleton is older than all *Cloudina* species described so far (Figure 1. 2).

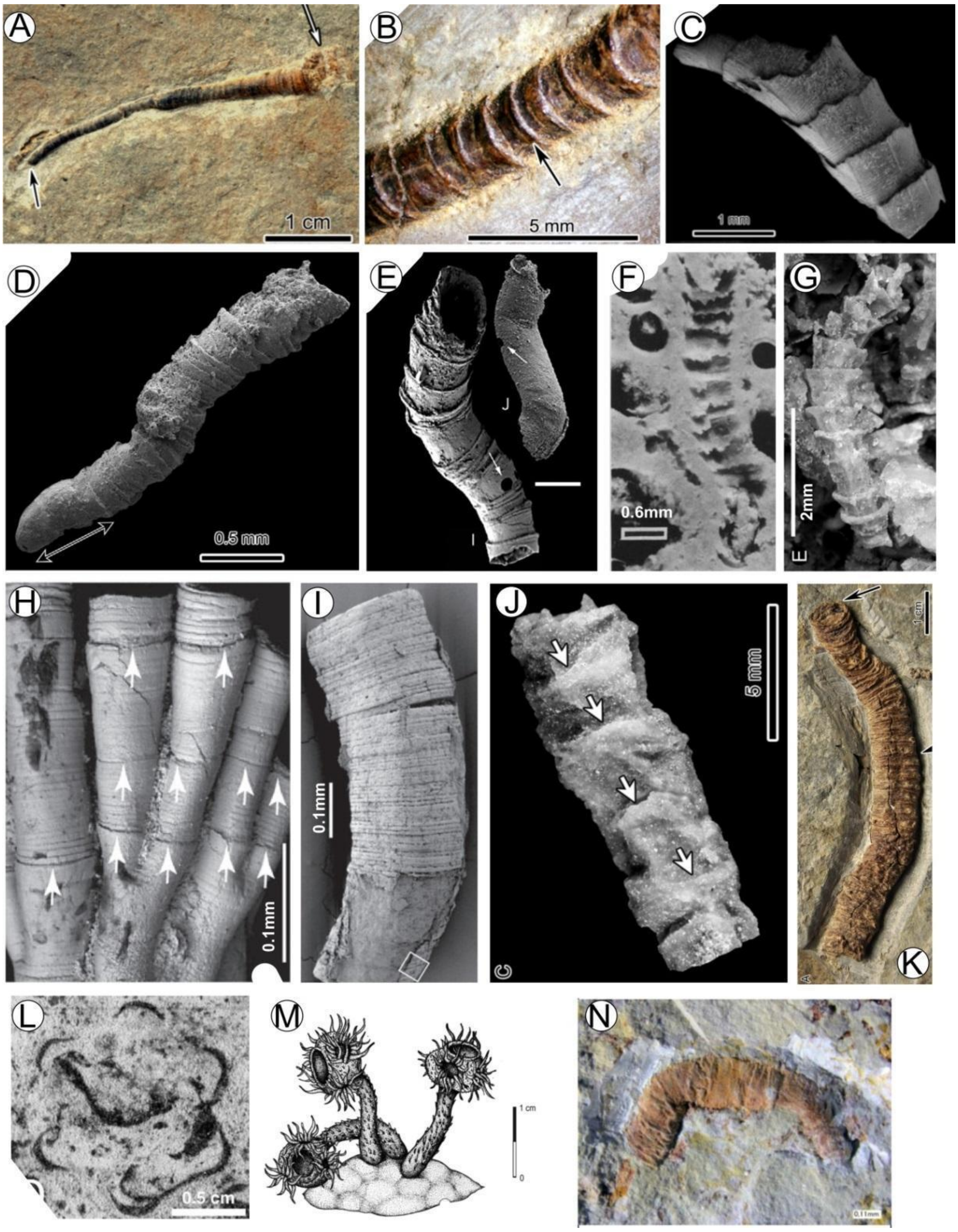


Figure 1. 2. Main species of tubular fossils of the upper and uppermost Ediacaran. A) (Cai et al., 2011, Fig. 3A) *Conotubus hemiannulatus* Zhang and Lin 1986; B) (Cai et al., 2011, Fig. 3C) Close-up view of a three-dimensionally pyritized specimen of *Conotubus hemiannulatus*; C) (Cai et al., 2017, Fig. 7A) *Cloudina xuanjiangpingensis* Cai et al., 2017; D) (Cai et al., 2017 Fig. 6A). *Cloudina ningqiangensis* Cai et al., 2017; E) Hua et al., 2003, Fig. 3A) *Cloudina lucianoi* (Beurlen & Sommer, 1957); F) (Grant, 1990, Fig. 5A) *Cloudina riemkeae* Germs, 1972; G) (Cortijo et al., 2010 Fig. 4E). *Cloudina carinata* Cortijo et al., 2010; H) (Liu et al., 2008 Plate 1 -6*) Ramitubus increscens* Liu et al., 2008; I) (Liu et al., 2008, Fig. 6C). *Quadratitubus orbigoniatus* Xue et al., 1992; J) (Cai et al., 2015 Fig 3C). *Sinotubulites baimatuoensis*. Chen, Chen and Qian, 1981; K) (Cai et al., 2013, Fig. 4A) *Gaojiashania cyclus* Yang et al., 1986 in (Lin et al., 1986); L) (Grotzinger et al., 2000, Fig. 8D) *Namacalathus hermanastes* Grotzinger et al., 2000. M) Digital reconstruction of *Namacalathus hermanastes* (Warren et al., 2017); N) (Walde et al., 2018, Fig. 12) *Corumbella werneri* Hahn et al., 1982.

The Tamengo Formation sections represent the best opportunities to study the terminal Ediacaran climate changes and biological innovations in South America (Boggiani et al., 2010) (Figure 1. 3). Corumbá Group crops out in the southern Paraguay Fold Belt in Brazil, representing one of the most complete Ediacaran sedimentary archives of palaeogeographic, climatic, biogeochemical and biotic evolution in southwestern Gondwana (Boggiani et al., 2010).

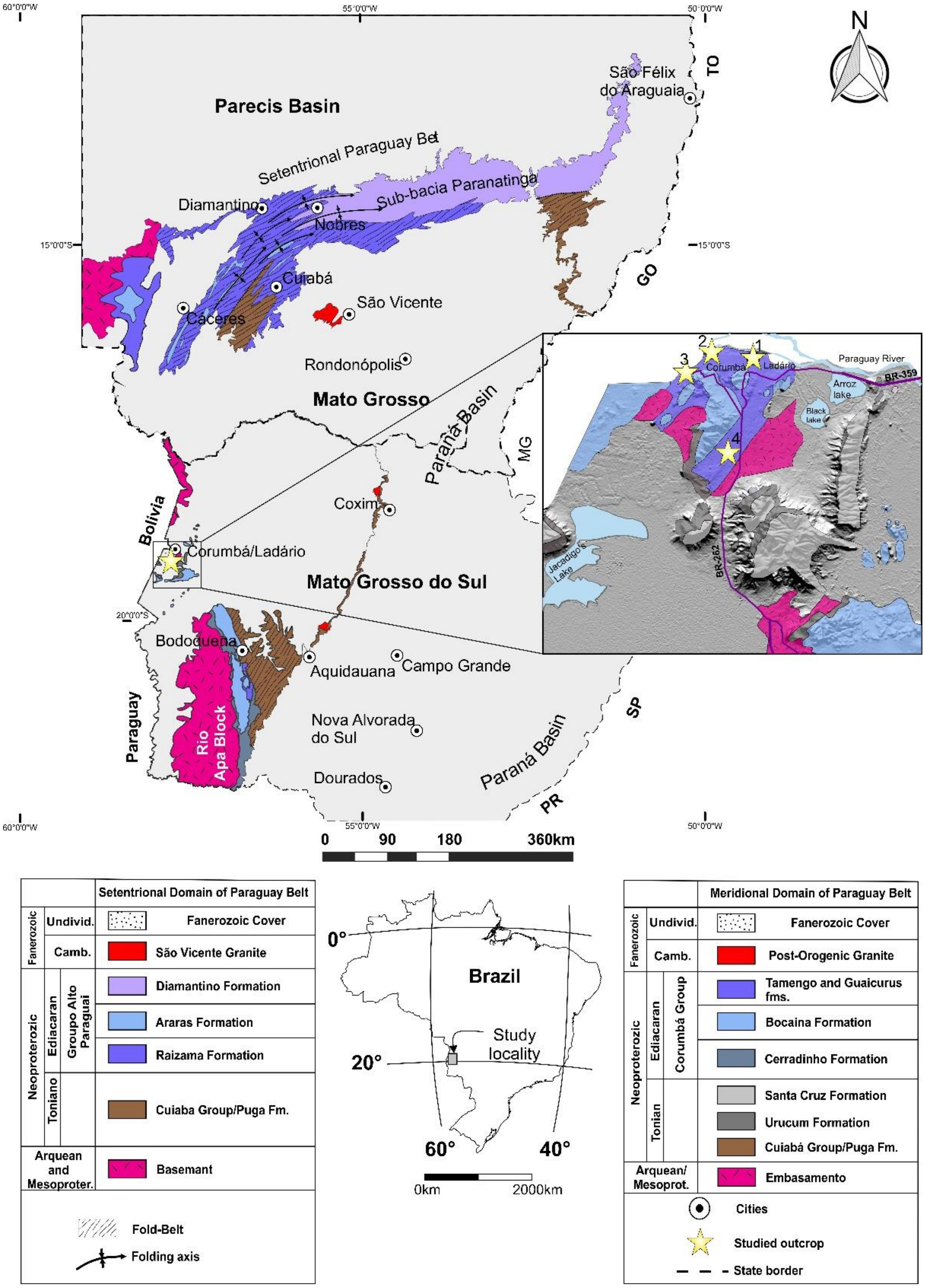


Figure 1. 3. Regional simplified geological map of the North and south Paraguay fold belt: 1) Section in the Sobramil port; 2) Section in the ecopark of Cacimba; 3) Corcal quarry; and 4) Laginha quarry section in Corumbá and Ladário, Mato Grosso do Sul State (Modified by Silva & Jost, 2006).

The first fossils of the Tamengo Formation, Corumbá Group, were discovered by Octávio Barbosa and later described by Beurlen & Sommer (1957) as *Aulophycus lucianoi* and the remains of algae were indicated to be Cambrian. Beurlen & Sommer (1957) describe and classify the tubular fossils in the limestones of the Tamengo Formation as *Aulophycus lucianoi* interpreted as algae fragments, possibly indicating Cambrian age. Fairchild (1978) noted the great similarity of *Aulophycus lucianoi* with two species of tubular fossils of the *Cloudina* genus Germs, 1972, which occur in limestones of the Nama Group, uppermost Ediacaran of Namibia. Hahn & Pflug (1985) and Zaine & Fairchild (1985) independently confirm the transfer of *Aulophycus lucianoi* to the *Cloudina* Genus.

In 1980, *Corumbella werneri*, a fossil metazoan, was descovered by Professor Detlef Walde. Two years latter, *Corumbella werneri*, was formally described by Hahn et al. 1982. This species presents centimetric dimensions, pinned shape, preserved three-dimensional and tubular geometry, with the possibility of noticing the presence of periderm probably chitinous, weakly biomineralized, possibly indicating a Cnidaria Scyphozoa.

The first mention of the occurrence of organic-walled microfossils was presented by Sommer in 1971 where the occurrence of *Bambuites* sp. in the limestones of Tamengo Formation was documented (Sommer, 1971b). Fairchild & Sundaram (1981) also documented organic-walled microfossils in Tamengo Formation, with occurrences subsequently confirmed by Zaine & Fairchild (1987). The first systematic paleontological framework was presented in Zaine (1991), which recorded occurrences of acritarchs, filamentous microfossils in the Tamengo Formation. Zaine (1991) also identified the Genus *Vandalosphaeridium* and, subsequently, macroscopic algae *Tyrasotenia* sp. (redescribed by Steiner, 1994 as *Vendotaenia* sp.) and the microfossil *Sphaerocongregus variabilis*, currently synonymous of *Bavlinella faveolata*. Possible ichnofossils, new stromatolites, oncolytes and probably cyanobacteria were described by Fairchild et al. (2000). Marine macroalgae *Eoholynia corumbensis* and *Tawuia* sp. were identified at the base of the Guaicurus Formation (Gaucher, 2000; Gaucher et al., 2003), while the agglutinate foraminifera *Titanoteca coimbrae* occurs in the phosphorites of the Bocaina Formation in the Serra da Bodoquena locality (Gaucher et al., 2003).

Updates on the trace fossils of the Corumbá Group were recently presented by Parry et al. (2017) and the stratigraphic distribution of ichnofossils *Multina minima* Uchman, 2001 and *Didymaulichnus lyelli* Rouault 1850 at the top of the Tamengo Formation and the base of the Guaicurus Formation were also presented. It should be noted that *M. minima* was described from the Hecho Group, Early to Mid Eocene of Spain, and *Didymaulichnus lyelli* was restricted to the Ordovician, been described from the Bell Island and Wabana groups in the locality of Newfoundland, Canada (Fillion, D. & Pickerill, 1990). Another important contribution of this work is the dating of zircon grains from volcanic ash at the base and top of the Tamengo Formation, allowing to date the beginning and the end of its deposition (Parry et al., 2017) (Figure 1. 4).

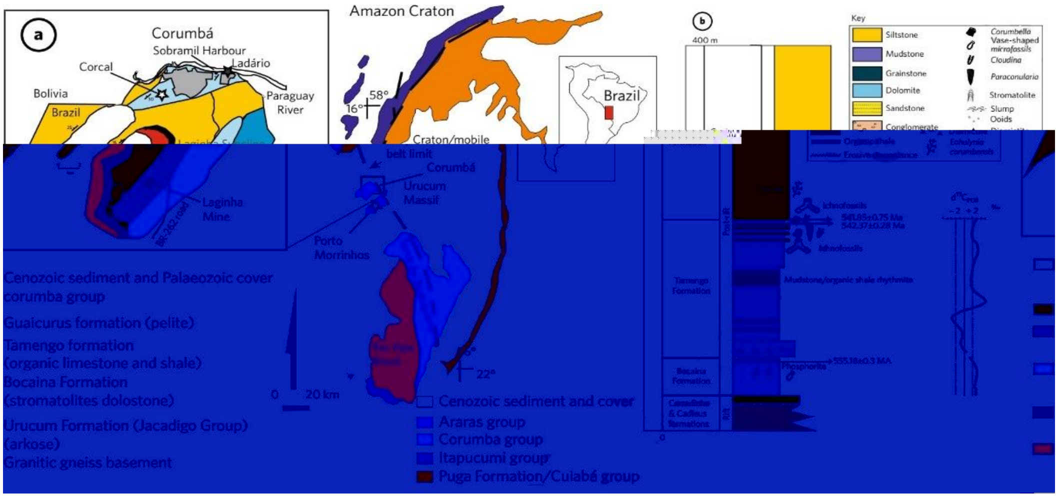


Figure 1. 4. Map of localities and stratigraphic column of the Neoproterozoic Corumbá Group: a) map of localities and b) stratigraphic column. The dates are from the work of Parry et al. (2017). White star indicates localities with samples collected for geochronology. Black stars locality with ichnofossil: Laginha quarry (Guaicurus Formation) 19 ° 07 '09.8' 'S, 057 ° 38' 40.4 " W. Ladário (Tamengo Formation) 19 ° 0 '04.0' 'S, 57 ° 36' 00.7 " W. The carbon isotope curve was obtained from Laginha quarry (Modified from Parry et al., 2017).

1.1. SPECIFIC OBJECTIVES

The main scientific question addressed in the present thesis is to describe occurrences of species in the studied area and to analyze their paleoecologic, stratigrafic distribution in order to understand their significance to paleoenvironmental evolution and potencial for application on biostratigraphy for latest Ediacaran and earliest Cambrian. The specific objetives are:

- ✓ to present a taxonomic study for the analyzed upper Corumbá Group fossil assemblage;
- ✓ to analyze the stratigraphic distribution of the studied species;
- ✓ to develop paleoecological and paleoenvironmental inferences for the uppermost Ediacaran/lowermost Cambrian, Tamengo and Guaicurus formations, Corumbá Group;
- ✓ to propose a chronobiostatigraphic essay for the fossil assemblage of the Tamengo and Guaicurus formations;
- ✓ to present lithostratigraphic description for five studied sections in Porto Sobramil, Laginha and Corcal quarries, Porto Figueiras and Ecoparque Cacimba sections;
- ✓ to integrate and compare the studied fossil assemblage with those published for other uppermost Ediacaran sections in Paraguay, Uruguay, Argentina, Namibia, China, Russia, Canada, United States and Oman;
- ✓ to propose an international biostratigraphic essay for the uppermost Ediacaran/lowermost Cambrian interval.

1.1. EDIACARAN PERIOD AND LIFE RECORD

The Ediacaran Period spans between 635 and 541 ± 1 million years (International Stratigraphic Chart v2018/8). The base of the Ediacaran System is defined as the base of the Marinoan cap carbonate Nuccaleena Formation in the Enorama Creek section of the central Flinders Ranges, Adelaide Rift Complex, South Australia (Knoll et al., 2006). The top of Ediacaran (and base of the Cambrian) is intended to coincide with the first appearance of the trace fossil *Treptichnus pedum* in southeast Newfoundland (Landing, 1994; Gehling et al., 2001; Darroch et al., 2018).

Since the formalization of this period (Knoll et al., 2004), internal subdivision and correlation of Ediacaran strata based on biostratigraphy when fossil is present and additional techniques using climatic and chemostratigrpahic events (e.g., Gaskiers glaciation and Shuram δ^{13}C excursion) as tools to correlate Ediacaran strata (Xiao et al.,

2016) have been proposed. Several problems regarding taphonomic limitation in Ediacaran restrain the usage of the first appearance datum (FAD) to define and correlate stratigraphic boundaries. Therefore, the uses of FAD for correlation and comparison for Ediacaran strata must be carefully examined and tested (Xiao et al., 2016). Recognizing the fossiliferous challenges for correlation of Ediacaran strata, Narbonne et al. (2012) presented alternative tools to divide the Ediacaran System into two or three series, although the initial survey of the Subcommission on Neoproterozoic Stratigraphy in 2009 recommended a two-series approach (Figure 1. 5) (see Xiao et al., 2016).

Together, the biostratigraphic, chemo-stratigraphic, lithostratigraphic, and geochronological data would enable the proposal of global correlation throughlinkages with climatic, geochemical, and evolutionary events. This integrative approach offers high potential to define the Ediacaran Stages (ES) as extensively discussed in Xiao et al. (2016). Several macrofossils from uppermost Ediacaran strata stand out for their potential as biostratigraphic markers, which include biomineralizing animals *Cloudina*, *Conotubus*, *Sinotubulites*, *Corumbella* and *Namacalathus*.

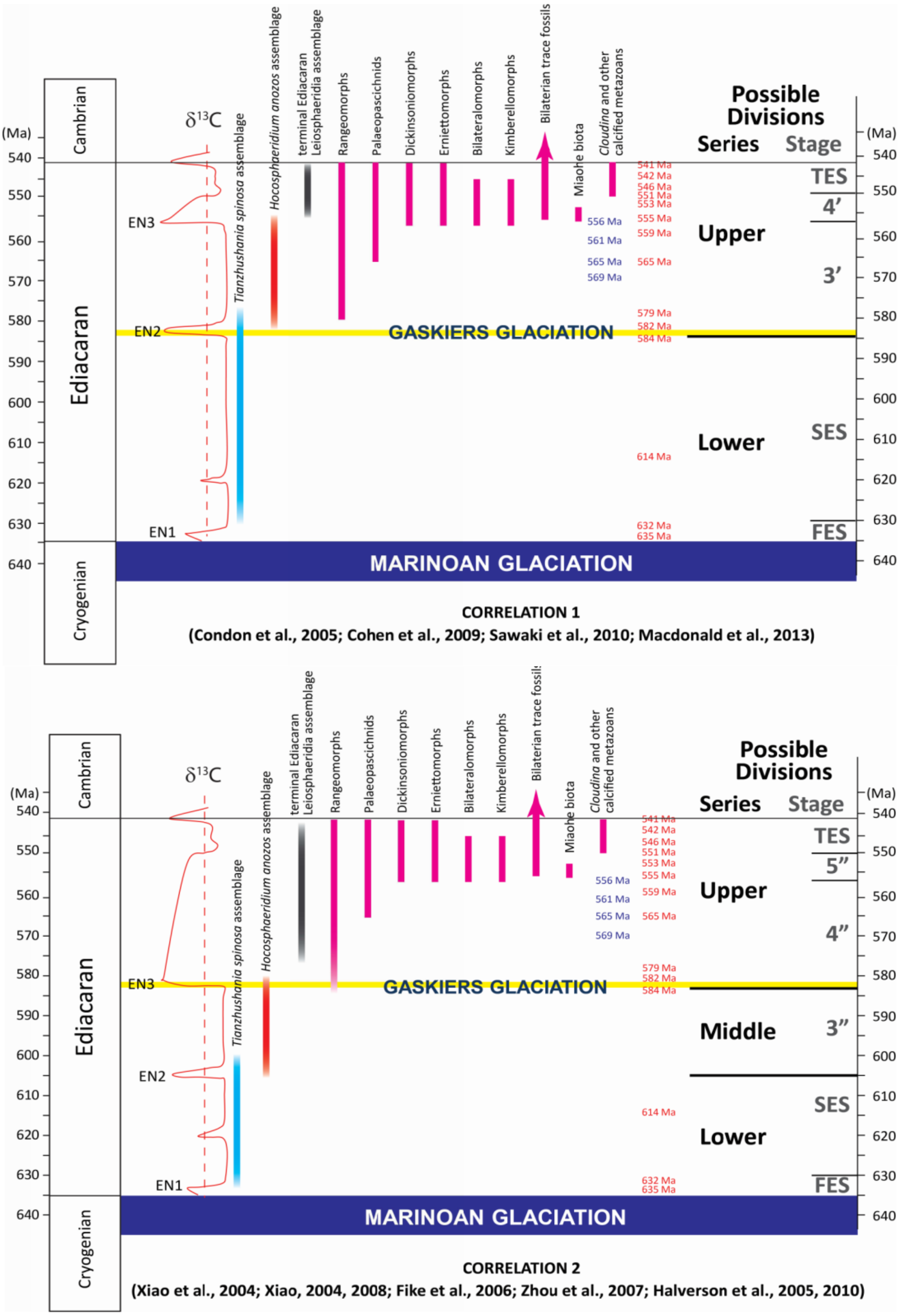


Figure 1. 5. Two models for Ediacaran subdivision and correlation. The key difference between these two models relates to how the Shuram excursion is correlated with the Gaskiers glaciation. FES: first Ediacaran stage; SES: second Ediacaran stage; TES: terminal Ediacaran stage (extracted from Xiao et al., 2016).

The Ediacara biota (600–541Ma) marks the first appearance of large, architecturally complex organisms in Earth history (Narbone, 2005). A detailed discussion and analyses of Ediacara biota cluster of the diverse fossils and localities that constitute the

Ediacara biota worldwide are presented in Waggoner (2003) and Narbone (2005). These analyses have shown that most or all occurrences of Ediacara-type fossils can be grouped into three main clusters or assemblages:

1) The **Avalon Assemblage** (Figure 1. 6) is the oldest (ca. 575– 560 Ma; Benus, 1988; Bowring et al., 2003) and occurs only in very deepwater, volcaniclastic settings of the Avalon Zone of Newfoundland (Misra, 1969; Anderson & Conway-Morris, 1982; Clapham et al., 2003; Narbone, 2005) and England (Ford 1958, Boynton & Ford 1995). None of the taxa were skeletonized or capable of mobility (Narbone 2005).

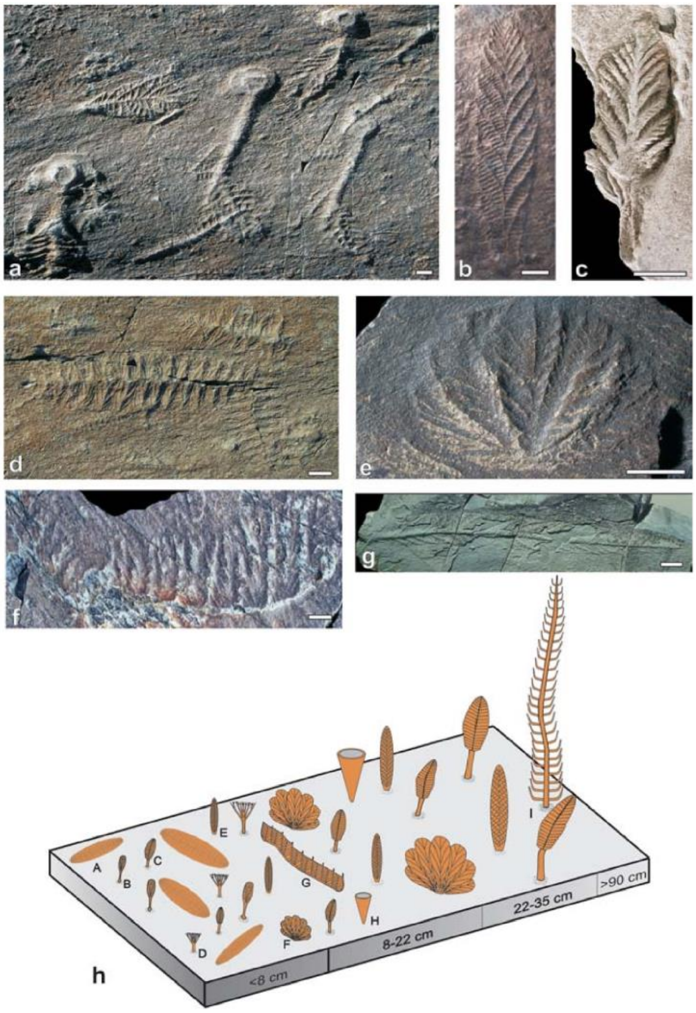


Figure 1. 6. Avalon Assemblage on upper bedding surfaces from Newfoundland (a, c–h) and Charnwood, England (b). Scale bar represents 2 cm (a, b; d–g) or 0.25 cm (c). (a) Current-aligned fronds of *Charniodiscus*, spindle-shaped rangeomorphs (lower and center), and a frond-shaped rangeomorph (upper left), Mistaken Point Formation. (b) Holotype of the probable rangeomorph frond *Charnia masoni*, New Walk Museum, Leicester (extracted from Narbone, 2005).

2) The **White Sea Assemblage** (Figure 1. 7) is known from the Vendian sections in the White Sea in Russia (Fedonkin, 1981, 1992; Sokolov & Iwanowski, 1990) and the

Ediacara Member in Australia (Glaessner & Wade, 1966, Jenkins, 1992). The oldest occurrences are older than 560 Ma and the youngest may be close to the base of Cambrian (Martin et al., 2000, Grazhdankin, 2004). Abundant worm burrows can be attributed to the presence of mobile bilaterians in the fauna, but none of the taxa were skeletonized. Lower diversity assemblages from mainly offshore and slope deposits in Finnmark (northern Norway), northwestern Canada, the Urals, and Khatyspyt in Siberia are plotted as a subassemblage in Waggoner's analysis (Narbone, 2005);

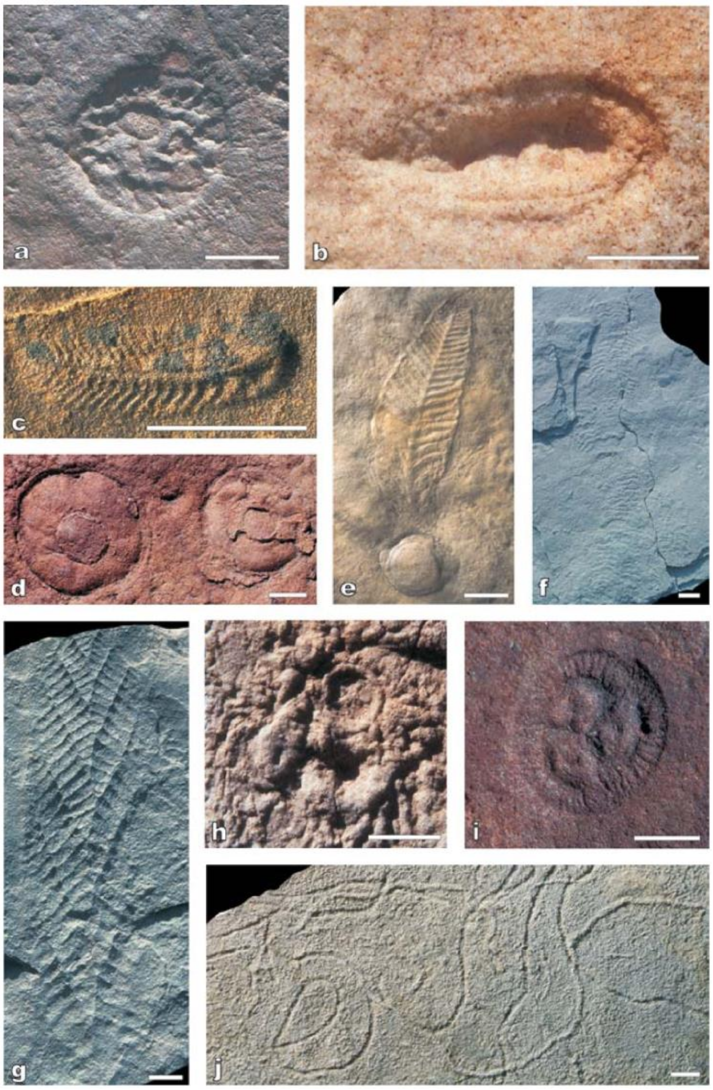


Figure 1. 7. White Sea assemblage preserved on bed soles from Australia (a–e, h–i), northern Russia (f – g), and northwestern Canada (j). Scale bar represents 1 cm (a–c), 2 cm (d, f–j), or 5 cm (e) (extracted from Narbone 2005).

3) The **Nama Assemblage** (Figure 1. 8) is best known from the Kuibis and Schwarzrand subgroups of the Nama Group in Namibia (Gürich, 1933; Germs, 1972; Narbonne et al., 1997; Grotzinger et al., 2000; Grazhdankin & Seilacher, 2002). This type of assemblage is

of shallow-water origin and has been dated as older than 549–542 Ma (Grotzinger et al., 1995), although similar assemblages occur in both older and deeper-water strata elsewhere. The assemblage consists mainly of multifoliate fronds, bilaterian burrows, and early calcifying metazoans (Narbone, 2005).

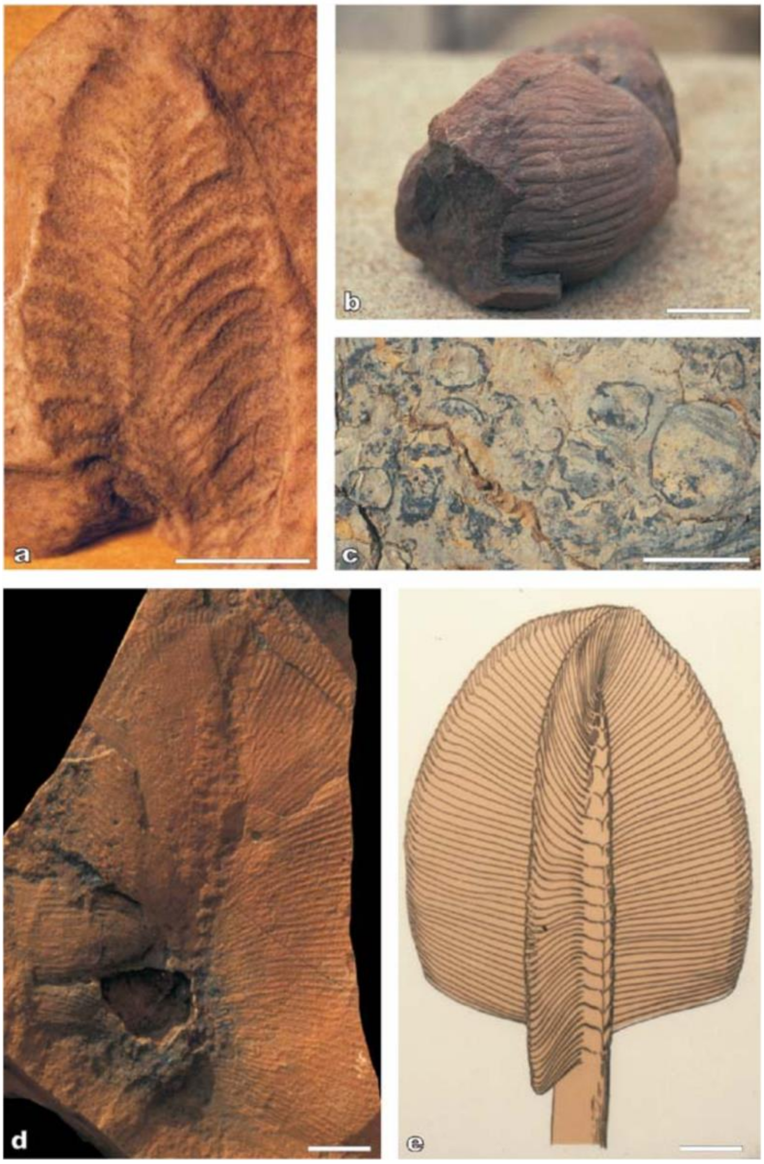


Figure 1. 8. Nama Assemblage fossils from Nambia. Scale bar represents 2 cm. (a) Mold of the holotype of *Rangea*, a rangeomorph frond. (b) *Ernietta* preserved as a natural cast. (c) *Namacalathus*, a weakly calcifying Ediacaran metazoan. (d, e) *Swartpuntia* holotype and reconstruction (extracted from Narbone, 2005).

Regarding biological changes in Ediacaran Period, until 2007, the oldest accepted multicellular fossils were represented by the macrofauna of the Drook Formation Newfoundland, which appeared about 60Ma after the Marinoan glaciation (635Ma) (Hoffman, 2009). However, metazoan embryos were described in the Doushantuo

Formation in South China, c.a 3Ma after the Nantuo glaciation, equivalent to Marinoan glaciation in Southern China (Chen et al., 2009; Hu et al., 2012). This occurrence in Doushantou Formation increased the age of the first well which accepted multicellular metazoa from 580Ma to about 630Ma. Moreover, diagnostic sponge biomarkers, 24-*isopropyl-cholestane,* occur in strata considered to be coeval in the Masirah Bay Formation, representative of post-glacial Marinoan siliciclastic sedimentation in Oman, also constituting evidence of presence of multicellular animals in strata related to post-Marinoan glaciation (Hoffman, 2009; Allen & Leather, 2006) (Figure 1. 9).

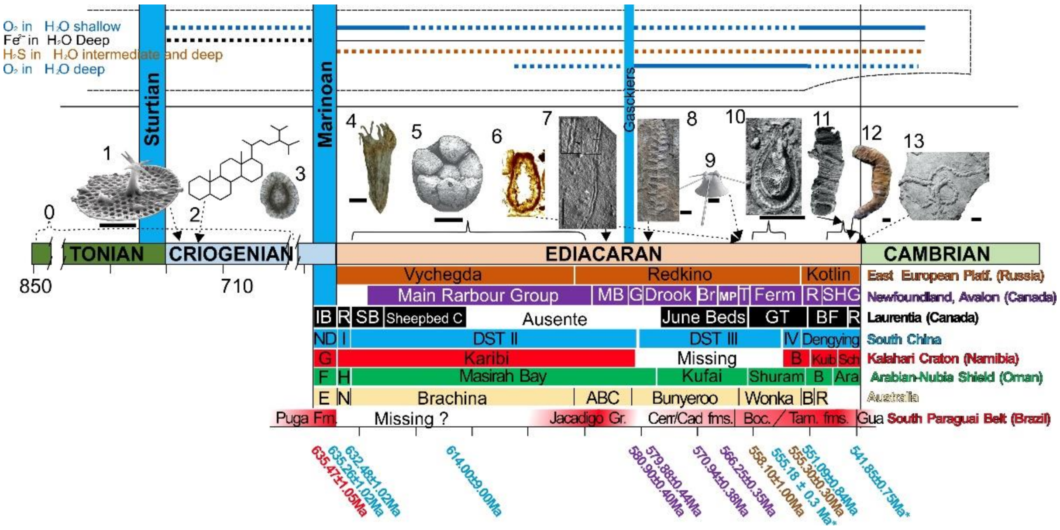


Figure 1. 9. Summary of major changes in ocean chemistry and biotic events through the Neoproterozoic. Major milestones of evolutionary events: 0, Origin of metazoa from molecular clock 850–650 Ma (Dos Reis et al., 2015), 1, 812–717 Ma, Phosphate biomineralization in microfossils, 15 Mile Group, Yukon, Canada (Figure 1a SEM of *Characodictyon*, scale bar (SB)= 2 µm; Cohen et al., 2011); 2, 713 Ma, maximum age of the demospongiae biomarkers (24-isopropylcholestane), Huqf Supergroup, Omã; 3, vase-shaped microfossils (VSM) *Cycliocyrillium simplex*, Urucum Formation, Brazil, ~740Ma (Morais et al., 2017; 2019); 4, 635–590 Ma, possible Cnidarian stem-group *Lantianella laevis*, preserved in black shale of the Lantian Member II SB = 3 mm (Yuan et al., 2011); 5, Phosphatized embryos Doushantuo members II and III Weng'na section, SB = 200 µm (Xiao et al., 1998); 6, VSM from Bocaina Formation (Moraes, 2013, 2017); 7, Older evidence trace fossil caused by the mobility of Bilateria, Tacuarí Formation, Uruguay, SB=2.5 mm (>585 ± 3.3 Ma) (Pecoits et al., 2012); 8, Mistaken Point biota, *Fractofusus misrai*, Drook Formation (>578.8 ± 1 Ma), =20 mm (Liu et al., 2015); 9, sponge spicules and "Multi-elements" metazoan, *Coronacollina acula*, Ediacara member, Austrália SB =~5 mm (equivalent to the White Sea assemblage, (~560–550 Ma) (Clites et al., 2012); 10, ~558–555 Ma, Motile bilateralian *Kimberella quadrata,* SB=10 mm (Fedonkin et al., 2007; Martin et al., 2000); 11, ~550 Ma, Biomineralizing metazoan reef bielders, *Cloudina* (Penny et al., 2014), SB=200 µm (Bengtson & Zhao, 1992); 12, metazoan *Corumbella werneri* assembled with *Cloudina lucianoi* from Tamengo Formation, Brazil (* indicates ash bad dated from base and top of the Tamengo Formation (Parry et al., 2017). 13, *Treptichnus pedum* which marks the Ediacaran/Cambrian boundary in the Global Boundary Stratotype Section and Point GSSP in Fortunehead, Newfoundland (Wilson et al., 2012), figure modified from Bowyer et al. (2016).

1.2. UPPERMOST EDIACARAN STRATA IN SOUTH AMERICA

South America has an important geological record of Neoproterozoic sedimentary rocks. The main sections of upper and uppermost Ediacaran in South America are present in four countries: Brazil (Corumbá Group, Bambuí Group, Pajucá Formation and Camarinha Formation), Uruguay (Arroyo del Soldado Group), Paraguay (Itapucumi Group); Argentina (Grupo Sierras Bayas) (Figure 1. 10).

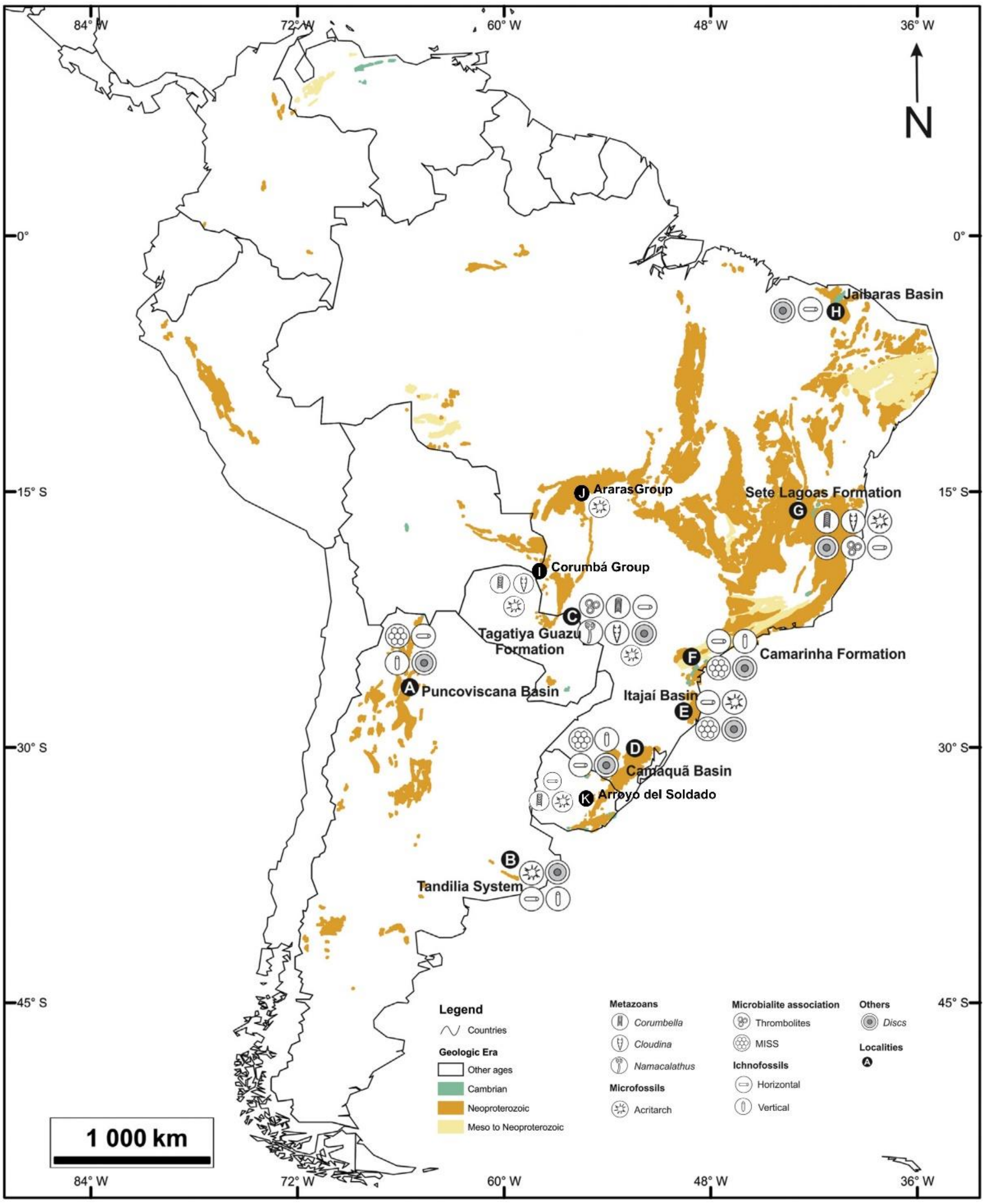


Figure 1. 10. Map of Proterozoic to Cambrian geologic units of South America highlighting the occurrence of discoidal structures, metazoans, microfossils and other main paleontological components. A – Puncoviscana Basin (AR); B – Tandilla System, La Providencia Group (AR); C – Itapucumi Group (PY); D – Camaquã Basin, Santa Barbara and Bom Jardim groups (BR); E–Itajaí Basin (BR); F – Camarinha Basin (BR), G – Bambuí Group (BR); H – Jaibaras Basin (BR); I – Corumbá Group (BR); J – Araras Group (BR); K – Arroyo del Soldado Group (UY) (modified from Inglez et al., 2019).

1.2.1. CORUMBÁ GROUP, BRAZIL

In South America, the lithostratigraphic interval that best represents the paleoclimatic, biochemical and biological evolution of the Ediacaran period is the Corumbá Group in the State of Mato Grosso do Sul, Midwestern Brazil (Boggiani et al., 2010; Adôrno, et al., 2017). The Corumbá Group rests on the glacial-marine sedimentary rocks of the Puga Formation, consisting of five formations: Cadiueus, Cerradinho, Bocaina, Tamengo and Guaicurus. The Cadiueus Formation is represented by conglomerates and arches deposited in proximal environments. The Cerradinho Formation is composed of a siliciclasic succession that gradually passes to the carbonates of the Bocaina Formation. The Bocaina Formation consists of a thick package of stromatolytic dolomites with lateral variations of facies, including occurrences of phosphorites with more than 34% of P_2O_5 (Boggiani et al., 1993; Boggiani, 1998). The Tamengo Formation lies above the Bocaina Formation, represented by black limestones, rich in organic matter where it occurs *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Corumbella werneri* Hahn et al., 1982 and *Paraconularia* sp. (Van Iten et al., 2014, 2016). Capping all carbonate and siliciclastic sequence of the Tamengo Formation lies the siltstones and shales of the Guaicurus Formation, marking the end of the deposition of the Corumbá Group (Gaucher et al., 2003; Boggiani et al., 2010) (Figure 1. 11).

In terms of paleoenvironmental conditions, the Tamengo Formation was deposited in a favorable environment for deposition of carbonates, which was episodically interrupted by immature siliciclastic supply from very finegrained rocks of a nearby source area. The Guaicurus Formation, on the other hand, is a result of an uninterrupted immature siliciclastic supply from a nearby source area, composed of very fine-grained rocks. Chemical variations, however, are observed especially in Na_2O content, higher in siltstones from the Guaicurus Formation, implying changes in the source area or in the chemistry of the water. The sediments of the Guaicurus Formation were deposited under a low energy setting in a high water level, below fair-weather wave (Fazio et al., 2019).

Several works have been produced on the palaeontology of the Corumbá Group (Beurlen & Sommer, 1957; Fairchild, 1978; Hahn et al., 1982; Walde et al., 1982; Zaine & Fairchild, 1985; Zaine 1991; Hidalgo, 2002; Gaucher et al., 2003; Becker-Kerber et al., 2013; Tobias, 2014; Pacheco, 2012; Leme et al., 2008; Pacheco et al., 2011; Walde et al., 2015; Adôrno et al., 2017; Van Iten et al., 2014, 2016; Parry et al., 2017), also on the stratigraphy and tectono-structural evolution (Barbosa, 1949; Almeida, 1964, 1965, 1984; Alvarenga & Trompette, 1992; Boggiani & Alvarenga, 2004; Gaucher et al., 2003; Babinski et al., 2008; Boggiani et al., 2010; Meira, 2011; Spangenberg et al., 2014; D'el-Rey et al., 2016; Sial et al., 2016); and finally on the sedimentological context (Boggiani et al., 1993; Boggiani, 1998; Oliveira, 2010; Campanha et al.,, 2011; Fontanela, 2012; Fazio et al., 2019).

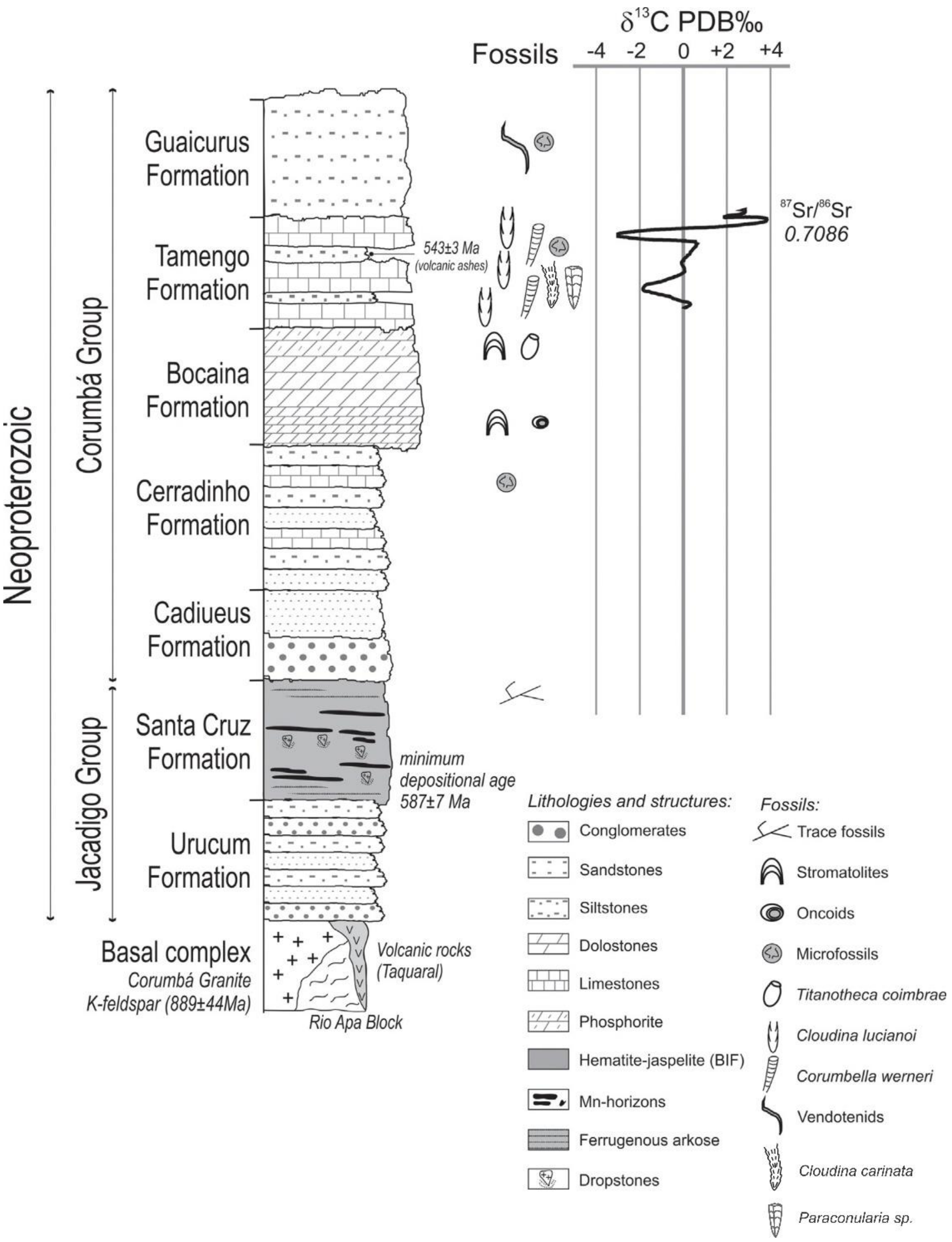


Figure 1. 11. Stratigraphic scheme of Jacadigo and Corumbá groups with fossil record and the 13C isotopic curve. Note the strong negative incursion (After Walde et al., 2015).

1.2.2. ARROYO DEL SOLDADO GROUP, URUGUAY

The Arroyo del Soldado Group was defined by Gaucher et al. (1996) being constituted by 5,000 meters of thickness of platform marine sediments occurring in the field Nico Pérez, Uruguay. The Arroyo del Soldado Group consists of four formations from the base to the top: Yerbal Formation, Polanco Formation, Barriga Negra Formation and Cerro Espuelitas Formation. Yerbal Formation, composed of conglomerates and arkoses at the base, passing to green siltstones and laminated siltstones at the top, representing a siliciclastic sequence of ascending *deepening-upward* (Gaucher et al., 1998; Gaucher & Sprechmann, 1999; Gaucher, 2000; Gaucher et al., 2003). The Yerbal Formation is succeeded by the Polanco Formation, composed of calcitic and dolomitic rhythmites of blue to black coloration, with frequent tempestites and rare oolitic calcarenites, marking the beginning of sedimentation in a carbonaceous ramp.

The west region of the basin corresponds to the shallower portions, in these localities, the carbonates of the Polanco Formation are capped by conglomerates and arkoses of the Barriga Negra Formation. The Black Belly Formation gradually passes to shales and siltstones of the basal portion of the Cerro Espuelitas Formation (Gaucher et al., 2003). To the east is located the deeper portion of the basin, in this locality, the Polanco Formation gives rise directly to the sediments of the Cerro Espuelitas Formation (Gaucher & Sprechmann, 1999; Gaucher et al., 2000).

Gaucher et al. (2003) presents a first attempt to correlate the Corumbá and Arroyo del Soldado groups, presenting the stratigraphic distribution of organic-walled microfossils, biomineralized fossils and ichnofossils that were described in these two groups. There is still a significant difference between the density of paleontological information of the sections from Brazil and Uruguay, the section of the Corumbá Group has fewer and less precise data with regard to stratigraphic distributions of the fossil occurrences (Figure 1. 12).

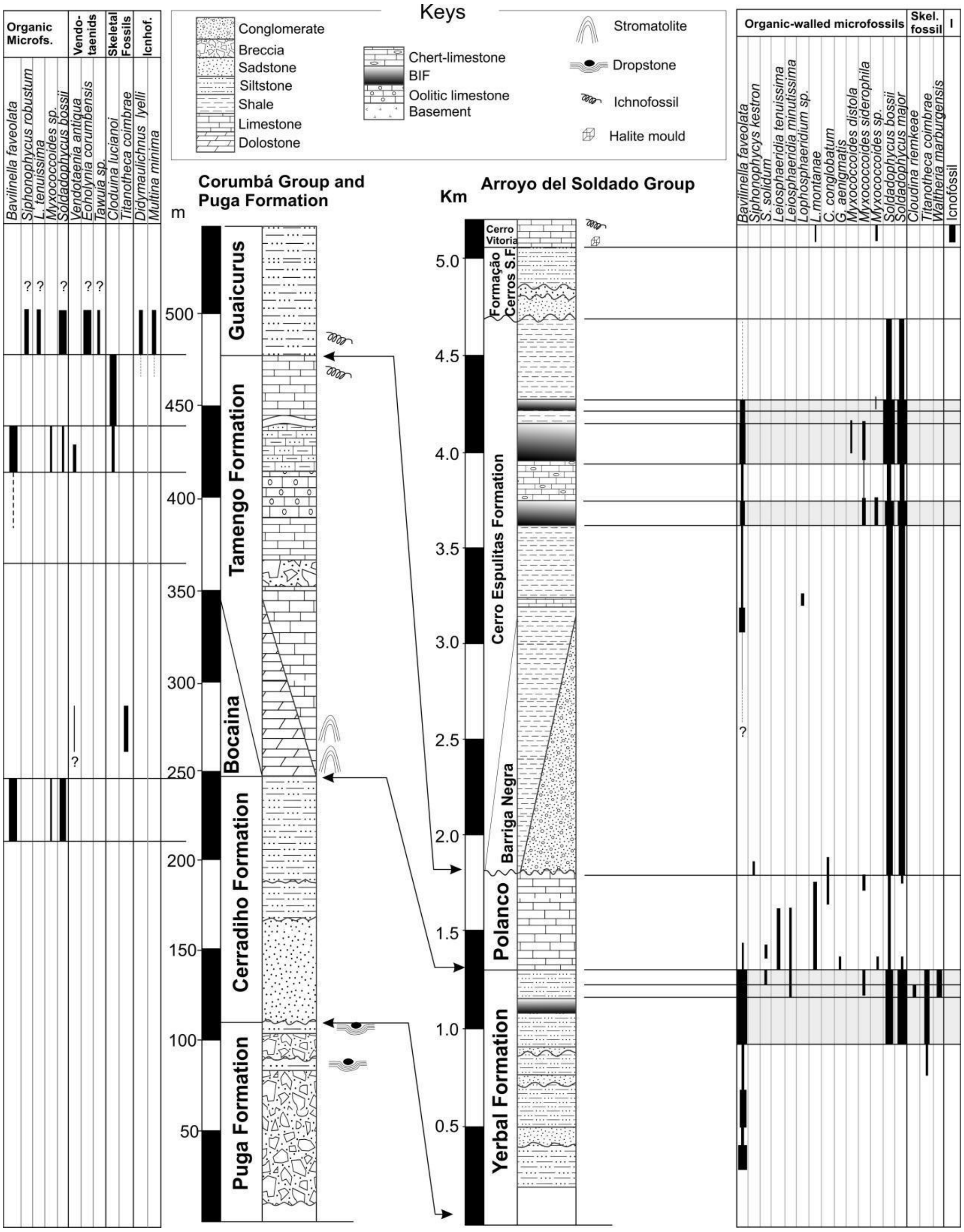


Figure 1. 12. Composite stratigraphic columns for the Corumbá and Arroyo del Soldado groups, showing a correlation between the lithostratigraphic units and the stratigraphic distribution of the taxa of palynomorphs, calcifying metazoan and ichnofossil (modified from Boggiani, 1998; Gaucher, 2000; Gaucher et al., 2003, with the paleontological updates of Parry et al., 2017).

1.2.3. SIERRAS BAYAS GROUP AND CERRO NEGRO FORMATION, ARGENTINA

In the Chillar-Olavarría area, the Sierras Bayas Group and the Cerro Negro Formation represent a sequence of sedimentary rocks composed of lithostratigraphic units limited by erosive discordances at the base and at the top (Poiré, 1987, 1993; Iñiguez et al., 1989; Cingolani & Dalla Salda, 2000; Zalba & Andreis, 2003; Gaucher et al., 2005b).

The Sierras Bayas Group consists of three formations, from the base to the top: Villa Mónica Formation, Cerro Largo Formation, and finally, the Loma Negra Formation. Villa Mónica Formation is constituted of sandstone at the base and stromatolitic limestones at the top. The Villa Mónica Formation has thin-walled sphaeromorph acritarchs microfossils described by Gaucher et al. (2005b); Cerro Largo Formation constitutes diamictites and pelites in the base passing to the sandstone in the intermediate portion and by pelite at the top. The microfossiliferous record of Cerro Largo Formation consists of sphaeromorphic acritarchs described by Pothe de Baldis et al. (1983) and updated by Gaucher et al. (2005b); finally, the Loma Negra Formation closes the depositional cycle of the Sierras Bayas Group, being constituted by organic matter rich limestone and levels of concentration of sedimentary phosphate where possible *Cloudina lucianoi* also occurs, previous classified as *Cloudina riemkeae* by Gaucher et al. (2005b). The Sierras Bayas Group is capped by pelite, marls and layers with heterolytic stratification. The Cerro Negro Formation has acritarch microfossils described by Cingolani et al. (1991). The stratigraphic distribution of the fossils present in the Sierras Bayas Group is presented by Gaucher et al. (2005b) (Figure 1. 13).

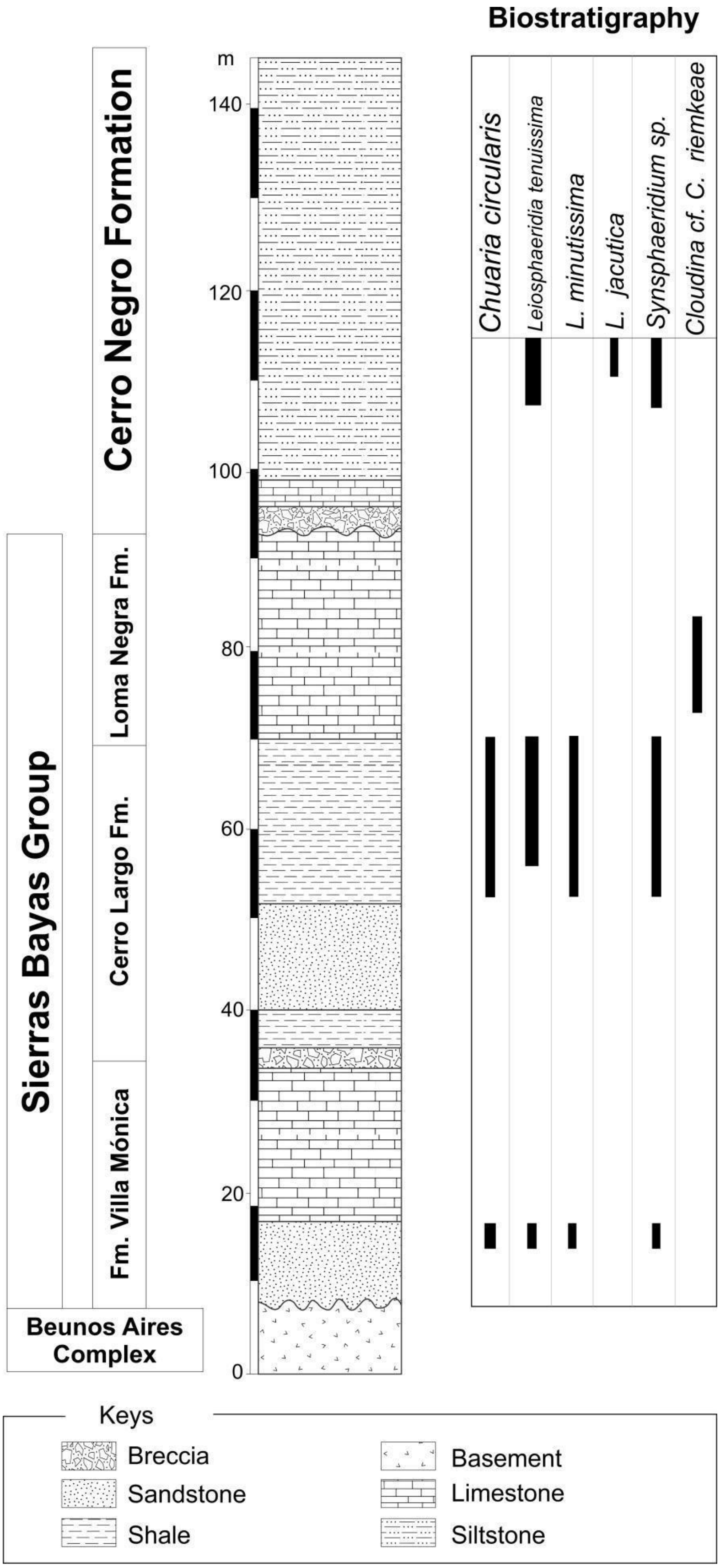


Figure 1. 13. Stratigraphic column for the Sierras Bayas Group and Cerro Negro Formation, Uruguay, presenting the stratigraphic distribution of the fossils and microfossils (Modified from Gaucher et al., 2005b).

1.2.4. ITAPUCUMI GOUP, PARAGUAY

The Itapucumi Group, northern Paraguay, has recently received considerable attention due to the occurrence of its remarkable uppermost Ediacaran skeletal fossil assemblage in carbonates of the Tagatiya Guazu Formation (Warren et al., 2011; 2012; 2013; 2019). The Itapucumi Group crops out in the Rio Apa Block, parallel to the course of the Paraguay River. This group consists of three formations from the base to the top: Vallemi Formation, consisting of sandstones and siltstones that gradually pass to limestones and dolomites of the Camba Jhopo Formation, culminating in pelites and dolomites of the Cerro Curuzu Formation. The Tagatiya Guazu Formation is considered the cratonic lateral equivalent of the Camba Jhopo Formation, which is in the Vallemi fold belt (Warren, et al., 2011; 2012; 2019) (Figure 1. 14).

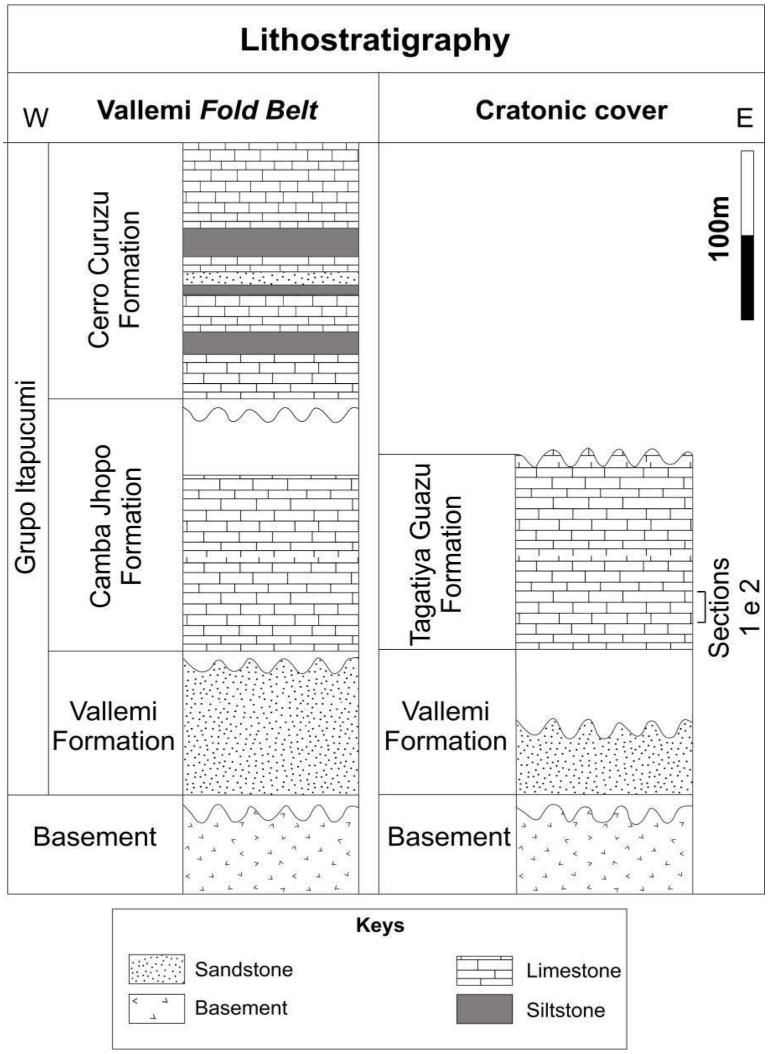


Figure 1. 14. Lithostratigraphic sections of the Itapucumi Group, Ediacarano, Northeast of Paraguay (modified from Warrem et al., 2011).

The Itapucumi Group has special relevance because it contains fossil assemblages shared with those of the Corumbá Group, making studies of biostratigraphic correlation between the sections of Brazil and Paraguay possible. The stratigraphic distribution of *Cloudina lucianoi* and *Corumbella werneri* in the Itapucumi Group presented by Warren et al. (2011; 2019) was used to extend the biozones proposed from the Tamengo Formation to the sections of Paraguay (Adôrno et al., 2017). For more detail, see the chapter on biostratigraphy.

1.2.5. SETE LAGOAS FORMATION, BAMBUÍ GROUP

The Bambuí Group is a north-south trending basin that covers hundreds of thousands of square kilometers in the states of Minas Gerais, Bahia, Goiás and Tocantins in east-central Brazil. The lithostratigraphic column most diffused in the literature was proposed by Dardenne (1978), in which the Bambuí Group is divided from the bottom up into the five formations, overlying rocks of the Macaúbas Group and Jequitaí Formation and the Carrancas conglomerate, units supposedly deposited during Sturtian glaciation. The Bambuí Group is 700–1000 m thick (Misi et al., 2007) and comprises: 1) Sete Lagoas Formation, composed of dolomites, limestone and pellets with well preserved stromatolites; 2) Serra de Santa Helena Formation, formed by shales, siltstones and secondarily sandstones; 3) Lagoa do Jacaré Formation by siltstones, marl and black limestones; 4) Serra da Saudade Formation, which includes green shales, pelites, siltstones and limestone lenses; 5) Três Marias Formation, which occupies the top of succession comprising siltstones and arcuate deposited in environments alluvial to shallow marine (Figure 1. 15). These five units make up two cycles of carbonic sedimentation (Vieira, 2007; Warren et al., 2014; Paula-Santos et al., 2017).

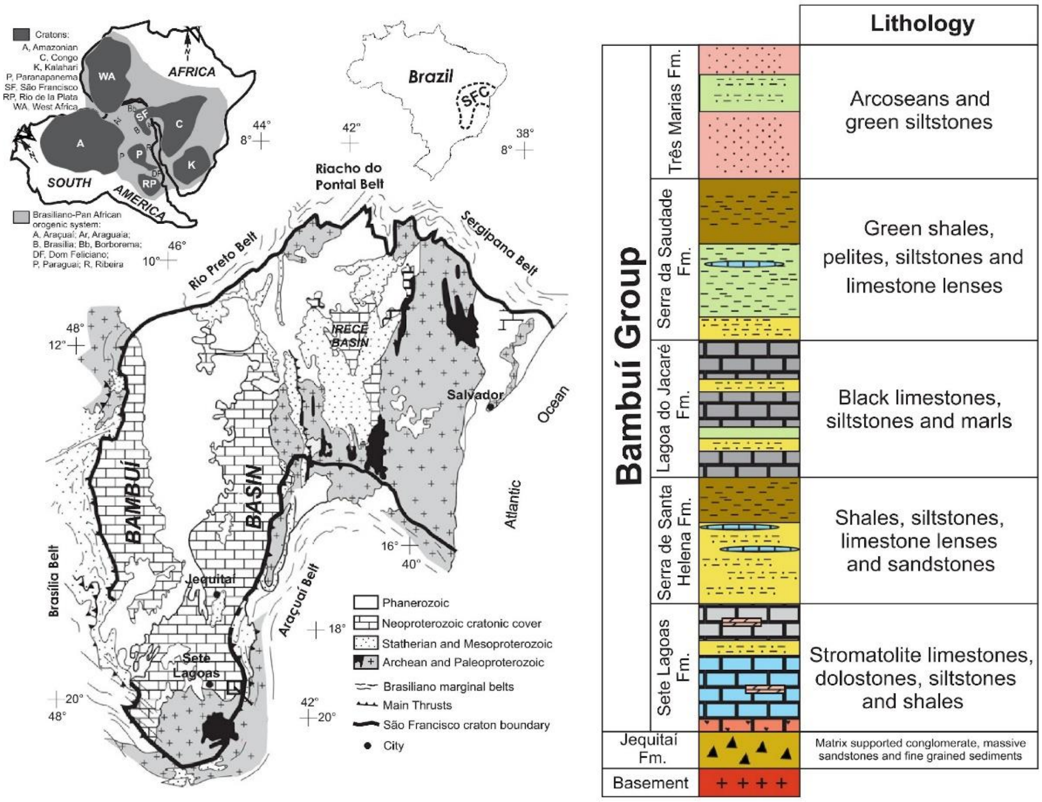


Figure 1. 15. Geological map of São Francisco craton with the paleogeographic reconstruction of West Gondwana (modified from Alkmim et al., 2006) and stratigraphic column of the Bambuí Group (extracted from Paula-Santos et al., 2015).

The age of the Bambuí Group is under debate since the investigation on Bambuí Group has started. Several attempts of direct dating of the rocks of the Bambuí Group by the Pb-Pb and U-Pb methods were not successful. A ^{207}Pb/^{206}Pb isochronous 686 ± 69 Ma was obtained by Babinski et al. (1999) in the Sete Lagoas Formation. The presence of *Conophyton* sp., silicified microbial mats, rare fossilized algal phytolites and microphytolites, and other long-ranging microfossils, such as coccoid and filamentous cyanobacteria (Fairchild et al., 1996), do not contribute to accurate age determination (Nobre-Lopes & Coimbra, 2000; Warren et al., 2014). Almost all radiometric ages on Bambuí Group and their considered lateral equivalents, fall in the range of 700 to 450 Ma (see Trompete, 1994). The apparent absence of key index fossils has led to several attempts to determine the age of Bambuí Group and related units based on geochronologic and isotopic methods (Misi et al., 2007; Babinski et al., 2007). It is currently been suggested that the Bambuí Group is entirely Neoproterozoic in age, ranging from the late Tonian to the early Ediacaran.

The description of *Cloudina* sp. and *Corumbella* sp. in the Sete Lagoas Formation in Januaria region indicates an even younger age for the base of Bambuí Group, possible latest Ediacaran (Warren et al., 2014, Paula-Santos et al., 2015, 2017; Perrella-Júnior et al., 2017; Uhlein et al., 2017; Caixito et al., 2018). In addition, new dates of detrital zircon suggest a maximum age of deposition of the Sete Lagoas Formation around 557 Ma (Paula-Santos et al., 2015). However, all *Cloudina* specimens illustrations published so far, are not clear, and the taxonomy is always open, making it difficult for additional interpretations based on this important finding.

Denezine (2018) performed a detailed study at Januaria region focused on the organic-walled microfossil assemblage. The Sete Lagoas Formation in the Santa Luzia quarry at Januaria was fitted into the *Leiosphaeridia jacutica* - *Leiosphaeridia crassa* Assemblage Zone. *Leiosphaeridia jacutica* - *Leiosphaeridia crassa* Assemblage Zone is characterized by the appearance of *Leiosphaeridia jacutica* together with three other species *Leiosphaeridia crassa, Leiosphaeridia minutissima* and *Leiosphaeridia tenuissima*. The top of this biostratigraphic unit has been attributed to Mid-Ediacaran, ~ 580 Ma, and marked with the impact of Acraman (Denezine, 2018). The base of this zone has been tentatively positioned in 587 Ma (Gray, 2005). Considering the issue regarding the age of Bambuí Group, this group was not included in the comparation for evading the purpose of the present research.

1.3. UPPERMOST EDIACARAN STRATA IN ÁFRICA

Sections of the African continent have their paleontological content intensively studied, since Germs (1972) described *Cloudina hartmanae* (currently considered synonym of *Cloudina lucianoi*) and *Cloudina riemkeae* from the limestones of the Nama Group. Three lithostratigraphic units are the most important for the study of fossils of the uppermost Ediacaran of Africa: The Cango Caves Group and the Port Nolloth in South Africa and Nama Group in Namibia (Gaucher et al., 2005a).

The Port Nolloth Group is represented by three depositional megasequences (M1-M3) (Frimmel et al., 2002). The Stinkfontein Subgroup represents the sequence M1, with deposition in alluvial fans in continental rift. The Kaigas Formation occurs along faults that limit the Gariep basin, being represented by discontinuous glacial diamictite lenses interspersed with arches and graviac where olistostromes develop. Based on the negative curves of $\delta^{13}C$ and low ratios of $^{87}Sr/^{86}Sr$, besides the similarity with other sequences of the Neoproterozoic, this glacial event is correlated with the global Sturtian glaciation (Frimmel et al., 2002).

The Pickelhaube Formation is represented by succession of postglacial carbonates interspersed with pellets, loams and sandstones representing the second megasequence M2. The Dabie River Formation represents areas that escaped from erosion and allowed the precipitation of carbonates in the form of stromatolytic bioconstructions and also in the form of oolitic calcarenite. The Numees Formation is located stratigraphically at the top of the M2 megasequence, where sea level fall is observed due to the advance of the glacial event, represented by the deposition of massive packages of diamytites.

The Numees Formation is capped by a thick sequence of carbonate Bloeddrif Member, Holgat Formation that represents the third megasequence M3. Elongated columnar stromatolites of about 2 to 5 cm in diameter occur in Bloeddrif Member. The upper part of the Holgat Formation consists of sandstone, arcoseum and siltstone. Above the three megasequences lies the Nama Group, representing the deposition in a shallow water foraland system whose deposition of the basal portion started around 550Ma, followed by the deposition of molybdenum siliciclastic sediments from the upper portion deposited in 540Ma. In the central and southern part of Namibia, the Nama Group rests discordantly on the crystalline basement, its basal portion is represented by a succession of siliciclastic and carbonate rocks with occurrences of skeletal fossils of *Cloudina lucianoi* and other fossils with calcareous skeletons, as well as ichnofossils and palynomorphs in the Kuibis Formation (Germs, 1995, Gaucher et al., 2005a). The upper portion of the Nama Group is represented by the Schwarzrand Subgroup which contains the ichnofossil Phycodes pedum and *Cloudina* as well as palynomorphs (Germs, 1983; Germs & Gresse, 1991; Gaucher et al., 2005a) (Figure 1. 16).

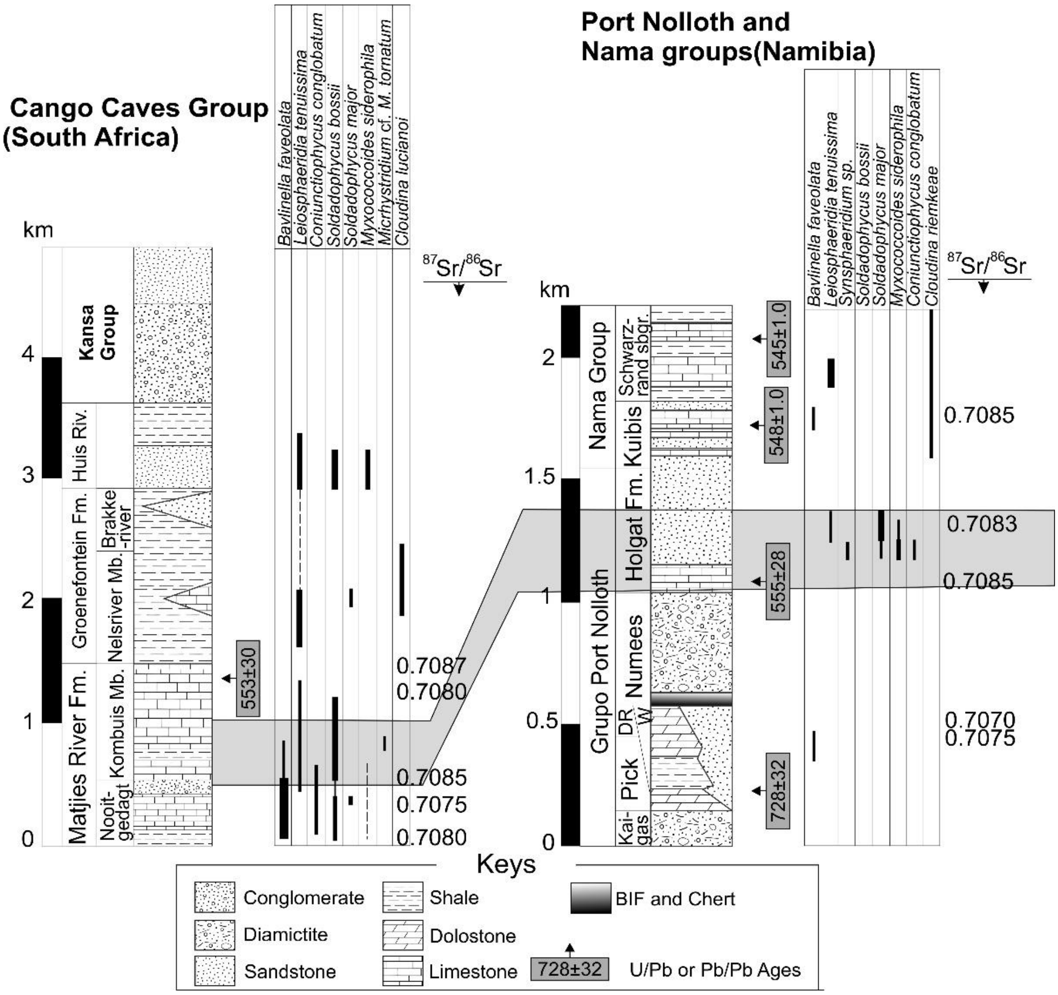


Figure 1. 16. Composite stratigraphic columns for the Cango Caves (South Africa), Port Nollth and Nama (Namibia) groups, showing correlation between the lithostratigraphic units and the stratigraphic distribution of the palynomorphs, mineralized fossil skeletons and ichnofossils (modified from Gaucher et al., 2005a).

1.4. UPPERMOST EDIACARAN STRATA IN CHINA

The Doushantuo Formation (635-551 Ma) in southern China is one of the most heavily studied Ediacaran lithostratigraphic units in the World, with recordings of exceptionally well preserved fossils (Yuan et al., 2002; Chen, 2005, Jiang et al., 2011). There are several localities where it is possible to access Ediacaran sections along the Yangtze platform, the most well-known locality is the area called Gorges area in southern

China which represents one of the most important locations for studying successions of Ediacaran.

The investigation of the Ediacaran sections of China began with the works of Lee (1924) who developed research at the Yangtze Gorges area, later chosen as the standard locality for the Sinian System. In 2002, the Sinian System was redefined to include only the Doushantuo and Dengying formations (*China Commission on Stratigraphy*, 2002). The lower limit of the Sinian System is positioned at the base of the carbonate layer, in contact with the top of the diamictite of the Nantuo Formation (local representative of the Marinoan glaciation), the top of this system was defined by the appearance of the first association of small shelly fossil of the Cambrian, namely, *Anabarites trisulcatus-Protohertzina anabarica* that appears in the Yanjiahe formation that also contains other groups of small shelly fossil such as the microfossils *Asteridium-Comasphaeridium-Heliosphaeridium* (Chen, 1984; Steiner et al., 2007; Dong et al., 2009; Jiang et al., 2012). Radiometric dates U/Pb in ash beds interspersed at the base of the Dengying Formation allow to position geochronologically, the deposition of this formation between 551 Ma and 541 Ma (Condon et al., 2005; Chen et al, 2014).

The Dengying Formation lies above the Doushantuo Formation, being constituted at the base by the Hamajing, Shibantan, and Baimatuo members and their equivalent in other areas in China. The Hamajing Member consists of dolomites deposited in a tidal environment, with features of karsification; Shibantan member consists of black limestone and dark ash and bituminous, deposited in a marine environment; and the Baimatuo Member is made up of clear and massive dolomite deposited in a tidal environment. Ichnofossils have been recorded in the Shibantan Member (Zhao et al., 1988; Weber et al., 2007), as well as macroscopic fossils similar to those of Ediacaran *Paracharnia* sp. (Sun, 1986) and *Yangtziramulus* sp. (Xiao et al., 2005; Shen et al., 2009) and the macroscopic algae *Vendotaenia antiqua* (Zhao et al., 1988; Shen et al., 2009) (Figure 1. 17).

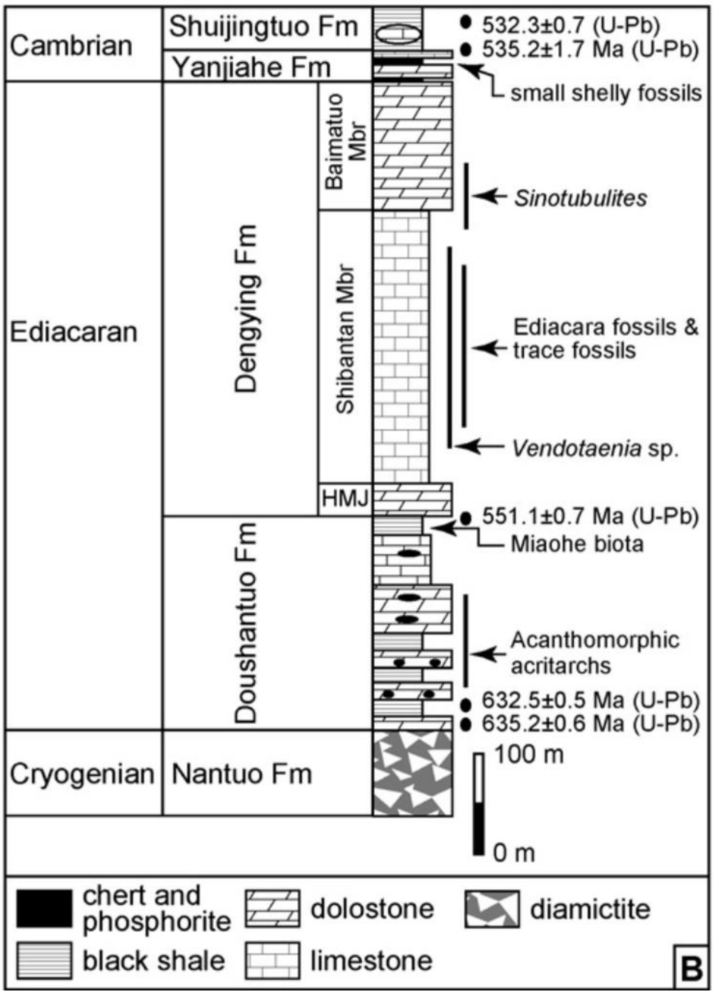


Figure 1. 17. Stratigraphic column for the Doushantuo and Dengying formations, showing the main associations of fossils and radiometric dating available (from Chen et al., 2013).

Sinotubulites species have been recorded in the lower portion of the Baimatuo Member of the Dengying Formation, Southern China (Zhao et al., 1988). In the Shaanxi region of southern China, strata equivalent to that of the Shibantan and Baimatuo members of the Dengying Formation also contains tubular fossils such as *Shaanxilithes*, *Conotubus*, *Gaojiashania*, *Sinotubulites*, and *Cloudina* (Grant, 1990; Hua et al., 2003, 2005; Chen et al, 2008;. Cortijo et al, 2009; Cai et al, 2010, 2011, 2012; Meyer et al, 2012).

1.5. UPPERMOST EDIACARAN STRATA IN THE USA

In the southwestern Great Basin, the Ediacaran-Cambrian boundary occurs within a 1 km-thick, northwestward-thickening siliciclastic-dominated succession of miogeoclinal sediments (Prave et al., 1991) that records the development of a passive margin along southwestern Laurentia (Stewart, 1982). In this region, the Stirling Quartzite is divided into five informal members (A through E) and the Wood Canyon Formation is divided into lower, middle, and upper members (Stewart, 1970, Hagadorn & Waggoner, 2000; Smith et al., 2017). The upper Stirling is a medium to coarse quartz arenite that interfingers with, and is conformably overlain by, the lower member of the Wood Canyon Formation (Wertz, 1982). The lower and middle members of the Wood Canyon Formation record a shallow marine-continental braidplain transition (Diehl, 1979; Fedo & Cooper, 1990; Fedo & Prave, 1991), with the lower member recording a highstand systems tract consisting of three carbonate-capped parasequences (Prave et al., 1991; Horodyski et al., 1994; Runnegar et al., 1995).

Smith et al. (2017) argued that Ediacaran fossils from the southwestern Great Basin may help constrain regional uppermost Ediacaran-Cambrian biostratigraphy and provide biogeographic links between facies in this region and elsewhere. For these authors, the presence of trace fossils suggest the Uppermost Ediacaran-Cambrian boundary which occurs within or below the upper third of the lower member of the Wood Canyon Formation. Ediacaran soft-bodied and tubular fossils, including the frondlike fossil *Swartpuntia* and tubular, mineralized or agglutinated fossils similar to *Archaeichnium*, *Cloudina*, *Corumbella*, and *Onuphionella* occur in the lowermost Wood Canyon Formation (Figure 1. 18). These fossils occur directly below Lower Cambrian trace fossils, including *Treptichnus pedum*, and confirm the persistence of the Ediacaran biota close to the base of the Cambrian. These faunas may also help strengthen previously proposed correlation schemes between the two main facies belts of the southwestern Great Basin (the Death Valley and White-Inyo facies), because a nearly identical Uppermost Ediacaran-lowest Cambrian succession of faunas occurs in both regions.

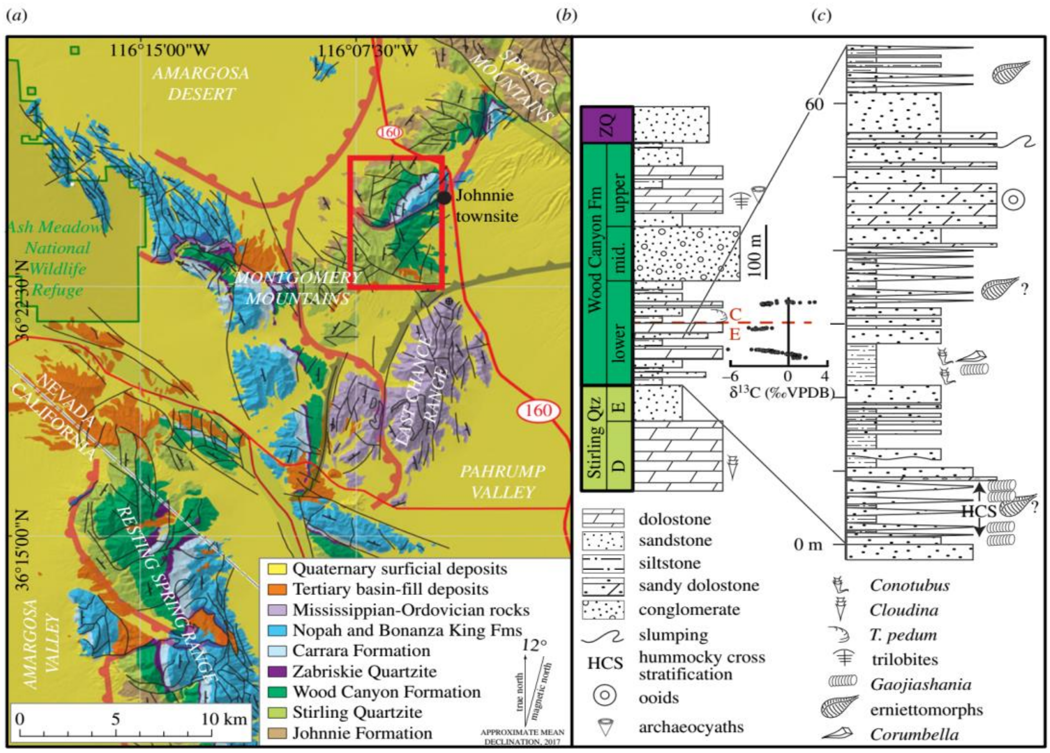


Figure 1. 18. (a) Geologic map of the Montgomery Mountains, Nevada. The fossils and measured sections included in this report are from within the red box near the Johnnie townsite. (b) Generalized regional stratigraphy and biostratigraphy, and carbon isotope chemostratigraphy. Dashed red line marks the Ediacaran–Cambrian boundary. (c) Composite detailed measured section of fossiliferous latest Ediacaran strata of the lower member of the Wood Canyon Fmormation. Fossil horizons are marked on the right-hand side of stratigraphic column (extracted from Smith et al., 2017).

1.6. UPPERMOST EDIACARAN STRATA IN CANADA

The uppermost Ediacaran strata in Canada is represented by biostromes and bioherms which are present in platform margin carbonates in the uppermost part of the Byng Formation, Miette Group, British Columbia. The Byng carbonate platform is exposed in several thrust sheets in the Mount Robson Provincial Park region (Mountjoy, 1980, Hofmann & Mountjoy, 2001). This platform is overlain abruptly by quartz-rich sandstones of the McNaughton Formation (Gog Group), traditionally assigned to the Cambrian (Mountjoy, 1962; Fritz & Mountjoy, 1975; Hofmann & Mountjoy, 2001) (Figure 1. 19).

The most common fossil types are the tubular *Cloudina lucianoi* and *Namacalathus hermanastes*. The biostromal platform carbonate overlies a thick sequence of siliciclastics that carries miscellaneous bedding parallel traces and burrows, particularly *Planolites* and *Helminthoidichnites*, and Ediacaran taxa such as Aspidella and, rarely, Bradgatia (Hofmann & Mountjoy, 1998). The Ediacaran biota is also present in correlative siliciclastics to the southeast (Hofmann et al., 1985, 1991; Hofmann & Mountjoy, 2001).

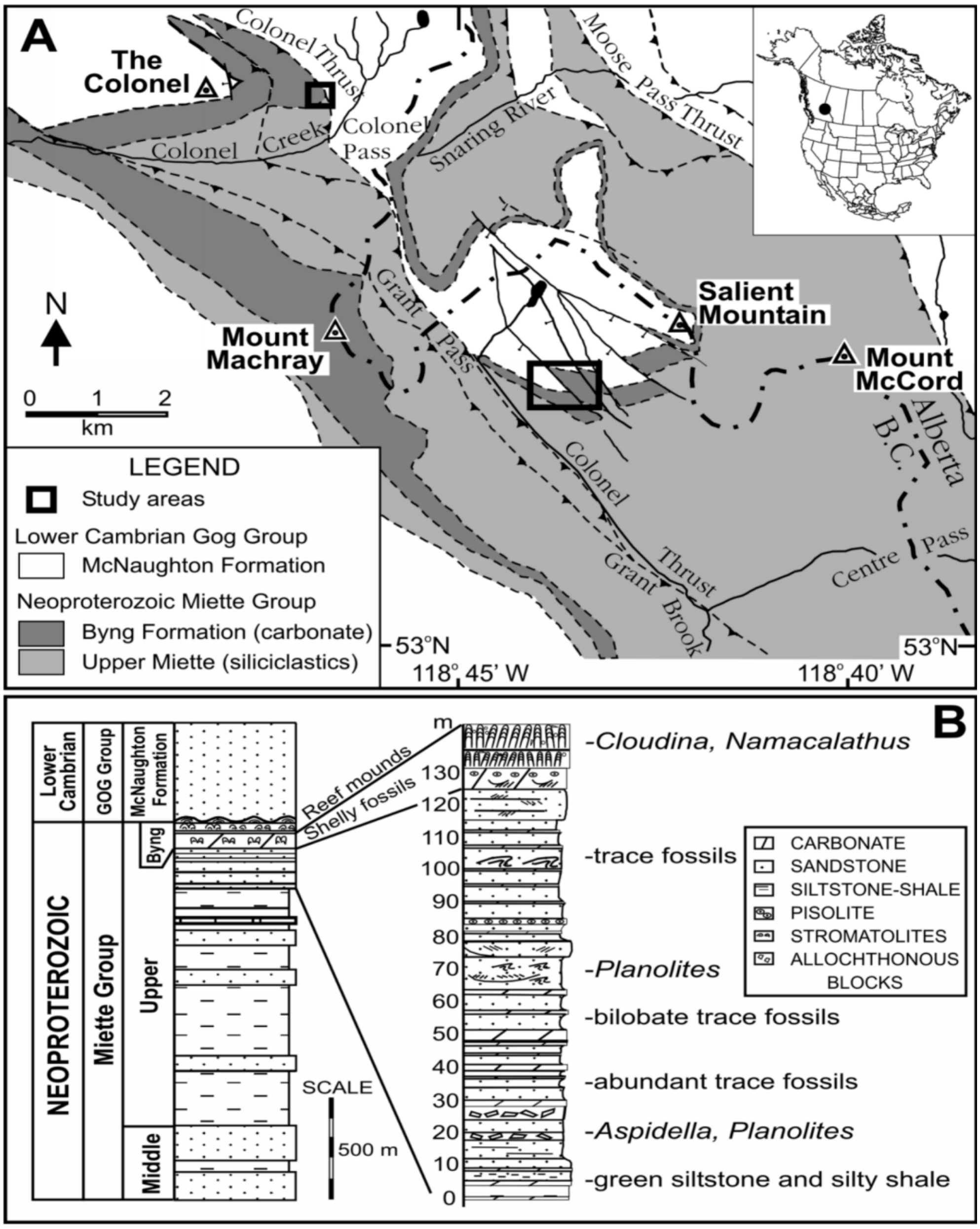


Figure 1. 19. Location of *Namacalathus hermanastes* Grotzinger et al., 2000 –*Cloudina lucianoi* (Beurlen & Sommer, 1957) assemblage in Miette Group, Salient Mountain area, British Columbia. A: Index map and general geologic map, updated from Mountjoy (1980). B: Generalized stratigraphic section (extracted from Hofmann & Mountjoy, 2001).

1.7. UPPERMOST EDIACARAN STRATA IN OMAN

Several sedimentary basins within the interior of Oman were developed on crystalline basement (ca. 800 Ma) and filled with unmetamorphosed strata of the Neoproterozoic to Cambrian Huqf Supergroup (Mattes & Conway-Morris, 1990; Burns &

Matter, 1993; Brasier et al., 1999, Amthor et al., 2003). The Huqf Supergroup comprises synrift volcanic, siliciclastic, and glacio-marine rocks (Ghadir Manquil Formation), siliciclastic and carbonate rocks (Masirah Bay and Shuram Formations), carbonates (Khufai and Buah Formations), and a thick carbonate-evaporite unit (Ara Group) (Amthor et al., 2003).

The record of early animal evolution from Oman includes biomarker evidence for eukaryotic sponges (Demospongiae) from the Abu Mahara Group onwards as well as abundant bacteria and chlorophyte microalgae primary producers (Bergmann, 2013). The Ara Group includes both *Cloudina lucianoi* and *Namacalathus hermanaste*, early calcifying organisms (Amthor et al., 2003) (Figure 1. 20). However, unlike most other late Precambrian records, the Huqf Supergroup does not contain abundant macroscopic Ediacaran fauna. Instead, the Nafun and Ara Groups are dominated by microbially-influenced carbonates including a variety of stromatolite morphologies, crinkly laminite and thrombolite facies (Bergmann, 2013).

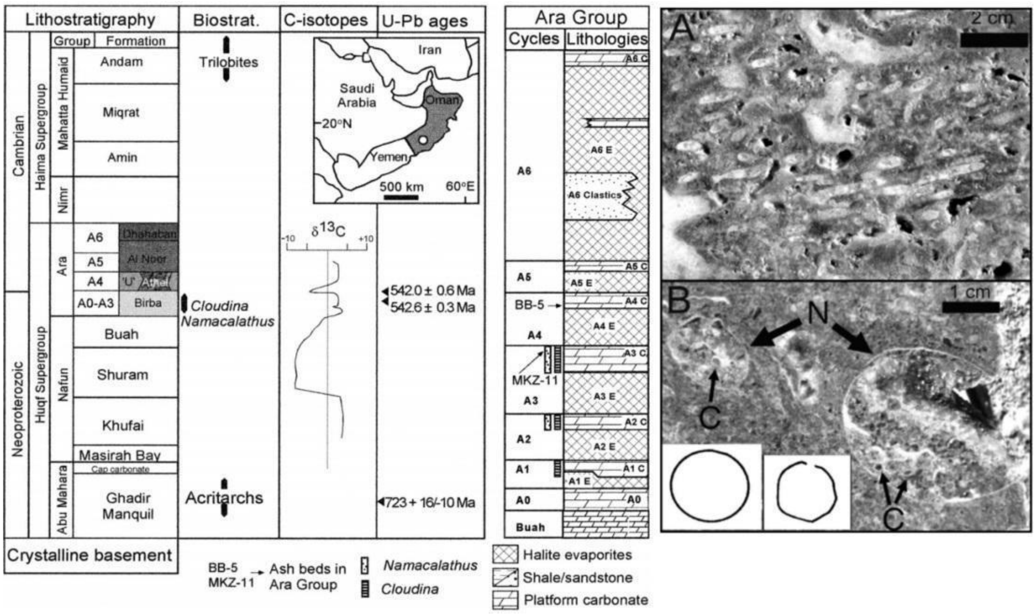


Figure 1. 20. Stratigraphy of Huqf Supergroup. Inset map shows location of subsurface basin in Sultanate of Oman (unfilled circle). Carbon isotope data (‰) for Ara Group derive from this paper; for Nafun Group, see Burns and Matter (1993). Right-hand column shows internal Ara Group stratigraphic subdivisions. Each cycle consists of a lower evaporite (halite and/ or anhydrite) unit and upper carbonate unit. *Cloudina lucianoi* (Beurlen & Sommer 1957) in well-developed thrombolite buildup; B) *Namacalathus hermanaste* Grotzinger et al., 2000 (''N'') in well developed thrombolite buildup (extracted from Amthor et al., 2003).

1.8. UPPERMOST EDIACARAN STRATA IN SIBERIA

It was selected from the Eastern Tomsk region in Siberia, Russia for comparison, based on information from the Borehole BH Vostok-3. The comparation between Corumbá sections and Eastern Tomsk section was possible because of the availability of the fossil distribution presented by Kontorovich et al. (2009) from the studied borehole.

The uppermost Ediacaran strata in Eastern Tomsk region are represented by deposits intercepted in the Borehole called Vostok-3. It is subdivided into three formations: the Poiga, Kotodzha, and Raiga formations (Kontorovich et al., 2009). The Poiga Formation is composed of gray, irregularly recrystallized dolomites in places with well preserved signs of the noncolumnar, dolarenitic, dolosiltitic, and pelitomorphic textures, which characterize the belt of stromatolithic biostromes under conditions of a relatively stable shelf. Overlying deposits of the Kotodzha Formation are represented by gray dolomites (dolarenites recrystallized to different extents, slightly recrystallized pelitomorphic dolomites, noncolumnar stromatolites, and microbiolites), which are interpreted as facies of a carbonate ramp. The Raiga Formation terminating the section of Ediacaran deposits is made of four progressive cyclites from 40 to 130 m thick, each being composed of alternating clastic limestones, micaceous sandstones, siltstones, and mudstones in the lower part, as well as by fine-clastic limestones in the upper part (see Kontorovich et al., 2009).

The latest Ediacaran age of the selected Siberia area was established by the occurrence of microbiolites *Korilophyton* in the lower part of the Poiga Formation, which are regarded as typical for deposits of late Ediacaran age. Deposits of the Kotodzha and Raiga formations comprise a typical latest Ediacaran assemblage with tubular (as nested funnels-within-funnels) calcitic skeletal fossils *Cloudina lucianoi*, goblet-shaped weakly mineralized skeletal fossils *Namacalathus hermanastes*, straight and bent tubular agglutinated skeletal fossils *Platysolenites* and *Spirosolenites*, and carbonaceous fossils *Vendotaenia* and sponge spicules (Kontorovich et al., 2009) (Figure 1. 21).

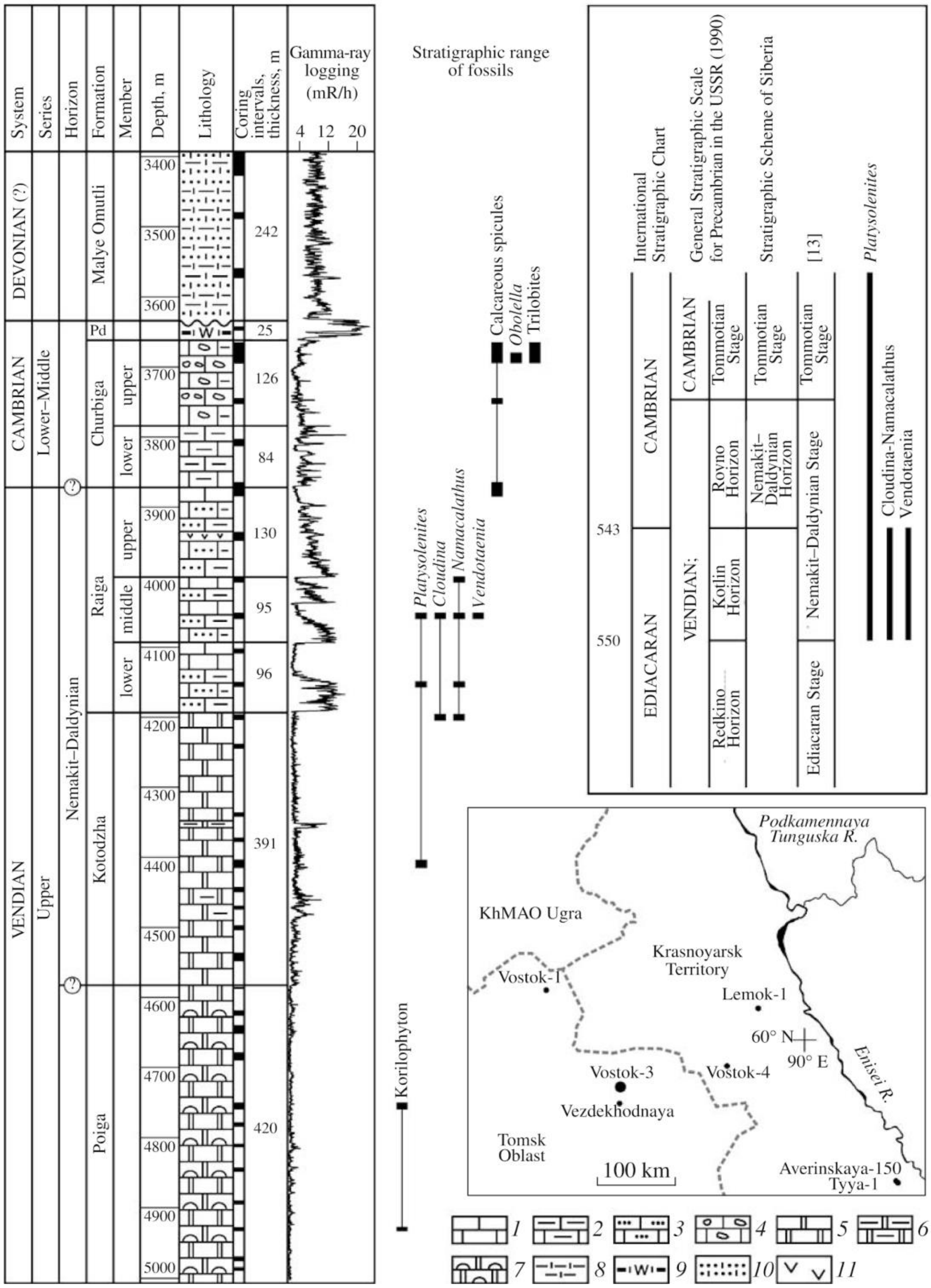


Figure 1. 21. The geological–geophysical section of uppermost Ediacaran and Cambrian deposits in BH Vostok-3, with stratigraphic distribution of fossils. The layout of boreholes penetrated pre-Mesozoic deposits in the southeastern part of the West Siberian geosyncline. Correlation of stratigraphic schemes of Ediacaran–Cambrian boundary deposits (age, Ma). (1) Limestones; (2) clayey limestones; (3) sandy limestones; (4) synsedimentary limestone breccia; (5) dolomites; (6) clayey dolomites; (7) noncolumnar stromatolithic dolomites; (8) mudstones, calcareous silt–mudstones; (9) carbonaceous carbonates, shales and silicites; (10) calcareous sandstones; (11) dolerites. (Pd) Paidugina Formation (extracted from Kontorovich et al., 2009).

CHAPTER – 2: LOCATION AND ACCESS ROADS TO THE STUDY SECTIONS IN BRAZIL

The studied outcrops of Corumbá Group are located in the municipalities of Corumbá, and Ladário Mato Grosso do Sul State, near the border with Bolivia in Midwestern Brazil. The access to Corumbá from Brasília is by the federal road BR-060 passing through municipalities of Goiânia, capital of Goiás State, and then through municipalities of Rio Verde, Jataí and Campo Grande, the capital of the Mato Grosso do Sul State. From Campo Grande, it goes west on federal road BR-262, passing through the municipalities of Aquidauana, Miranda and then Corumbá making a total of about 1500 km from Brasilia.

The access to the outcrops of the Porto Sobramil, Porto Figueiras, Ecoparque da Cacimba and Corcal quarry are within the urban zone of Corumbá. The section of the Laginha quarry is remote and can be accessed following the south by the state road MS-228 about 10 kilometers from Corumbá (
Figure 2. ***1***).

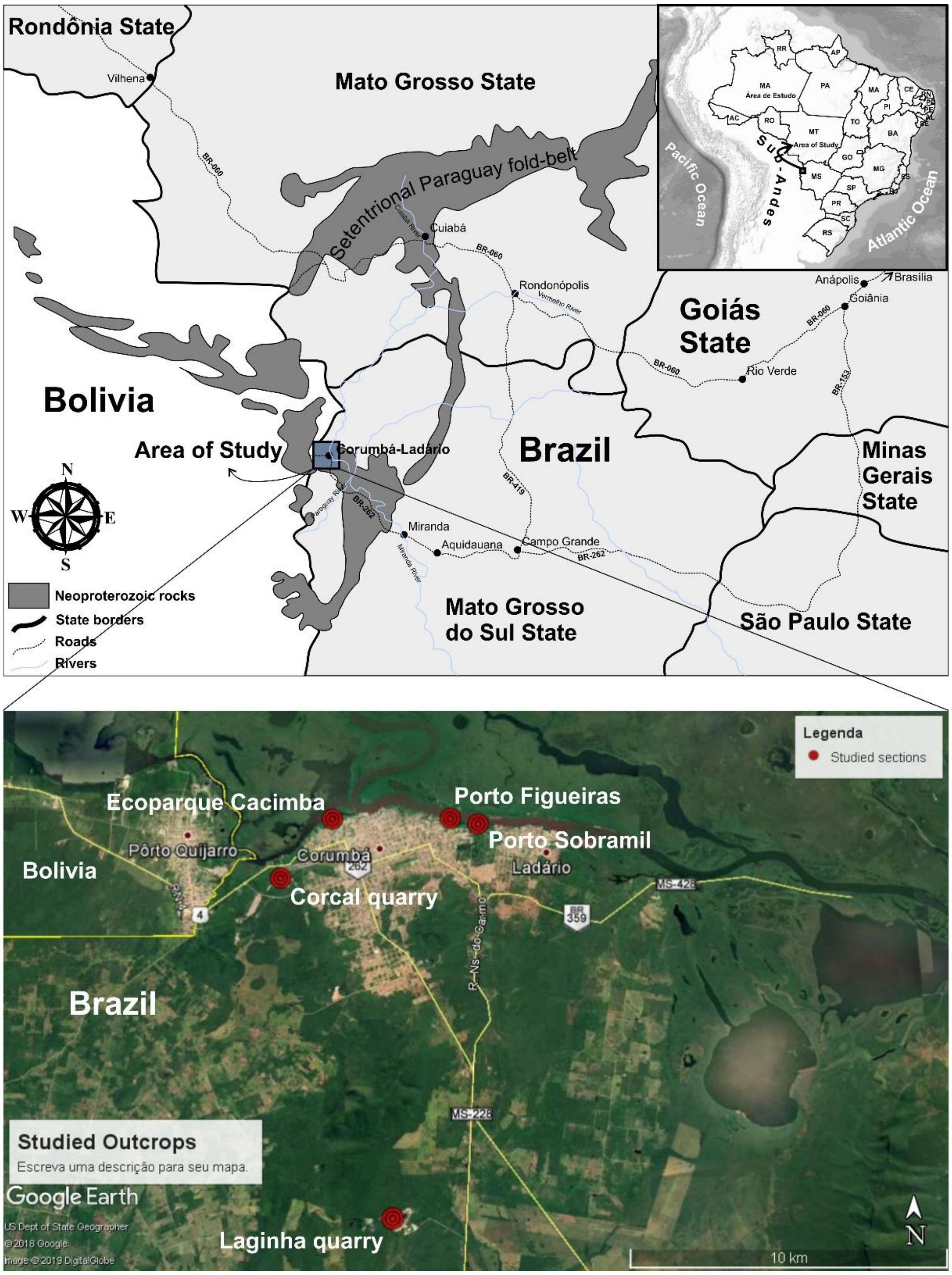


Figure 2. 1. Location of the studied outcrops (sections) in Corumbá region and the main access roads.

CHAPTER – 3: METHODOLOGY

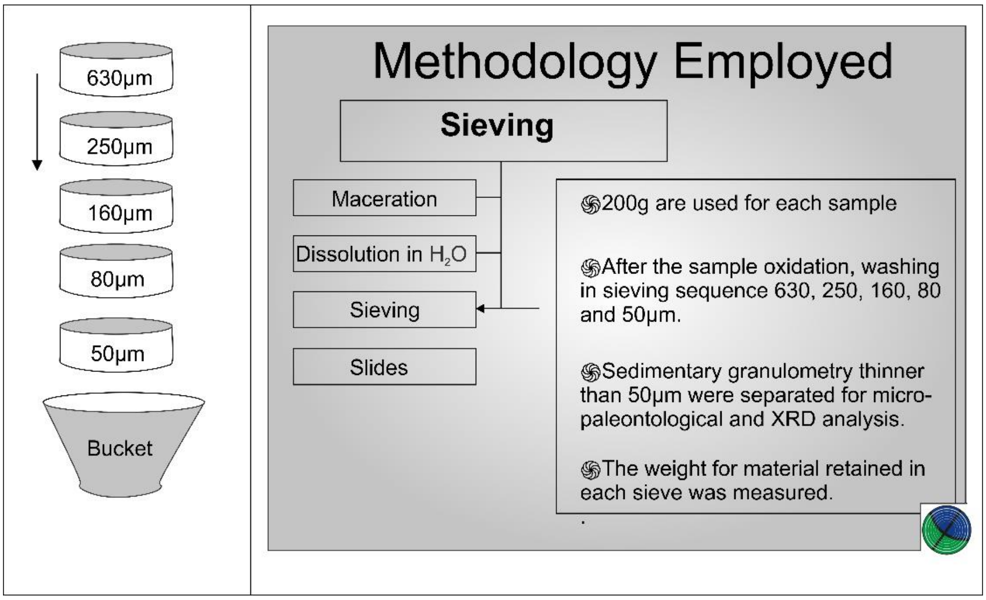
Several fieldworks were carried out in the Corumbá region, Mato Grosso do Sul State. During the fieldwork lithostratigraphic logs were made with positioning of the collected rock samples, always as possible observing the systematic methodology, with regular spacing between each collected sample whenever possible. The studied locations of the Tamengo Formation, Corumbá Group include the outcrops of five main localities: Ecoparque da Cacimba, Corcal quarry, Laginha quarry, Sobramil quarry and Porto Figueiras section.

A total of 544 rock samples were collected from the Corumbá Group, with a focus on the Tamengo and Guaicurus formations material. From the total, 389 samples are from the Tamengo Formation and 155 from the Guaicurus Formation. All samples, specimens and slides were housed in the collection of the UnB micropaleontology laboratory on MP-prefix, with each organic maceration extract, screening residue, and palynological slides also carrying the MP- number of the respective sample of origin and CP- that represents the internal number of the research collection of the Museum of Geosciences at UnB.

The record of all macrophossiliferous occurrences was indicated in the lithostratigraphic logs and include *Cloudina lucianoi*, *Corumbella werneri* in the Tamengo Formation and ichnofossils and carbonaceous impressions of macroalgae in the Tamengo and Guaicurus formations. The micropaleontological records mainly include palinomorphs acritarchs that will also have their positioning later recorded in each log made in the fieldworks.

Three modalities of sample preparation were employed aiming at the fossiliferous recovery: 1. Invertebrates, 2. Mineralized microfossils and, 3. Organic-walled microfossils maceration (palynomorphs). As for the study of the occurrence of invertebrates such as *Corumbella werneri* and *Cloudina lucianoi*, as well as ichnofossils and macroscopic algae, the study initially consists of the description and direct analysis from rock using stereoscopic microscopy; for the preparation of polished sections and study of thin sections, stereoscopic microscopy and petrographic microscope were used, and in specific cases, scanning electron microscopy (SEM) was used.

The micropaleontological preparation was used with the objective of recovering mineralized microfossils besides fragments of invertebrates, sponge spicules, and remains of cyanobacteria or even protists diagenetically mineralized, through battery of sieves. The methodology employed follows the one proposed by Do Carmo et al. (2011) which aims at the recovery of mineralized skeletons and mineralized particles from the disintegration of the sedimentary rocks samples and washing them in sieves. After mechanical disaggregation, the sample is left in a beaker of 2 L for 48 h with water, then the sample is washed in sieves (630, 250, 160, 80,56 and 10 µm opening sizes) (Figure 3. 1). The granulometric fractions smaller than 10 µm are retained in an appropriate container, together with the other fractions, to be dried in a kiln at 60 °C and also to be examined in a stereoscopic microscope for the screening of microfossils and subsequent imaging in SEM.



Methodology Employed

Sieving

Maceration

Dissolution in H_2O

Sieving

Slides

- 200g are used for each sample
- After the sample oxidation, washing in sieving sequence 630, 250, 160, 80 and 50µm.
- Sedimentary granulometry thinner than 50µm were separated for micro-paleontological and XRD analysis.
- The weight for material retained in each sieve was measured.

Figure 3. 1. Micropaleontological preparation flowchart (Do Carmo et al., 2011).

For the chemical preparation and concentration of the particulate organic components (palynomorphs), the methodology developed in the Laboratory of Micropaleontology of UnB was used. The methodology involves attacking the samples for 2 h with 37% hydrochloric acid. The samples were neutralized and then treated with 47% hydrofluoric acid for 12 hours. Again the samples were neutralized by distilled water until the pH reaches 7. A further 10% hydrochloric acid digestion can be applied for fluorite consumption and finishing the preparation with neutralization step in distilled water. Finally, the organic material is allowed to decant in the bottom (one day standby) and then stored in its own pots ready to make the slides. For the assembly of the permanent palynological slides, the supernatant is used, employing Entelan as the standard mounting medium and cover slides, according to standard preparation flowchart adopted in the UnB micropaleontology laboratory (Figure 3. 2)

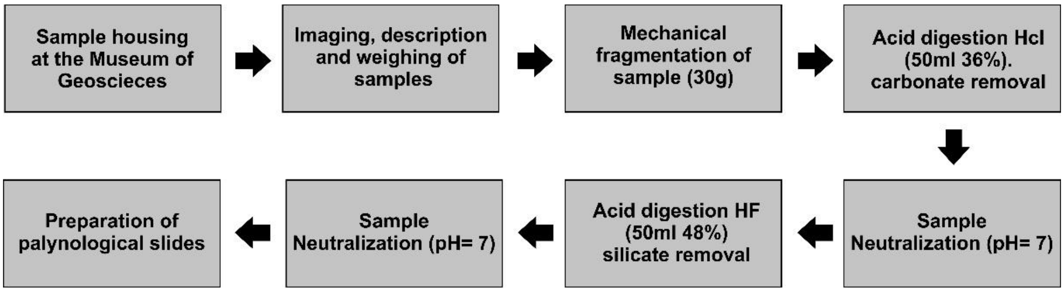


Figure 3. 2. Flowchart of the palynological preparation of the Laboratory of Micropaleontology, University of Brasília (Denezine, 2018).

Tests were conducted in order to recover *Cloudina lucianoi* from the Corumbá and Nama groups in three dimensions. Studies of this nature have been successfully conducted by Chinese research studies, with phosphatized material from the Doushantuo and Dengying formations (Hua et al., 2007). The preparation that returned a positive result uses 4% acetic acid, able to attack preferentially the carbonate matrix, in detriment of the carapace, which, because of its slightly larger magnesium content, is dissolved more slowly than the carbonate matrix (Figure 3. 3). The dissolved fraction of the sample is separated for analysis of the palynological content.

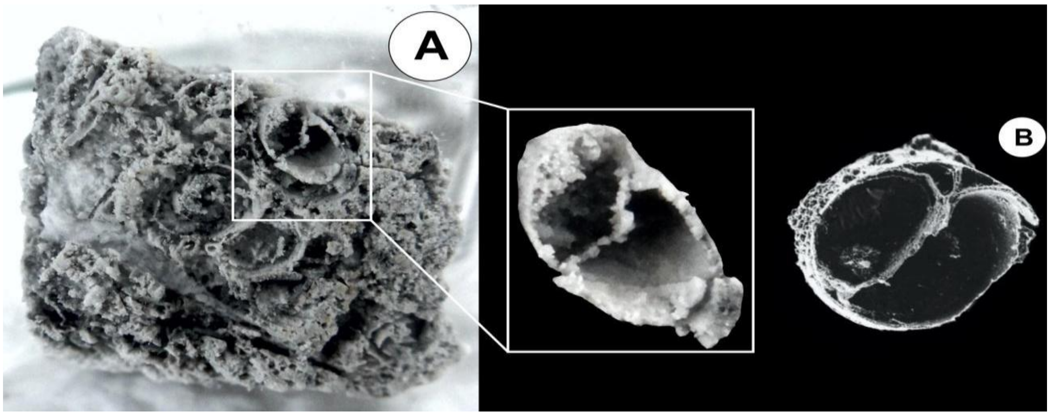


Figure 3. 3. Specimens of *Cloudina lucianoi* (Beurlen & Sommer, 1957) after preparation using 3D extraction. A) Carbonate Skeleton of *Cloudina lucianoi* from the Nama Group, Namibia with new preparation procedure. B) Phosphatized skeleton of *Cloudina lucianoi* from the Dengying Formation, South China (Hua et al., 2005) (Adôrno et al., 2016a).

CHAPTER – 4: RESULTS

It is presented herein results on update of lithostratigraphic description of studied sections, species identification of Tamengo and Guaicurus formation paleobiota, paleoenvironmental inferences and, a biostratigraphic essay. Five sections were studied: Corcal and Laginha quarries, Porto Sobramil, Porto Figueiras and Ecoparque Cacimba. In these five sections, Tamengo Formation crops out, and Guaicurus Formation crops out only at Laginha quarry section.

Twenty-six described species integrate the fossil assemblage of the Tamengo and Guaicurus formations, and were clustered six categories: biomineralizing metazoan, biomineralizing microfossils, vendotaenids, ichnofossils, organic-permineralized microfossils and organic-walled microfossils. In addition, paleoecological and paleoenvironmental inferences are presented based on the occurrence of the species and the lithostratigraphic update of Tamengo Formation sections.

Furthermore, in order to compare microfossil assemblage recovered from Tamengo Formation, sampling was conducted in three additional sections: Dengying Formation, China, Tagatiya Guazu Formation, Paraguay and Nomtsas Formation, Namibia. The result of the preparation and analysis of these samples complemented the scarce register of organic-walled microfossil species for these uppermost Ediacaran sections.

Finally, the results obtained from the analysis of the Tamengo Formation fossil assemblage were compared with those published for other uppermost Ediacaran selected sections in Paraguay, Uruguay, Argentina, Namibia, China, Russia, Canada, the United States and Oman which were presented as a proposal of biostratigraphic essay. This essay represents an advance on the previous one presented in Adôrno et al. (2017).

4.1. DESCRIPTION OF TAMENGO FORMATION SECTIONS

The results presented for Tamengo and Guaicurus formations in the region of Corumbá were obtained from the geological sections in five localities: 1) Porto Sobramil;

2) Corcal quarry; 3) Ecoparque Cacimba; 4) Laginha quarry; 5) Porto Figueiras and Porto Figueiras sections (Table 4. 1). The descriptions for the localities 1-3 have been presented in Adôrno et al. (2017) and herein an uptdated description for the Laginha quarry and Porto Figueiras sections is presented.

Table 4. 1. Localities and coordinates of the studied outcrops in Corumbá-Ladário region, Mato Grosso do Sul State, Brazil.

LOCALITY	**GEOLOGY**	**COORDINATES**
1. Corumbá - Corcal quarry	Tamengo Fm.	21K 0428106 / 7897065
2. Corumbá – Ecoparque Cacimba da Saúde	Tamengo Fm.	21K 0429794 / 7899135
3. Ladário - Porto Sobramil*	Tamengo Fm.	21K 0434770 / 7898980
4. Corumbá - Laginha quarry	Tamengo Fm.	21K 0432101 / 7886020
5. Corumbá – Porto Figueiras	Tamengo Fm.	21K 0433880 / 7899144

* This locality also refers to the limestone quarry area of the company Itaú, known by two denominations: Cláudio quarry and Saladeiro quarry. These two quarries were located side by side on the same bank of the Paraguay River. In order to avoid confusion, the name Sobramil is chosen, which refers to the company that owns the property where the two quarries were formerly located. Currently, in this classic locality, there is activities of iron and manganese port.

4.1.1. PORTO SOBRAMIL SECTION

The section of the Tamengo Formation in the Porto Sobramil area is a total of 29 m thick and comprises six layers. The first layer, L1, comprises laminated siltstone, three meters thick, in which occurrences of *Corumbella werneri* are found. The second layer, L2, is 13 m thick and comprises mainly calcarenite and limestone with the occurrence of *Cloudina lucianoi*. The third layer, L3, represents the middle portion of the outcrop and comprises siltstone and claystone with *Corumbella werneri*. The fourth layer, L4, comprises a calcarenite with occurrences of *Cloudina lucianoi*. The fifth layer, L5, comprises siltstone with occurrences of *Corumbella werneri*. The sixth layer, L6, of the Tamengo Formation in the Sobramil port area represents the top of the Tamengo Formation and consists of 5.5 m of limestone with *Cloudina lucianoi* (Figure 4. 1). (Adôrno et al., 2017).

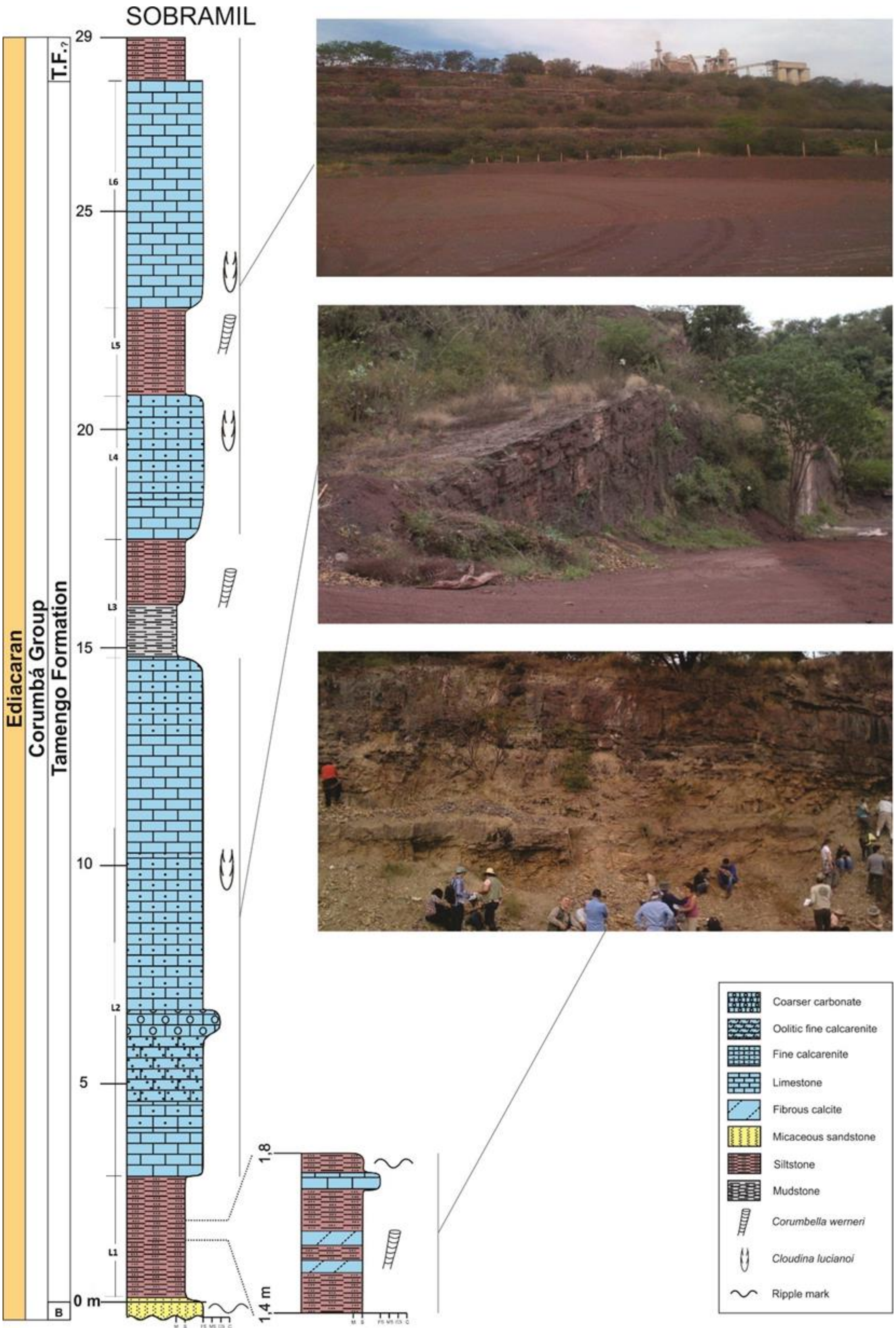


Figure 4. 1. Lithostratigraphic log and biostratigraphic data of the upper Tamengo Formation at Sobramil port, Ladário Municipality, Mato Grosso do Sul State, Brazil (Adôrno et al., 2017).

4.1.2. ECOPARQUE CACIMBA SECTION

The section of the Tamengo Formation in the Ecoparque Cacimba is composed of six layers and is 28 m thick. The first layer, L1, comprises laminated siltstone three meters thick in which occurrences of *Corumbella werneri* are found. The second layer, L2, is 2.5 m thick and comprises mainly calcarenite and limestone with occurrence of *Cloudina lucianoi*. The third layer, L3, is represented by siltstone and calcarenite with occurrence of *Cloudina lucianoi*. In these calcarenites, it is possible to observe ripple marks and overload structures. The fourth layer, L4, comprises a calcarenite layer with occurrence of *Cloudina lucianoi*. The fifth layer, L5, comprises siltstone intercalated with discontinuous carbonate layers. The sixth layer, L6, of the Tamengo Formation in the Cacimba Ecopark represents the top of the Tamengo Formation and consists of 12 m of a huge intercalation of siltstone and limestone with *Cloudina lucianoi* (Figure 4. 2) (Adôrno et al., 2017).

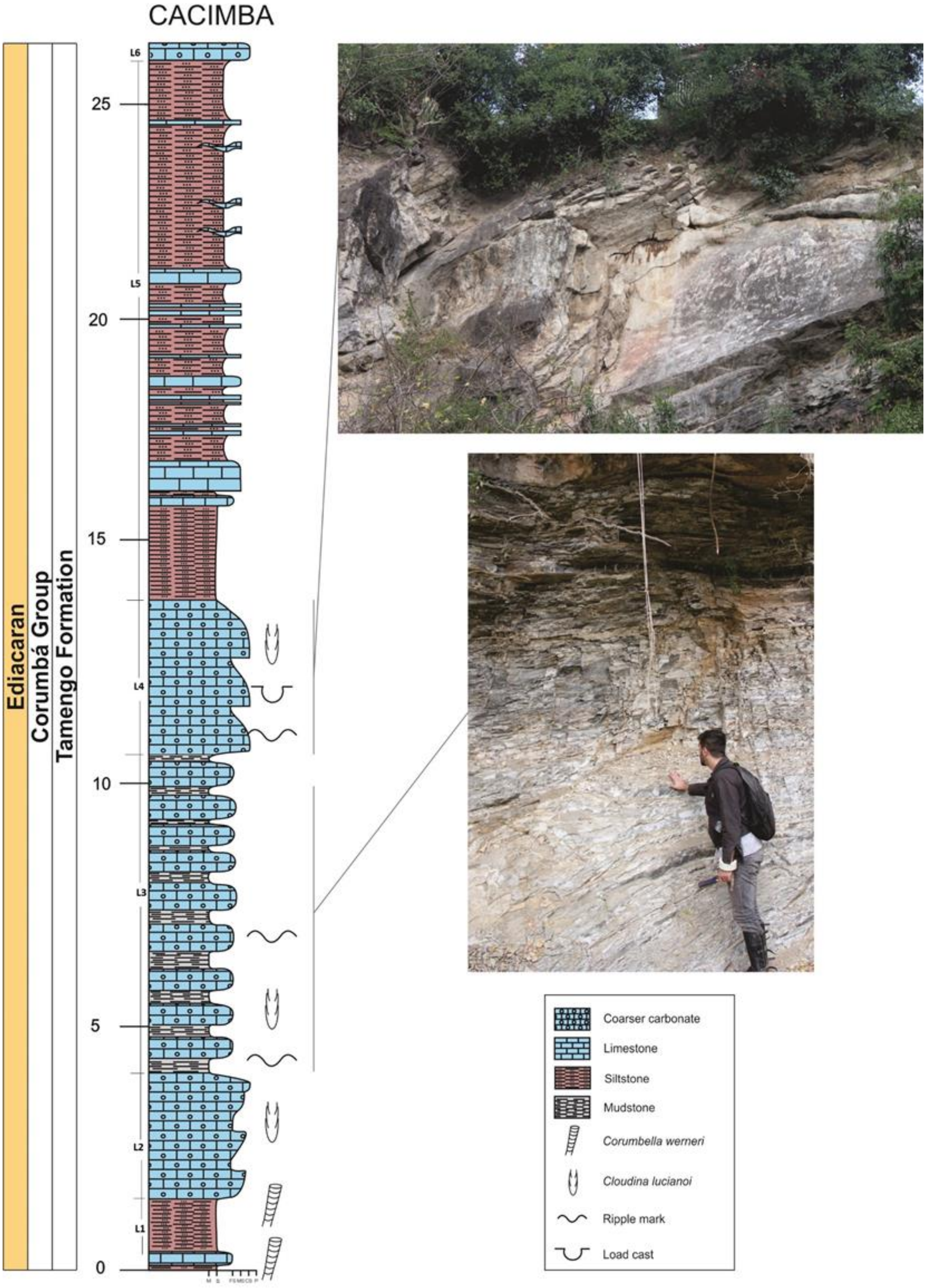


Figure 4. 2. Lithostratigraphic log and biostratigraphy data of the upper Tamengo Formation at Ecoparque Cacimba, Corumbá Municipality, Mato Grosso do Sul State, Brazil (Adôrno et al., 2017).

4.1.3. CORCAL QUARRY SECTION

In the Corcal quarry, the Tamengo Formation is composed of six layers. The first layer, L1, comprises laminated siltstone, 1.5 m thick. The second layer, L2, is seven meters thick and is mainly composed of calcarenite with the occurrence of *Cloudina lucianoi*. The third layer, L3, comprises mainly siliciclastic rock with Corumbella werneri intercalated with carbonate layers with *Cloudina lucianoi*. The fourth layer, L4, represents the middle portion of the outcrop and consists of calcarenite with occurrences of *Cloudina lucianoi*. The fifth layer, L5, comprises siltstone with occurrences of *Corumbella werneri*. The sixth layer, L6, of the Tamengo Formation in Corcal quarry comprises a thick layer with 19 m of calcarenite with *Cloudina lucianoi* (Figure 4. 3).

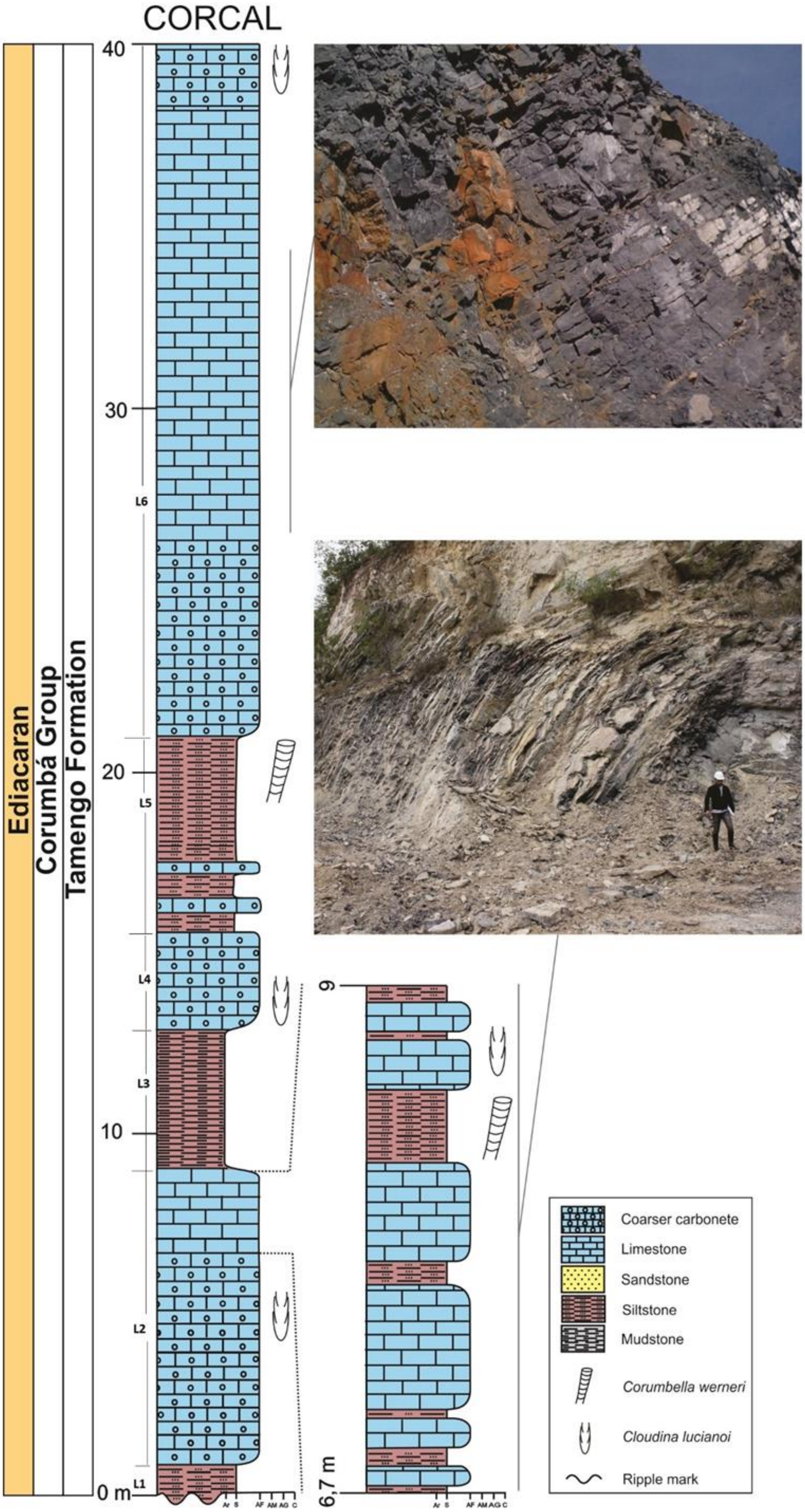


Figure 4. 3. Lithostratigraphic log and biostratigraphic data of the upper Tamengo Formation at Corcal quarry, Corumbá Municipality, Mato Grosso do Sul State, Brazil (Adôrno et al., 2017).

4.1.4. LAGINHA QUARRY SECTION

At the base of the section, there are approximately 16 m of diamictite with clasts of up to 30 cm diameter, composed of granite, quartzite, chert, oolitic limestone and eventually limestone (Figure 4. 4). The matrix of this diamictite is gray in color. Above the diamictite, occurs one layer with about 6 m of breccia, constituted by angular clasts of limestone and fragments of black phosphorite. The matrix is composed of gray carbonate with intense calcite venulation and fluorite of intense violet color. Above the carbonate breccia layer, there are oolitic black grainstone.

Figure 4. 4. Panoramic view of the Laginha quarry section.

Samples were collected at intervals of 10 to 60 cm, in the sequence of dark gray grainstone with intercalations of black pelitic levels, also sampled. The base is formed by layers of massive mudstone, succeeded by layers smaller than 0.5 m thick, with black shale, containing pyrite. Toward the top, the darkest laminated grainstone predominates, usually oolitic, presenting load structures. This is a 50 m packet of medium gray grainstone, very fractured and recrystallized, with calcite veins. This carbonate sequence is covered by a layer of finely-laminated, light gray shale, which when altered gives ocher coloring, this layer represents the basal portion of the Guaicurus Formation (Figure 4. 5).

The sequence ends with the siltistones of the Guaicurus Formation that are persistently laminated, well sorted and homogeneous. Occurrences of *Cloudina lucianoi* at Laginha quarry are rarer than other localities and *Corumbella werneri* was not found thus far at this section. The fossil assemblage recovered is mostly composed of microfissils in the Tamengo Formation and rare remains of fragments of macroalgae as impressions and trace fossils in the Guaicurus laminated siltstones.

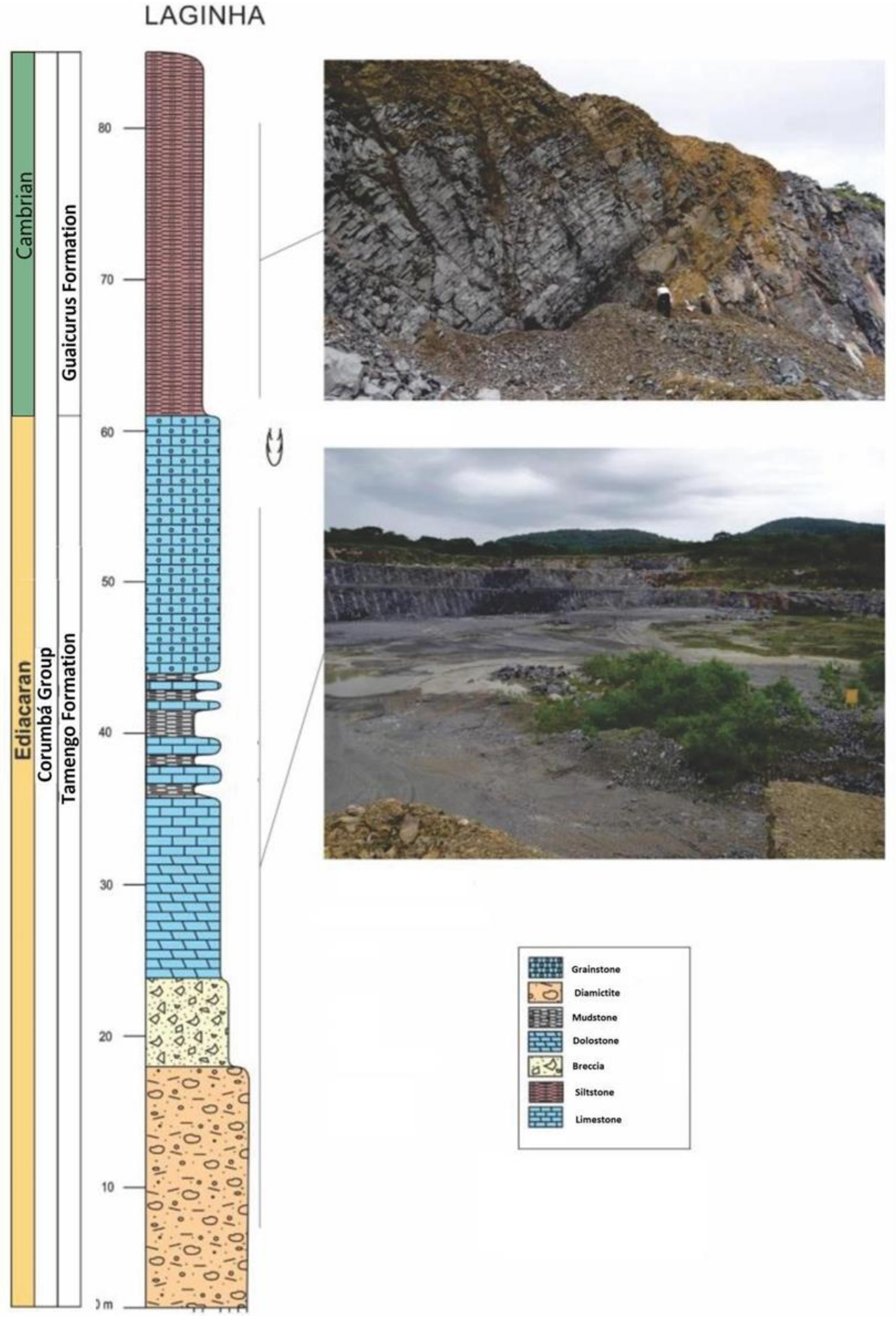


Figure 4. 5. Lithostratigraphic section of the Laginha quarry, in the Municipality of Corumbá, Mato Grosso do Sul State, Brazil. UTM Coordinates zone 21K 0432101mE/7886020mS.

4.1.5. PORTO FIGUEIRAS SECTION

The section of Porto Figueiras is located behind the Gerson's Marina in Corumbá (Brazil), around 200m from the southern banks of the Paraguay River. It consists of light yellow siltstone and dark gray limestone, with total thickness of 8.25m (Figure 4. 6).

At the base of the section, there are approximately 2.5m of massive siltstone with several lenses of sandstone - with tens of centimeter wide and a few centimeters thick. Around 0.4m from the basal level, there are fossil occurrences of *Corumbella werneri* and *Cloudina carinata*. Above the siltstone, lies 5.75m of recrystallized limestones arranged as thick massive beds showing planar cross-stratification or as amalgamated sets of thin beds with wavy contacts.

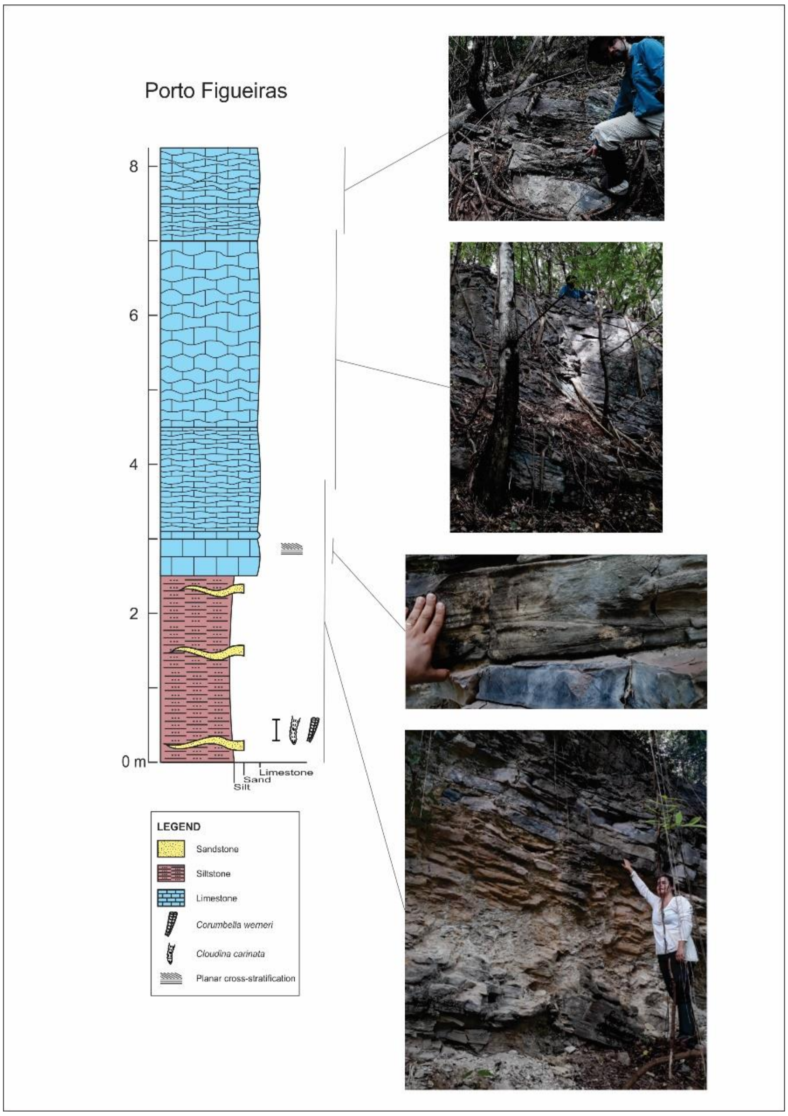


Figure 4. 6. Lithostratigraphic section of the Porto Figueiras (Marina do Gerson) section, in the municipality of Corumbá, Mato Grosso do Sul State, Brazil. UTM Coordinates zone 21K 0433880mE / 7899144mS.

4.1.6. DISCUSSION ON LITHOSTRATIGRAPHIC RECORD

The results presented for Tamengo and Guaicurus formations in the region of Corumbá and Ladário Municipalities were obtained from the geological sections in five localities. These sections were lithologically described, and the fossil occurrences were positioned in the updated logs.

The description of lithology represents an advance to understand the package, yet, it is not itself enough to understand the sequence stratigraphy and for the reconstruction of deeper analysis such as paleobathymetry for example. It is recommended further integrative and complementary research, especially on sequence stratigraphy, necessary for more robust paleoenvironmental reconstructions.

Further investigation regarding the lithologic characterization of Tamengo and Guaicurus formation must be done. Some efforts have already been made in order to individualize the siltstones of the upper portion of Tamengo Formation and the siltistones of the base of Guaicurus Formation. According to Fazio et al. (2019) at Corcal quarry section, the Guaicurus Formation is composed for yellow siltstone with some carbonate, but this limit is not completely clear. Still according to Fazio et al. (op. cit.) there is a huge marine paleoenvironmental shift marked by petrography, X-ray diffraction and mineral composition between Tamengo and Guaicurus formations, which is clearer at Laginha quarry than other sections.

4.2. STUDIED FOSSIL ASSEMBLAGE OF TAMENGO AND GUAICURUS FORMATIONS

Twenty-six species integrate the studied fossil assemblage of Tamengo and Guaicurus formations from five sections in Corumbá and Ladário regions. Three sessile benthic biomineralizing metazoan species were described from Tamengo Formation: *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010, *Corumbella werneri* Hahn et al., 1982. Additionally, sponge spicules were recovered, but a question remains regarding its original composition, if it is calcareous or siliceous.

Regardless of the original composition, these sponge spicules present a calcareous composition.

The taxonomy for four ichnoespecies *Didymaulichnus lyelli* and *Multina minima* Uchman, 2001 from Guaicurus Formation, and for the two other new occurrences identified as *Gordia marina* Emmons, 1844 and *Pilichnus cf. P. dichotomus* Uchman, 1999, is presented from Tamengo Formation. Additionally, the taxonomy for three species of Vendotaenids *Vendotaenia antiqua* Gnilovskaya, 1971 from Tamengo Formation, *Eoholynia corumbensis* Gaucher et al., 2003 and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) is presented from Guaicurus Formation.

The micropaleontological content of Tamengo Formation consists of one species of permineralized and fifteen species of organic-walled microfossils. Permineralized microfossils identified as *Chuaria circularis* Walcott, 1899, and a small chamber microfossil (sponge gemmule?) with uncertain taxonomic affinity inserted in the reticular surface of a specimen of a putative poriferous. This possible sponge gemmule is similar to that described in Du et al. (2014) from Doushantuo Formation. The organic-walled microfossils are mainly represented by small and spheroidal species without process and ornamentation (Table 4. 2).

Table 4. 2. Described species from Tamengo and Guaicurus formations.

	Paleoecology	**Species**	**Locality (Brazil)**	**Formation**
Biomineralizing Metazoan	Sessile-Epibenthic	*Cloudina lucianoi* (Beurlen & Sommer, 1957)	Corcal, Cacimba, Sobramil,	Tamengo,
	Sessile-Epibenthic	*Cloudina carinata* Cortijo et al., 2010	Porto Figueiras	Tamengo
	Sessile-Epibenthic	*Corumbella werneri* Hahn et al., 1982	Corcal, Cacimba, Sobramil	Tamengo
Biomineralizing Microfossils	Sessile-Epibenthic	Undeterminated sponge spicules and wall fragments	Sobramil	Tamengo
	Undetermined	Undeterminated microfossil chamber sponge gemmule?	Sobramil	Tamengo
Vendotaenids	Sessile-Epibenthic	*Vendotaenia antiqua* Gnilovskaya, 1971	Corcal	Tamengo, Cerradinho and Bocaina
	Sessile-Epibenthic	*Eoholynia corumbensis* Gaucher et al., 2003	Laginha	Guaicurus

	Sessile-Epibenthic	*Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979)	Laginha	Guaicurus
Ichnofossils	Vagile-Epibenthic	*Gordia marina* Emmons, 1844	Corcal	Tamengo
	Vagile-Epibenthic	*Pilichnus cf. P. dichotomus* Uchman, 1999	Corcal	Tamengo
	Vagile-Endobenthic	*Multina minima* Uchman, 2001	Laginha	Tamengo, Guaicurus
	Vagile-Endobenthic	*Didymaulichnus lyelli* (Rouault, 1850)	Laginha	Guaicurus
Permiineralized microfossils	Possible marine planktic	*Chuaria circularis* Walcott, 1899	Cacimba	Tamengo
Organic-walled microfossils	Possibly marine planktic	*Arctacellularia januarensis* Denezine, 2018 *nomem nudum*	Sobramil	Tamengo
	Possibly marine planktic	*Leiosphaeridia ternata* (Timofeev, 1966)	Cocal	Tamengo
	Possibly marine planktic	*Leiosphaeridia crassa* (Naumova, 1949)	Corcal, Laginha, Cacimba, Sobramil	Tamengo
	Possibly marine planktic	*Leiosphaeridia jacutica* (Timofeev, 1966)	Corcal, Cacimba	Tamengo
	Possibly marine planktic	*Leiosphaeridia minutissima* (Naumova, 1949)	Corcal, Laginha, Cacimba, Sobramil	Tamengo
	Possibly marine planktic	*Leiosphaeridia tenuissima* Eisenack, 1958	Corcal, Cacimba, Sobramil	Tamengo
	Possibly marine planktic	*Bavlinella faveolata* Vidal, 1976	Corcal, Laginha, Cacimba, Sobramil	Tamengo
	Possibly marine planktic	*Bambuites erichsenii* Sommer, 1971	Porto Sobramil	Tamengo
	Possibly marine planktic	*Leiosphaeridia obsuleta* (Naumova, 1949)	Corcal, Laginha, Cacimba, Sobramil	Tamengo
	Possibly marine planktic	*Synsphaeridium* sp.	Corcal	Tamengo
	Possibly marine planktic	*Jacutianema* sp.	Corcal	Tamengo
	Possibly marine planktic	*Lophosphaeridium* sp.	Corcal	Tamengo
	Possibly marine planktic	*Ostiama microcystis* Hermann in Timofeev et al., 1976	Corcal	Tamengo
	Possibly marine planktic	Gen1. Sp. 1 (flask-shaped) Chitinozoan like	Cacimba	Tamengo
	Possibly marine planktic	*Navifusa* sp.	Corcal	Tamengo

Biomineralizing species

Two categories of biomineralizing species were recovered in Tamengo Formation: biomineralizing metazoan and biomineralizing microfossil species. Biomineralizing metazoan comprises three cnidarian species and undetermined remains of sponge. Three cnidarian species are: *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010 and *Corumbella werneri* Hahn et al., 1982.

The taxonomy of *Cloudina* Germs, 1972 was updated and had its diagnosis emended in Adôrnoet al. (2017). The type-material of *Cloudina lucianoi* (Beurlen &

Sommer, 1957) was revised and compared with other *Cloudina* species, especially *Cloudina hartmanae* Germs, 1972. The comparative study between these two species was based on objective morphological and morphometric criteria, which allowed to propose that *Cloudina hartmanae* should be considered a junior synonym of *Cloudina lucnianoi*. Based on this concept, *Cloudina lucianoi* occupied the position of type-species of genus and had its geographical distribution extended to all continents, revealing a great importance for paleozoogeographic studies and biostratigraphic correlation. The list of valid *Cloudina* species was updated and composed of five species: 1) *Cloudina riemkeae* Germs, 1972, 2) *Cloudina lucianoi* (Beurlen & Sommer, 1957), 3) *Cloudina carinata* Cortijo et al., 2010, 4) *Cloudina ningqiangensis* Cai et al., 2017, 5) *Cloudina xuanjiangpingensis* Cai et al., 2017 (Table 4. 3).

Table 4. 3. Updated list of valid species of *Cloudina* Germs, 1972 after Adôrno et al. (2017) and Cai et al. (2017).

SPECIES	COUNTRY
1. *Cloudina lucianoi* (Beurlen & Sommer, 1957)	Namibia, Brazil, Paraguay, China, USA, Canada, Mexico, Spain, Oman, Siberia
2. *Cloudina riemkeae* Germs, 1972	Namibia, Brazil? Uruguay, Russia
3. *Cloudina carinata* Cortijo *et al.*, 2010	Spain, Siberia, Brazil*
4. *Cloudina ningqiangensis* Cai et al., 2017	China
5. *Cloudina xuanjiangpingensis* Cai et al., 2017	China

*This is the first occurrence of *Cloudina carinata* in South America.

From the eleven described species of *Cloudina*, six species has taxonomic issues. Two were transferred to other genus, three were synonymized and one does not followed the statement of the International Code of Zoological Nomenclature (ICZN). Considering these issues, a discussion for each species with problematic issues is presented below.

Remarks are presented dealing with the taxonomic position of two *Cloudina* species: *Cloudina waldei* Hahn & Pflug, 1985, *Cloudina? borrelloi* Yochelson & Herrera, 19. Considering the original description for *Cloudina waldei* type-material presented in Hahn & Pflug (1985), the skeleton has wrinkled walls instead of funnel-in-funnel or even cone-in-cone skeletal architecture. Based on this description, *Cloudina waldei* would fit better as *Sinotubulites waldei* (Hahn & Pflug, 1985). Unfortunately, the type-materials of this species are at the Institute of Geosciences, University of Marburg (responsibility of Prof. Gerhard Hahn) and in the Institute of Geosciences of the University of Giessen (Prof. Hans D. Pflug, deceased) and therefore was not accessed during this research. Tubes of lower Cambrian from the locality named Sierra de Villicum, Argentina, were identified as *Cloudina? borrelloi* Yochelson & Herrera, 1974. This material was subsequently studied in Hahn & Pflug (1985) and transferred to *Acuticloudina borrelloi* (Yochelson & Herrera, 1974) (Conway Morris et al., 1990; Brasier et al., 2017).

Three species are synonymized: *Cloudina hartmanae* Germs, 1972, *Cloudina lijiagouensis* Zhang et al., 1992 and *Cloudina sinensis* Zhang et al., 1992. For *Cloudina hartmanae*, as earlier discussed in this text, based on Adôrno et al. (2017), it is a junior synonym of *Cloudina lucianoi*. The other two species were revised in Cai et al. (2017). This study includes analysis of the type-material from Dengying Formation, China: *Cloudina lijiagouensis* Zhang et al., 1992 and *Cloudina sinensis* Zhang et al., 1992. The holotype of *Cloudina lijiagouensis* was synonymized with *Cloudina hartmanae*, and as earlier discussed, it is considered a junior synonym of *Cloudina lucianoi* in Adôrno et al. (2017). It was also proposed in Cai et al. (2017) that a part of the *Cloudina sinensis* illustrated material in Zhang et al. (1992) is synonymized with *Cloudina hartmanae* and another part synonymized with *Cloudina ningqiangensis* Cai et al., 2017.

The validity of *Cloudina latilabrum* Meira, 2011 *nomem nudum* is questionable considering Article 8.1, Chapter 3 of the International Code of Zoological Nomenclature (ICZN). The ICZN determines that a valid species must have its proposition in a scientific journal of wide circulation and also printed on paper. What’s more, Article 9, Chapter 3 of the ICZN also defines “*What does not constitute published work*” and it includes, among others, Ph.D. thesis and dissertations explicitly. Furthermore, Becker-Kerber (2015) presented arguments to consider *Cloudina latilabrum* as a synonym of *Cloudina lucianoi*, which present small morphological variations due to its taphonomic processes.

Among the five valid *Cloudina* species, two species occur in uppermost Ediacaran Tamengo Formation sections of Brazil: *Cloudina lucianoi* and *Cloudina carinata* (Table 4. 3). *Cloudina lucianoi* has the greatest geographic distribution in the sections of Tamengo Formation at Corumbá and Ladário regions with occurrences recorded in four studied sections: Corcal quarry, Porto Sobramil and Ecoparque da Cacimba (Figure 4. 7) (Adôrno et al., 2017; 2018). *Cloudina lucianoi* also occurs in coeval strata in Paraguay (Warren et al., 2011), Namibia (Germs, 1972), China (Cai et al., 2017), USA (Hagadorn & Wagoner, 2000), Canada (Hofmann & Mountjoy, 2001); Mexico (Sour-Tovar et al., 2007), Spain (Cortijo et al., 2010); Oman (Conway Morris, 1990) and Russia (Terleev et al., 2011).

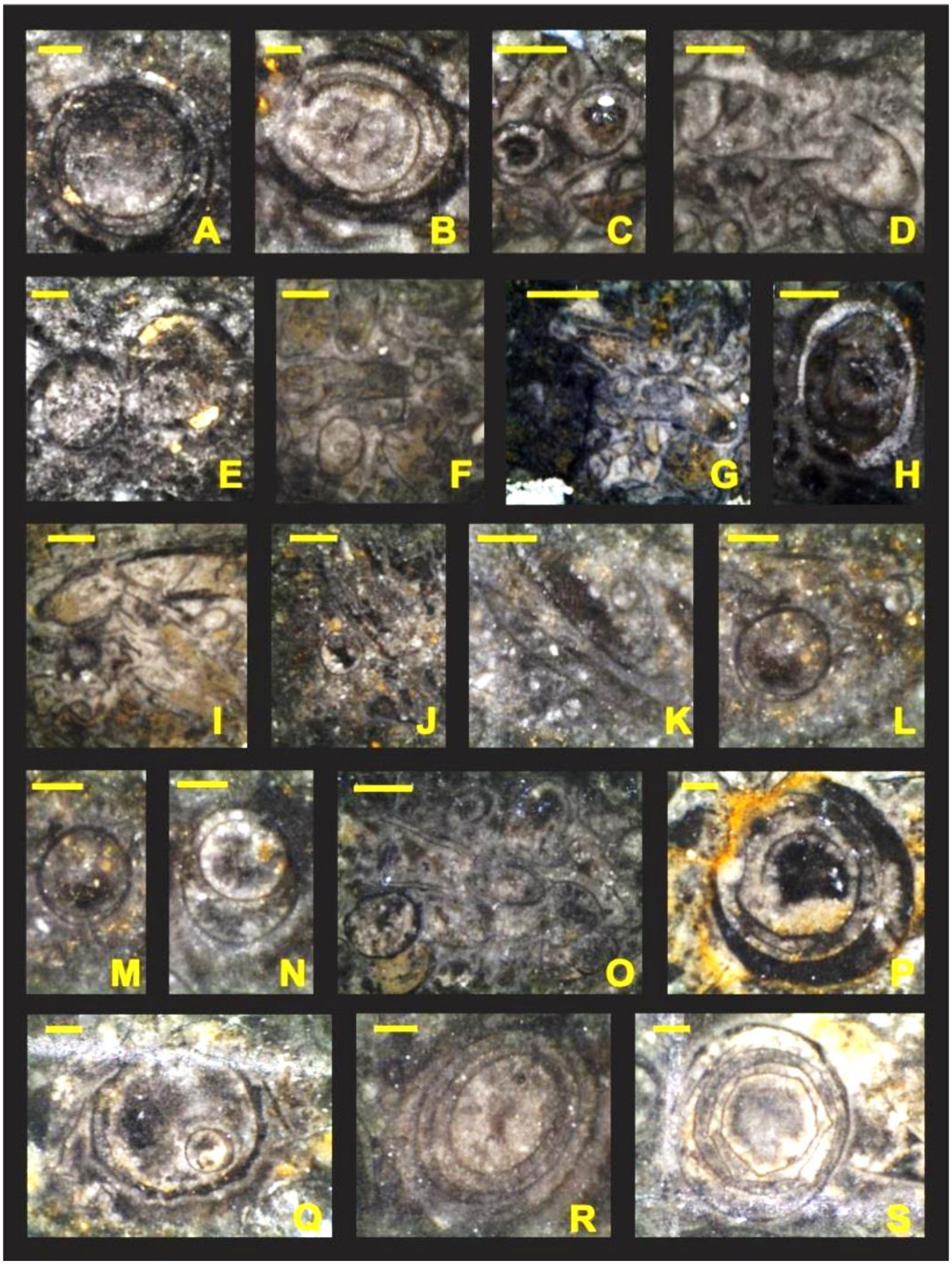


Figure 4. 7. Polished sections with specimens of *Cloudina lucianoi* (Beurlen & Sommer, 1957). Section 1153: A-C and E, specimens in transverse section (Obs: Note the funnel-within-funnel structure); D, specimens in longitudinal section. Section 1154: F, overview of the sample; G, I, longitudinal section emphasizing the thickness of the wall of the skeletal body, including transverse sections; H, Specimen possibly recrystallized. Section 1157: J, K and N, longitudinal sections highlighting the variation in diameter along the wall of the skeletal body; cross sections are also presented; L, M, transverse section (note the funnel-within-funnel structure). Section 1158: O, transverse and longitudinal sections; P–S, transverse sections (note the funnel-in-funnel structure). Scale bars: A, B, E, L, M, N, P–S = 500 µm; D, H, K = 1000 µm; C, F, G, I, O = 2000 µm (Extracted from Adôrno et al., 2017).

The occurrence *Cloudina carinata* Cortijo et al., 2010 is recovered from siltstones of the Tamengo Formation in the locality named Porto Figueiras, Municipality of Corumbá, Mato Grosso do Sul State, Brazil. This occurrence is the first record of this species in the

American continent (Figure 4. 8), expanding the geographic distribution of this species, whose occurrence has been documented in sections in Spain and Siberia (Cortijo et al., 2010; 2015b; Terleev et al., 2011).

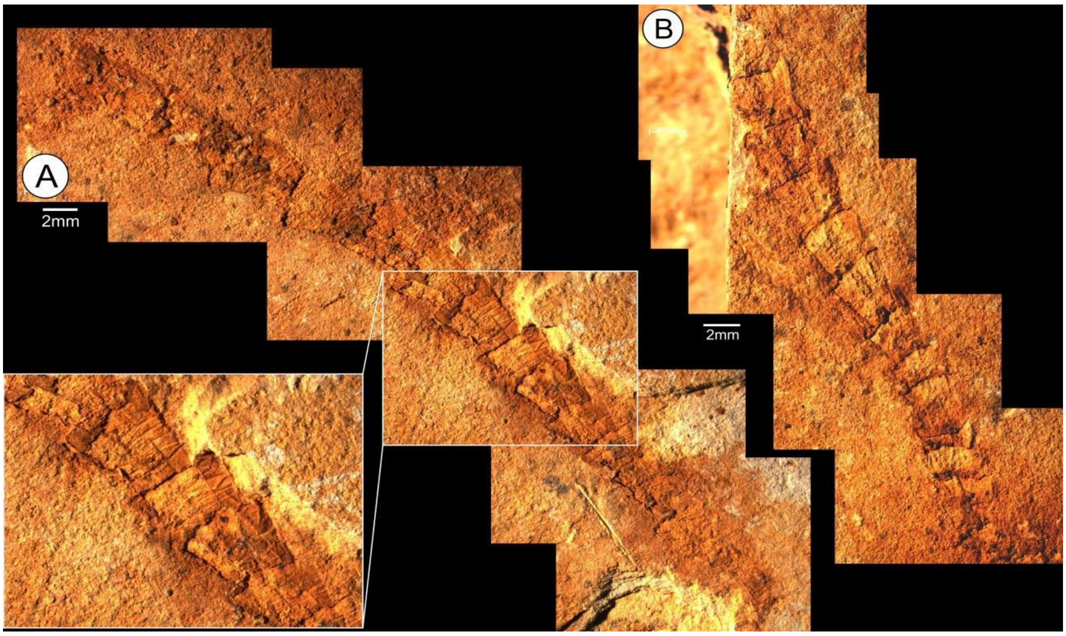


Figure 4. 8. Two specimens of *Cloudina carinata* Cortijo et al., 2010, Tamengo Formation, Porto Figueiras section, Corumbá Municipality, Mato Grosso do Sul State, Brazil. UTM coordinates Zone 21K 433880.06m E/7899144.76 m S, illustrated specimen MAF-522 (original number MP-717).

The biological affinities of the sessile benthic metazoan *Corumbella werneri* Hahn et al., 1982 remain under discussion. Some publications have considered *Corumbella werneri* as conulariids, and more recently, new interpretations of the morphology and the fossil diagenesis have led to alternative proposition, considering this species as closer allied to cloudinids. In fact, there are currently three diagnosis for *Corumbella werneri*, the original presented in Hahn et al. (1982), the other one from Babcock et al. (2005) and the last one published in Pacheco et al. (2015). These three diagnoses include conflicting characteristics, including interpretations of morphological features such as the presence of carina in the internal portion of the septa. Babcock et al. (2005) describe the presence of carina as a diagnostic property of the genus and species, but in the emended diagnosis presented in Paccheco et al. (2014), it is explicitly stated that such structure is not present.

Furthermore, it was proposed that *Corumbella weneri* would have tetragonal geometry and a longitudinal midline (mandatory element for conulariids) (Pacheco et al., 2010, Van Iten et al., 2014, Pacheco et al., 2015). Walde et al. (2018), on the other hand, argue that such longitudinal median lines are crack-lines formed due to diagenetic compaction. The argument that supports this interpretation is multiple and based on the fact that crack-lines occur only in incomplete skeleton. Warren et al. (2011) examined rocks of the Itapucumi Group, Paraguay, where *Corumbella werneri* occurs completely cylindrical and without the median line or crack-line (Warren, 2011; Warren et al. 2012; 2014). New occurrences of specimens with no compaction features, nor crack-lines, and seems to corroborate the assertion that such longitudinal lines are occasionally present in *Corumbella werneri* skeleton could be interpreted as postmortem processes (Figure 4. 9) (Walde et al., 2015; Erdtmann & Walde, 2016; Walde et al., 2018; Adôrno et al., in preparation, appendix 2).

Corumbella werneri is mostly associated with the siltstone layers of Tamengo Formation (Hahn et al., 1982; Walde et al., 2015; Erdtmann & Walde, 2016; Walde et al., 2018, Adôrno et al., 2017; 2018). This genus is thus far monospecific, occurring in the uppermost Ediacaran Tamengo Formation, Brazil and in the coeval Itapucumi Group, Paraguay (Warren et al., 2011). Occurrences of undetermined species assigned as *Corumbella* sp. have been described in other localities such as Sete Lagoas Formation, Bambuí Group, Brazil (Warren et al., 2014) and Wood Canyon Formation in the United States of America (Hagadorn & Wagoner, 2000, Smith et al., 2016; 2017).

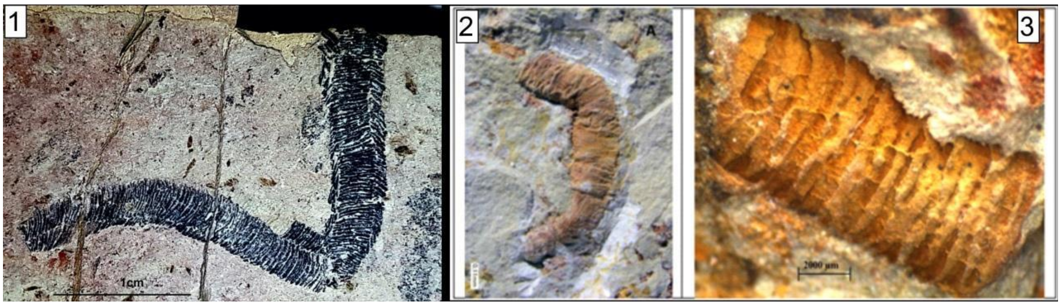


Figure 4. 9. Specimens of *Corumbella werneri* Hahn et al., 1982 from the Tamengo Formation, Corumbá Group, Corumbá Municipality, Mato Grosso do Sul State, Brazil. 1) Adult specimen with exceptional preservation of the original cuticle MAF-523. 2) Possible basal part (juvenile form?), CP-746. 3) Median portion of *Corumbella werneri* tube showing cylindrical geometry and absence of midline, CP-747 (Walde et al., 2018).

The sponge spicules were recovered from Tamengo Formation at Corcal quarry, Porto Sobramil and Laginha quarry sections. The mineralized spicules were recovered isolated and in an imbricated assemblage possibly related to sponge wall (Figure 4. 14: 13.3). These mineralized putative spicules, one sponge gemmule and wall fragments are remains of sessile benthic biomineralizing metazoan possibly related to marine sponge (Adôrno et al., in preparation, appendix 2).

Vendotaenids

Three species of vendotaenids occur in the studied sections: *Vendotaenia antiqua* Gnilovskaya, 1971, *Eoholynia corumbensis* Gaucher et al., 2003 and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979). *Vendotaenia antiqua* constitutes the benthic fossil assemblage of Cerradinho, Bocaina (Gaucher et al., 2003) and Tamengo Formation (Figure 4. 10) (Adôrno et al., in preparation, appendix 2). *Eoholynia corumbensis* and *Tawuia dalensis* are benthic fossil assemblage and are restricted to Guaicurus Formation.

The systematic taxonomy for *Vendotaenia antiqua*, *Eoholynia corumbensis* and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) was presented in Gaucher et al. (2003). *Eoholynia corumbensis* was assigned as remains of eucaryotic algae, probably Phaeophyta or Rhodophyta. *Vendotaenia antiqua* is assigned as probably abandoned sheaths of sulfide-oxidizing organotrophic bacteria related to the Beggiatoaceae (Vidal, 1989; Gaucher et al., 2003, Adôrno et al., in preparation, appendix 2). *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) were probably photosynthesizers species assigned to cyanobacteria (Steiner et al., 1996).

On preservational mode, *Vendotaenia antiqua* was recovered in three distinct modalities: as impressions from red siltistone bedding (Figure 4. 11), as organic-walled remains and as permineralized fragments (Figure 4. 14: 9) (Adôrno et al., in preparation, appendix 2).

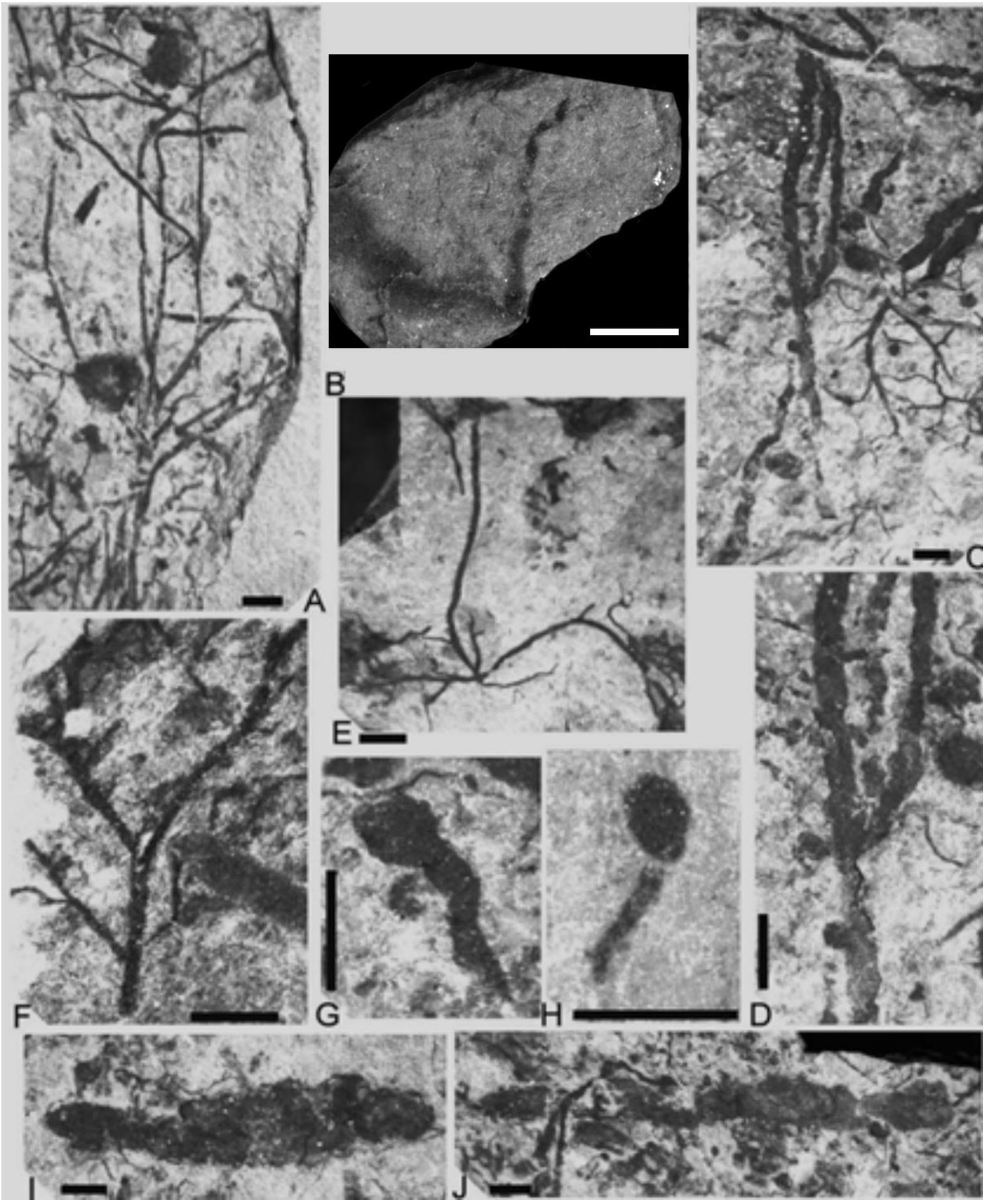


Figure 4. 10. *Eoholynia corumbensis* Gaucher et al., 2003 and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) from the bedding surface of the gray siltstones of the lower portion of the Guaicurus Formation in the Laginha quarry, lower Cambrian. A-H) *Eoholynia corumbensis*; A) Full rectilinear thalli (FCDP 3613 specimen) with multiple branches; B) Specimen from Laginha quarry, Guaicurus Formation (original number MP 3225) recorded during this doctorate; C-D) Holotype PDGF 3615, with main branch covered with spherical bodies (sporangia); E) PDGF Paratype 3222 with intense ramifications from the main stem; F) Rectilinear thalli; G) terminal sporangium; H) FDCP specimen 3616, terminal sporangium parenchyma; I-J) *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979); I) slightly curved specimen FCDP 3617; J) rectilinear specimen with numerous overlapping of *Eoholynia* stems. Scale bars have 1 mm (modified from Gaucher et al., 2003, with the inclusion of illustration of studied specimen B).

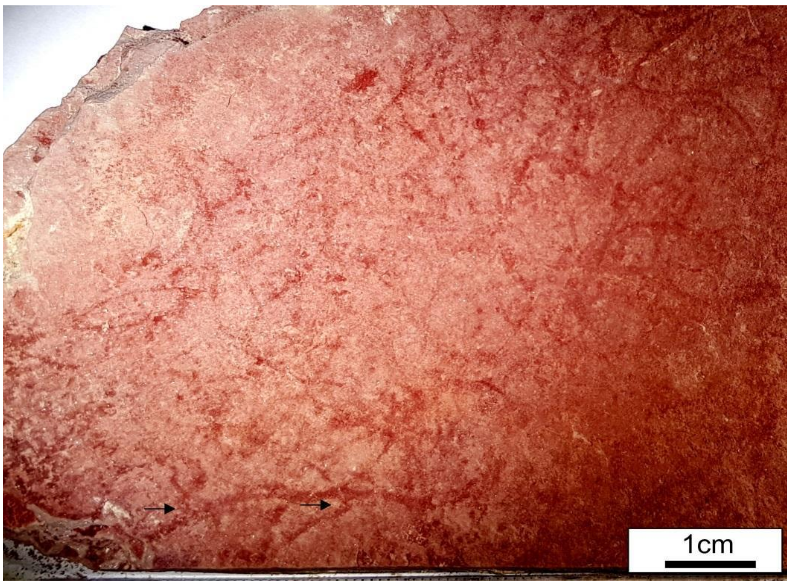


Figure 4. 11. *Vendotaenia antiqua* Gnilovskaya, 1971 from the surface of the red siltstone of the upper portion of the Tamengo Formation, sample MAF-516, locality Corcal quarry.

Ichnofossils

Four ichnospecies have occurrences recorded in this work: *Didymaulichnus lyelli* (Rouault, 1850), *Multina minima* Uchman, 2001, *Gordia marina* Emmons, 1844 and *Pilichnus cf. P. dichotomus* Uchman, 1999. These four ichnospecies integrate the updated ichnoassemblage for upper Corumbá Group (Parry et al., 2017; Adôrno et al., in preparation, appendix 2).

Didymaulichnus lyelli is represented by small excavations around 5 mm in diameter, probably produced by vagile endobiont organisms. *Multina minima* is represented by complex patterns microtunnels, 2mm diameter, that represent excavations possibly associated with small, endobiont organisms that are able to penetrate portions made up of soft and unconsolidated sediment. *Gordia marina* represents tracks possibly produced by vagile epibiont organisms, consisting of simple curved or loop-like surficial tracks with 0.5 to 2 mm diameter that are possibly associated with substrate exploratory, vagile epibiont organisms at the water-sediment interface. *Pilichnus cf. P. dichotomus* consists of complex and bifurcated excavations, representing epibiont organisms with elaborate excavation strategies (Figure 4. 13).

Didymaulichnus lyelli have occurrences restricted to Guaicurus Formation. *Multina minima* occurs at the top of the Tamengo Formation and at the base of the Guaricurus Formation in the section of the Laginha quarry (Figure 4. 12) (Parry et al., 2017). *Gordia marina* and *Pilichnus cf. P. dichotomus* are described herein in the Tamengo Formation at the Corcal quarry section (Figure 4. 13) (Adôrno et al., in preparation, appendix 2).

Additional occurrences of *Didymaulichnus lyelli* are recorded in Badhaura Formation, Permian of India (Kulkarni & Borkar, 2014) and in Bell Island and Wabana groups, Ordovician of Canada, Newfoundland (Fillion & Pickerill, 1990). *Multina minima* besides the occurrences in the Tamengo and Guaicurus formations, also occurs in the Grupo Hecho Pirineus, Eocene in Northern Spain (Uchman, 2001) and lower Cretaceous of Bulgaria (Uchman & Tchoumatchenco, 2003). *Gordia marina* are also recovered from Spain (Vidal et al., 1994), Canada and China (Crimes, 1987) and the United States of America (Hagadorn & Wagoner, 2000). *Pilichnus cf. P. dichotomus* are also recovered from Cambrian of China (e.g., Zhang et al., 2007) and Canadá (Mángano, 2011) and Ordovician shallow-marine deposits (Mikulás, 2003), and Carboniferous turbidities of Czech Republic (e.g. Mikulás et al., 2004). Considering these publications mentioned above, excepted for *Gordia marina*, occurrences in Tamengo Formation represent the oldest record of *Didymaulichnus lyelli*, *Multina minima* and *Pilichnus cf. P. dichotomus*. *Gordia marina* occurs in uppermost Ediacaran strata in Spain and also occurs in the Phanerozoic strata (Hofmann, 1990; Vidal et al., 1994).

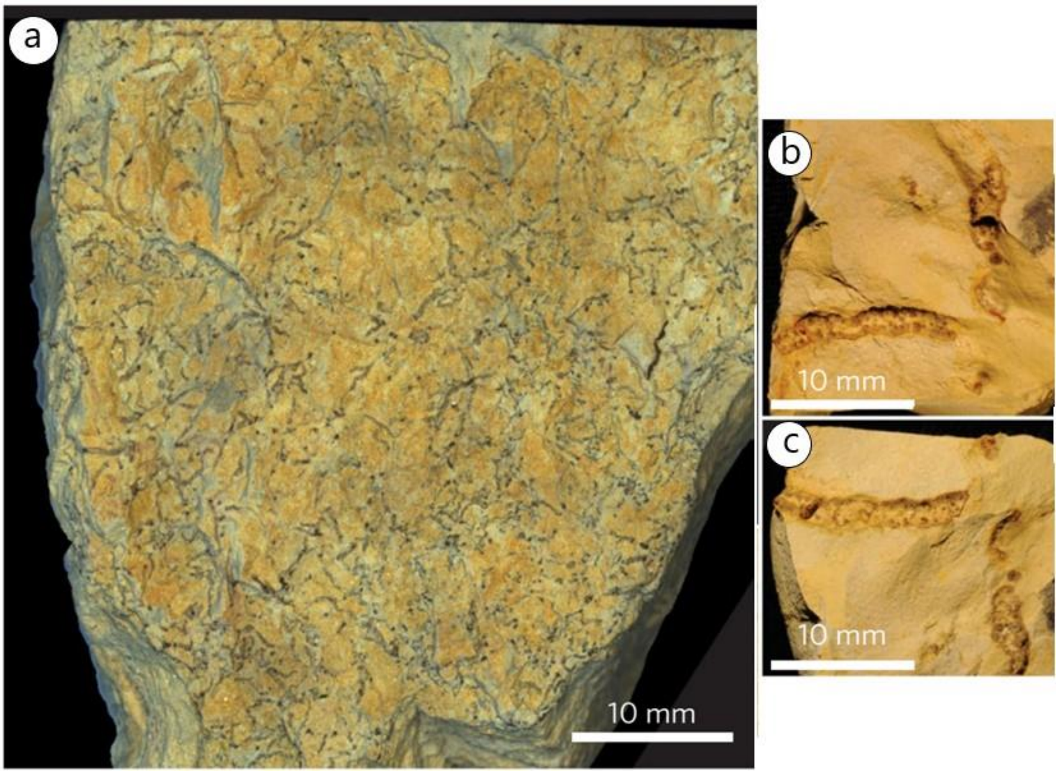


Figure 4. 12. Photographs of hand samples and SEM images of the ichnofossils *Multina minima* (Uchman, 2001) from the Tamengo and Guaicurus Formation and *Didymaulichnus lyelli* (Rouault, 1850) from the Guaicurus Formation, Laginha quarry, Corumbá Municipality, Mato Grosso do Sul State, Brazil. a) *Multina minima* specimens; b-c) part and counterpart of bilobed traits of *Didymaulichnus lyelli* seen on the bedding surface (modified from Parry et al., 2017).

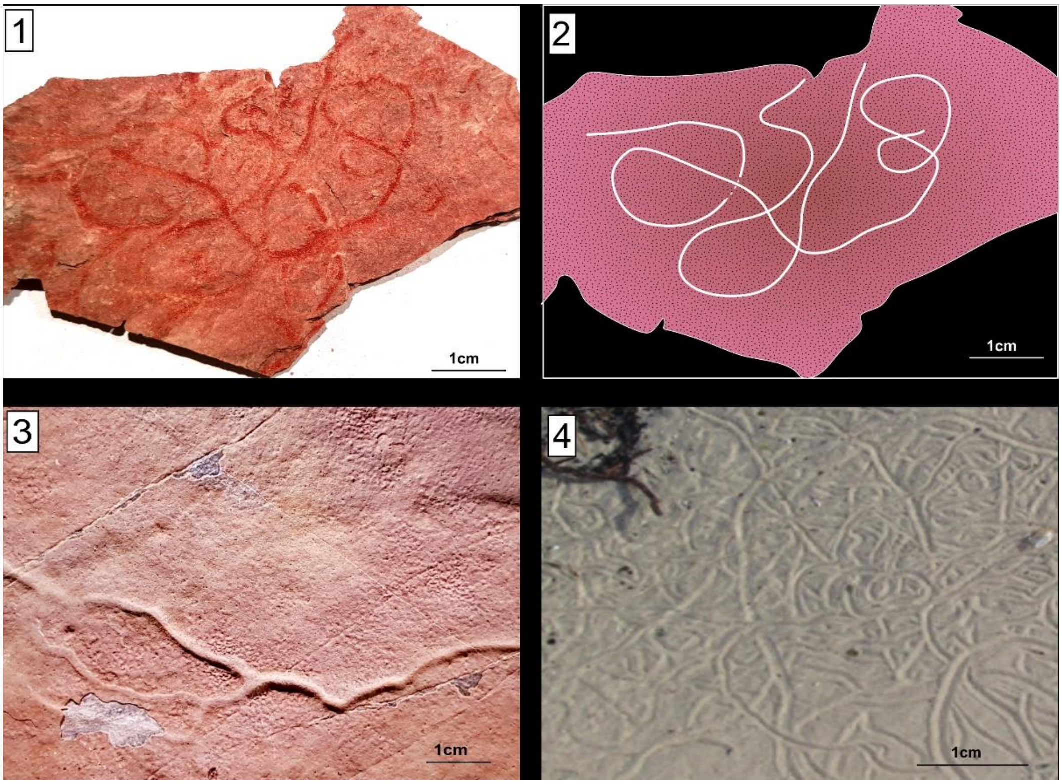


Figure 4. 13. Trace fossils of the Tamengo Formation, Corcal quarry, Corumbá Municipality, Mato Grosso do Sul State, Brazil. 1-2) *Gordia marina* Emmons, 1844; 1. Sample MAF-517; 2) schematic representation of the trace fossil 1; 3) *Pilichnus cf. P. dichotomus* Uchman, 1999, Sample MAF-520; 4) Wormtrack in recent beach sand.

Permineralized microfossils

Permineralized vesicles assigned to *Chuaria circularis* Walcott, 1899, were recovered from pelites of Tamengo Formation at Ecopoarque Cacimba, Corumbá Municipality, Mato Grosso do Sul State, Brazil section. This permineralized vesicles were assigned with *Chuaria circularis* considering the size of the specimens (between 500 and 600 µm), their subcircular morphology and the absence of surface ornamentation, it is assigned as *Chuaria circularis* (Ford & Breed, 1973; Gussow, 1973; Vidal et al., 1993). This species was already been reported in pelites of Tamengo Formation, in the locality of Ecoparque Cacimba (Pacheco, 2012). However, this occurrence was related to only one specimen preserved as a carbonaceous impression, reported to be associated with *Corumbella werneri* Hahn et al., 1982. In addition, few other specimens of *Chuaria circularis* were recovered from palynological macerations (Pacheco, 2012). Permineralized *Chuaria circularis* represents unprecedented preservation and recovery (Figure 4. 14: 5-7) (Adôrno et al., in preparation, appendix 2).

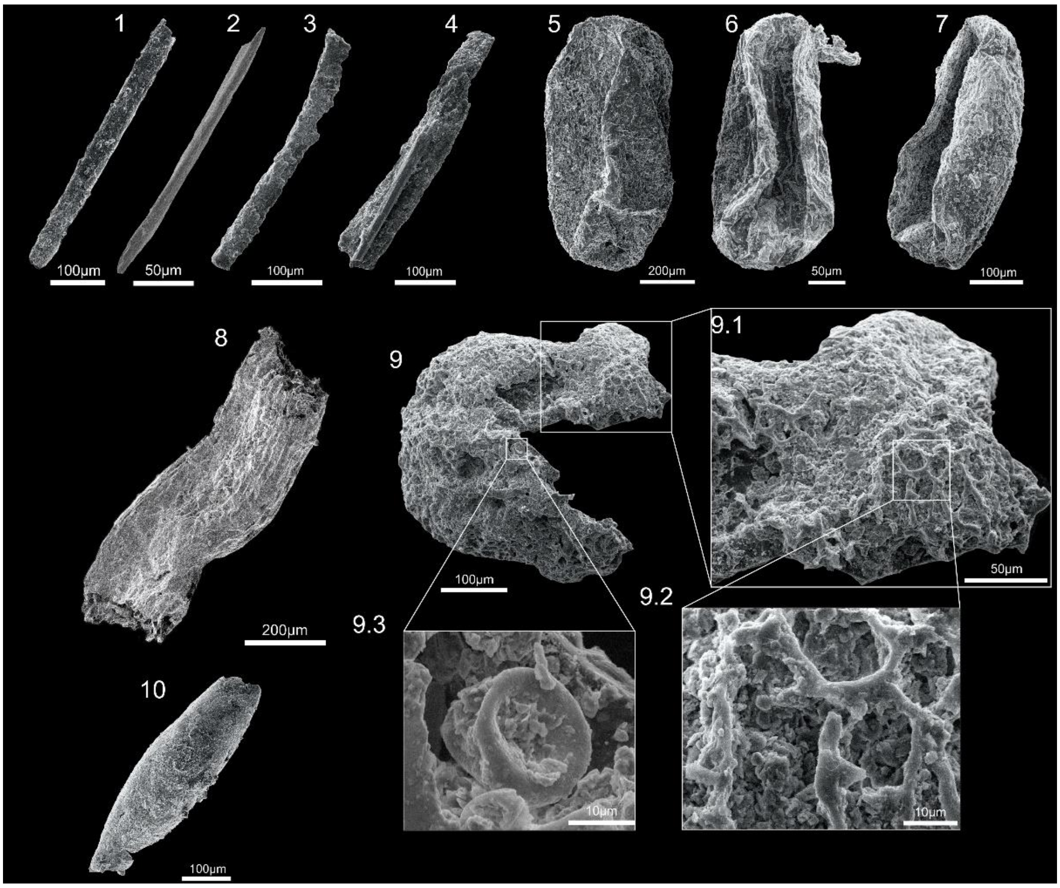


Figure 4. 14. Mineralized and permineralized microfossils from the Tamengo Formation. 1-4 and 13) putative mineralized sponge spicules, 1) MP-1713 Needle-shaped spicule fragment, Porto Sobramil; 2) MP-1649 outcrop of Corcal quarry; 3) MP-1710, Porto Sobramil; 4) MP-1667- Fragment acicular (spicule) fragment encrusted in rock, Laginha quarry; 5-7) Permineralized *Chuaria circularis* Walcott, 1899, 5) MP-1603, Ecoparque Cacimba, 6-7) MP-1607 Ecoparque Cacimba. OBS: Note flattened and folded vesicular appearance on all three specimens; 8) Permineralized fragment of *Vendotaenia antiqua* Gnilovskaya, 1971 MP-1656 Pedreira Corcal, 9) MP-1710 putative mineralized sponge wall fragment, Porto Sobramil, 9.1 Enhanced for cross-linked appearance formed by needles (putative sponge mineralized spicules); 9.2. Even larger zoom showing detail reticulated structure; 9.3. Small microfossil chamber with uncertain taxonomic affinity (sponge gemmule?); 10) Unamed permineralized microfossil vase-shaped microfossil MP-1607 Ecoparque Cacimba.

Organic-walled microfossils

Fifteen species of small sphaeromorphs organic-walled microfossils that possibly represented marine planktic: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann, 1976 in (Timofeev et al., 1976), *Navifusa* sp. and Gen 1. sp. 1 (chitinozoan like flask-shaped).

Additionally, organic fragments of the species *Vendotaenia antiqua* Gnilovskaya, 1971 were recovered in palynological macerations.

From these fifteen species of organic-walled microfossils, five have occurences in both Tamengo and Dengying formations: *Bavlinella faveolata*, *Leiosphaeridia minutissima*, *Leiosphaeridia crassa*, *Leiosphaeridia obsuleta* (Naumova, 1949) and *Ostiama microcystis*. Six of them also occur in the Nomtsas Formation, Namibia: *Bavlinella faveolata*, *Ostiama microcystis*, *Leiosphaeridia crassa*, *Leiosphaeridia obsuleta* (Naumova, 1949), *Leiosphaeridia tenuissima*, *Leiosphaeridia minutíssima*. Four of the fifteen organic-walled microfossils of Tamengo Formation also occur in Tagatiya Guazu Formation, Paraguay: *Ostiama microcystis*, *Leiosphaeridia obsuleta* (Naumova, 1949), *Leiosphaeridia minutissima* and Gen.1 sp. 1 (Adôrno et al., in preparation, appendix 2).

The organic-walled microfossil assemblage of Tamengo, Nomtsas, Tagatiya Guazu and Dengying formations, constitutes small and simple sphaeromorphs (Adôrno et al., in preparation, appendix 2). This assemblage is described as typical for uppermost Ediacaran sections globally distributed (Figure 4. 15; Figure 4. 16 and Figure 4. 17) (Knoll, 1996; Vidal & Moczydlowska-Vidal, 1997; Gaucher, 2000).

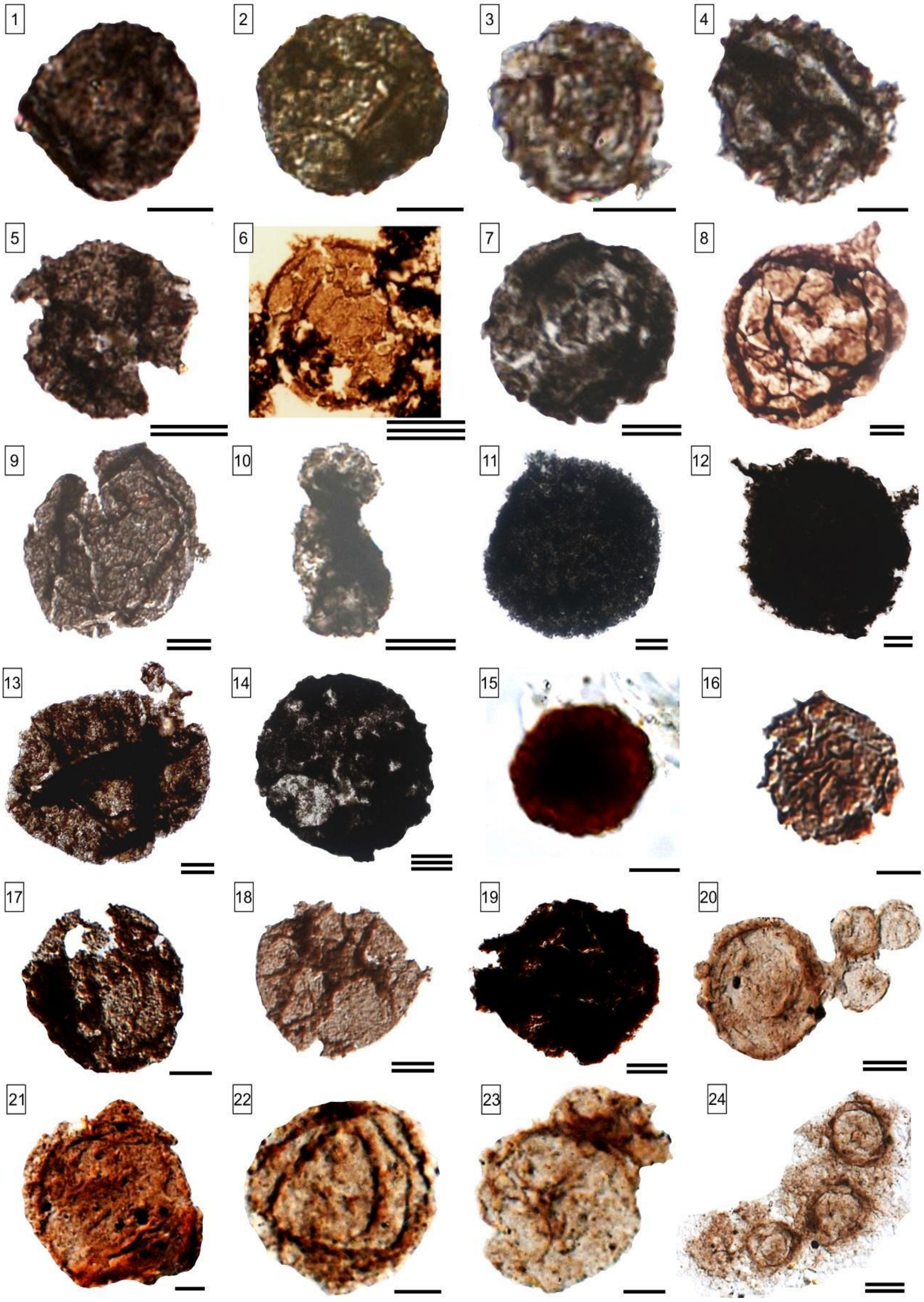


Figure 4. 15. Sphaeromorph organic-walled microfossils from acidic macerations. 1-15) Coming from the Tamengo Formation, Corumbá Group (Brazil); 16-19) From Dengying Formation, China; 20-24) From Tagatiya Guazu Formation, Paraguay. 1-5) *Leiosphaeridia crassa* (Naumova, 1949), specimens and England Finder slide location: 1. CP-941 (original slide number MP-1632) L34[2]; 2. CP-942 (original slide number MP-1626) Q43[3]; 3 MP1626 Y57[2]; 4. CP-943 (original slide number MP-1630) T45; 5. CP-944 (original slide number MP-1633) H54[1]; 6) *Leiosphaeridia tenuissima* Eisenack, 1958: lâmina CP-793; 7) *Lophosphaeridium sp.*: CP-941 (original slide number MP-1632) K53[1]; 9) *Leiosphaeridia obsuleta* (Naumova, 1949): CP-943 (original slide number MP-1630) T45[3]; 10) *Jacutianema* sp.: CP-945 (original slide number MP-1621) G43[3]; 11-12, 19) *Leiosphaeridia obsuleta:* 11. CP-946 (original slide number MP-1714) N55[3], 12. CP-940 (original slide number 1706) V53[4], 19. CP-949 (original slide number MP-2218) S41[4]; 13-14) *Leiosphaeridia jacutica* (Timofeev, 1966): 13. MP1626 T52, 14. CP-947 (original slide number MP-1714) M44; 15) *Bavlinella faveolata* Vidal, 1976: CP-948 (original slide number MP-1636) O46[4]; 8, 16-

18, 20-23) *Leiosphaeridia minutissima* (Naumova, 1949): 8. CP-941 (original slide number MP-1632) L40[2], 16. CP-950 (original slide number MP-2183) E50[3], 18. CP-951 (original slide number MP-2203) B42[1], 20. CP-952 (original slide number MP-4312-II) U40; 21. CP-952 (original slide number MP-4312-II) H27[2], 22) CP-952 (original slide number MP-4312-II) F43. 23. CP-952 (original slide number MP-4312-II) L41[4]; 20, 24) *Ostiama microcystis* * small vesicles: 20. CP-952 (original slide number MP-4312-II) U40, 24. CP-952 (original slide number MP-4312-II) U24. Scale bar: single= 5µm, double= 10 µm and triple=50µm.

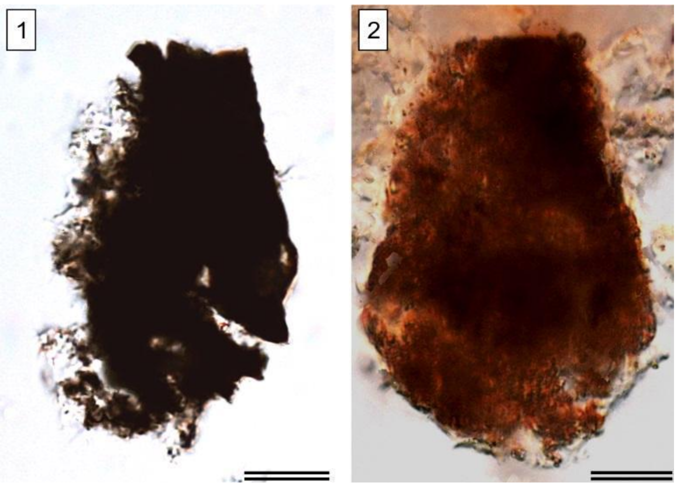


Figure 4. 16. Gen. 1 sp.1. Flask-shaped organic-walled microfossils (Chitinozoa like) recovered from acidic maceration. 1) Specimen and England Finder slide location CP-953 (original slide number MP-1590) C37[1], Tamengo Formation, Corumbá Group (Brazil); 2) CP-952 (original slide number MP-4312)-Q24[2] from Tagatiya Guazu Formation (Paraguay). Scale bar = 10µm.

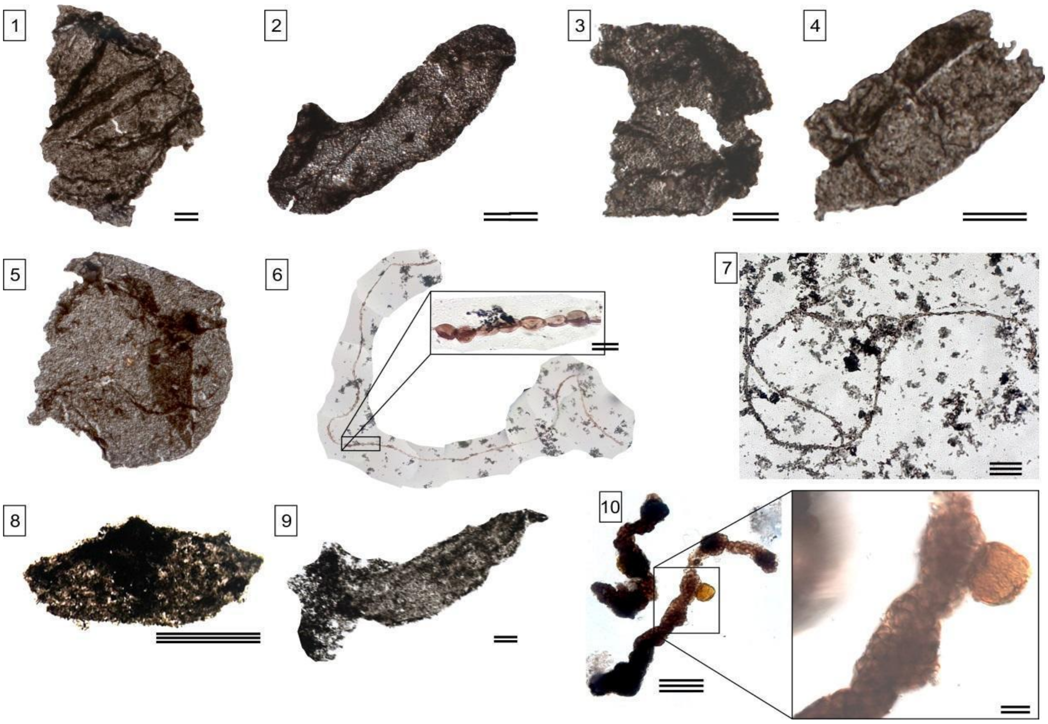


Figure 4. 17. Miscellaneous palynomorphs recovered from acidic macerations. 1-9) Samples from Tamengo Formation, Corumbá Group, Brazil; 10) Specimens from Nama Group, Namibia. 1, 3, 4, 5, 8 and 9) unnamed forms. 2) *Navifusa* sp.; 6) *Arctacellularia januarensis*; 10) *Ostiama microcistis*. Specimens and England Finder slide location 1) CP-943 (original slide number MP-1630) V41[1]; 2) CP-942 (original slide number MP-1626) S56; 3) CP-943 (original slide number MP-1630) D52[2]; 4) CP-943 (original slide number MP-1630) EJ47[3]; 5) CP-943 (original slide number MP-1630) F39[4]; 6) CP-940 (original slide number 1706) X31; 7) CP-940 (original slide number 1706) T33; 8) CP-954 (original slide number MP-3189) S56[2]; 9) CP-947 (original slide number MP-1714) N32[1]; 10) CP-955 (original slide number MP-2289) G44 [4]. Scale bar: double= 10 µm and triple=50µm.

4.2.1. DISCUSSION ON FOSSIL ASSEMBLAGE

The illustrated species presented in this thesis are from the study of the fossil material from samples from upper Corumbá Group, Itapucumi Group, Nama, and Dengying Formation. From the total of 26 studied species, only *Didymaulichnus lyelli* (Rouault, 1850) specimen was not direct studied. This species was included in this thesis due to its availability of positioning in the Guaicurus Formation at Laginha quarry section and its relevance to the understanding of the paleoecology and paleoenvironmental reconstruction during the latest Ediacaran/earliest Cambrian transition.

It is important to mention that the 26 studied species do not represent all the described occurrences for upper Corumbá Group. Only species with information regarding the positioning in the lithostratigraphic log from one of the five studied sections were considered from bibliography, case of the inclusion of *Didymaulichnus lyelli* in the list of studied species. There are many other occurrences form upper Corumbá Group to be studied in order to determine their positioning (first/last appearance datum FAD) in the additional sections and to the complementation of the proposed biostratigraphic framework.

The complete and formal taxonomy is presented for all 26 studied species. The original information such as, type-locality, type-horizon, type-species and other important informations were complemented and presented in the article in preparation (Adôrno et al., in preparation, appendix 2).

For some species, it was presented illustrations from previous publications, it was done because it was not possible to find complete specimens as good as the already published. One of the objectives of this thesis is to be a reference for future identification of the representants of the upper Corumbá Group fossil assemblage. In order to reach this objective, it was considered to present illustrations of complete specimens, rather than to present illustrations of incomplete and fragmented specimens, hard to identify.

4.3. PALEOECOLOGY AND PALEOENVIRONMENTAL INFERENCES

In Brazil, all twenty-six identified species are related to neritic marine paleoenvironment of Corumbá Group. Twenty-one of them are restricted to Tamengo Formation: *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010, *Corumbella werneri* Hahn et al., 1982, *Gordia marina* Emmons, 1844, *Pilichnus cf. P. dichotomus* Uchman, 1999, *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann, 1976 in (Timofeev et al., 1976), *Navifusa* sp. and Gen1. sp. 1. Only *Multina minima* Uchman, 2001 has occurrences in Tamengo and Guaicurus formations. *Vendotaenia antiqua* Gnilovskaya, 1971 occur in occurs not only in Tamengo Formation, but also in lower Corumbá Group strata: Cerradinho and Bocaina formations. Three species have occurrences restricted to Guaicurus Formation: *Eoholynia corumbensis* Gaucher et al., 2003, *Didymaulichnus lyelli* (Rouault, 1850) and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979). It is worthy of note that, Tamengo Formation yielded the greatest diversity of species for the upper Corumbá Group.

Sixteen species of small sphaeromorphs organic-walled microfossils that possibly represented marine planktic: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann in Timofeev et al., 1976, *Navifusa* sp., *Chuaria circularis* Walcott, 1899 and Gen1. Sp. 1. Among this assemblage, *Arctacellularia januarensis*, *Chuaria circularis* and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) were probably photosynthesizers species assigned to cyanobacteria. The *Leiosphaeridia*, *Lophosphaeridium* and *Synsphaeridium* species are considered protist. The other *Bavlinella*, *Ostiama*, *Jacutianema* species are assigned to acritarch group.

Six species represent the benthic assemblage of Tamengo Formation: three sessile epibionts metazoan *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010, *Corumbella werneri* Hahn et al., 1982; sessile epibionts prokaryotic-colony *Vendotaenia antiqua* Gnilovskaya, 1971; two vagile epibiont: *Gordia marina* Emmons, 1844 and *Pilichnus cf. P. dichotomus* Uchman, 1999. The vagile endobiont *Multina minima* Uchman, 2001 occurs in both Tamengo and Guaicurus formations.

Among the three benthic metazoans, *Cloudina lucianoi* has been considered as responsible for the first reef constructions produced by metazoans in several uppermost Edicarian sections (Grotzinger & Al-Rawahi, 2014, Wood, et al., 2011; Penny et al., 2014). The occurrences of *Cloudina lucianoi* in the Tamengo Formation are attributed to carbonate rock interpreted as representing paleoenvironments with low siliciclastic input and in shallow water conditions in the photic zone and microbial mats. On the other hand, the benthic metazoans *Corumbella werneri* and *Cloudina carinata* and in addition, the ichnospecies *Multina minima* have occrurences most frequently associated with layers of siliciclastic rocks of Tamengo Formation. Two hypotheses of paleoenvironmental conditions could explain these siliciclastic layers: deposition in a relatively deeper water column than the carbonate where *Cloudina lucianoi* is recovered; the second hypothesis could be a complement to the first and consists of episodes of higher siliciclastic sediment input condition, which would be responsible for the inhibition of the precipitation of carbonate.

Thin fossiliferous layers composed of fine reddish-colored siltstones are intercalated with afossiliferous gray siltstone layers in the Tamengo Formation at Corcal quarry section. These reddish siltstones present large numbers of occurrences of benthic assemblage mainly represented by *Corumbella werneri*, *Gordia marina, Pilichnus cf. P. dichotomus* and *Vendotaenia antiqua*. The reddish coloration of the thin fossiliferous siltstone layers, could be interpreted as the result of the presence of possibly primary oxidized material, which may represent episodes of oxygenation of the paleoenvironment, concomitantly with episodic colonization by sessile and vagile benthic metazoans. The redish color is confined to continuous layers, which supports at least two explanations: 1) primary oxidized sediments in oxidized paleonvironments; or 2) posterior oxidation of sedimentary rocks deposited in reduced paleoenvironments with presence of material such as sufides. The presence of large number of autochthonous and *in situ* specimens of sessile benthic metazoans and vagile metazoans are suggestive of oxidized paleonvironment. The colonization of the paleoenvironment by these assembled metazoans is not expected in anoxic marine regions.

The assemblage of Guaicurus Formation is represented by two sessile epibenthic species: *Eoholynia corumbensis* and *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) and two vagile endobenthic: *Multina minima* and *Didymaulichnus lyelli* (Rouault, 1850). No microfossil occurrences were recoverd from the Guaicurus formation.

The dramatic change in the fossil assemblage from Tamengo to Guaicurus formations is followed by changes in the depositional paleoenvironment. At Laginha quarry, the Tamengo and Guaicurus formations present an abrupt contact, defined by the dark gray carbonate rocks underlying 1 m of yellowish beige siltstone. The Tamengo Formation was deposited in a favorable paleoenvironment for deposition of carbonates, which was episodically interrupted by immature siliciclastic supply from very fine-grained rocks of a nearby source area. The Guaicurus Formation on the other hand, is a result of an uninterrupted immature siliciclastic supply from a nearby source area, composed of very fine-grained rocks (Fazio et al., 2019).

When comparing paleoenvironmental conditions for deposition of Tamengo and Guaicurus formations, a possibility of these changes contributing to elimination of 95% of uppermost Ediacaran fossil assemblage recovered from Tamengo Formation is clearly seen. Apparently, the greatest part of the twenty-three species of Tamengo Formation disappeared, only the ichnospecies *Multina minima* could exceed the limit between these two formations. Possibly, the endobenthic habit of this ichnospecies could be the strategy to resist the paleonvironmental changes recorded in these two formations of the upper Corumbá Group.

The extinction in the uppermost Tamengo Formation is materialized by the elimination of three epibenthic biomineralizing metazoans: *Cloudina lucianoi*, *Cloudina carinata* and *Corumbella werneri*. The extinction of these species could be correlatetad to the Ediacaran-Cambrian extinction globally recorded (Amthor et al., 2003; Darroch et al., 2018).

Together with the extinction of the three basal cnidarian species, the disappearance of other nineteen epibenthic and planktic species of the Tamengo-Guaicurus transition was also observed: *Gordia marina* Emmons, 1844, *Pilichnus cf. P. dichotomus* Uchman, 1999 and *Vendotaenia antiqua* Gnilovskaya, 1971 plus fifteen species of small sphaeromorphs organic-walled microfossils that possibly represented marine planktic: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum*, *Leiosphaeridia ternata* (Timofeev, 1966), *Leiosphaeridia crassa* (Naumova, 1949), *Leiosphaeridia jacutica* (Timofeev, 1966), *Leiosphaeridia minutissima* (Naumova, 1949), *Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949), *Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp., *Jacutianema* sp., *Lophosphaeridium* sp., *Ostiama microcystis* Hermann in Timofeev et al., 1976, *Navifusa* sp., *Chuaria circularis* Walcott, 1899 and Gen 1. sp. 1. The disappearance of these nineteen species is herein interpreted as possibly a local response related to the Ediacaran-Cambrian extinction (Figure 4. 18).

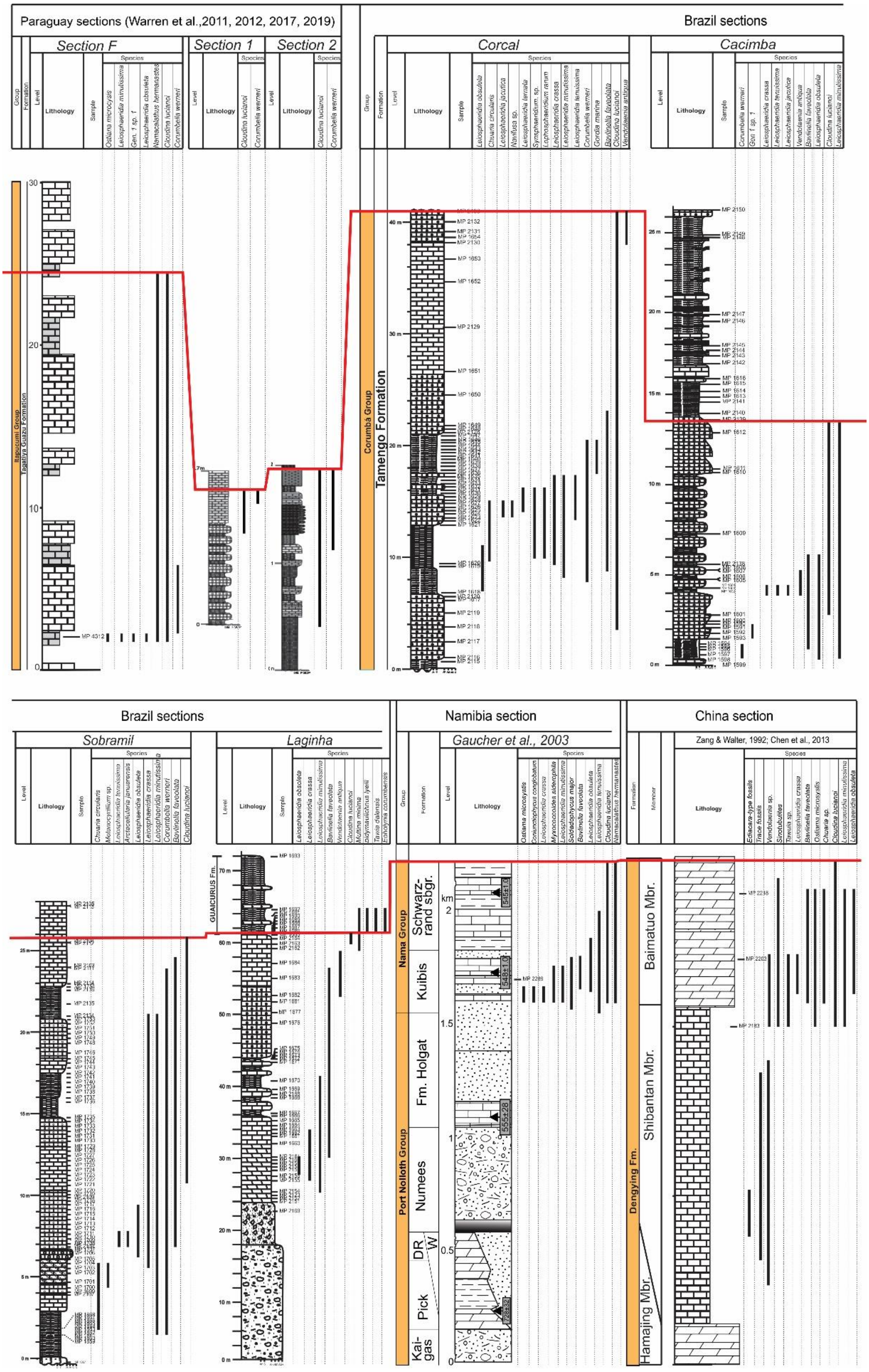


Figure 4. 18. Stratigraphic distribution of the uppermost Ediacaran fossil assemblage of the Tamengo Formation and the additional complementary micropaleontology species for section in Paraguay (after Warren et al., 2011), Namibia (after Gaucher et al., 2005) and China (after Chen et al., 2013). The red line marks the extinction of epibenthic biomineralizing metazoan: *Cloudina lucianoi*, *Cloudina carinata* and *Corumbella werneri*.

The chronostratigraphic positioning of the extinction and disappearance of species at the upper Corumbá Group as related to the global Ediacaran-Cambrian extinction is reinforced by the age of 541.85 ± 0.75 Ma for ash beds at the upper portion Tamengo Formation at Corcal quarry section (Figure 4. 19) (Parry et al., 2017). Moreover, it is worth mentioning that all occurrences of the planktic organic-walled microfossil assemblage from Tamengo Formation have small size (majority between 5 - 70µ diameter). Moreover, no organic-walled microfossil was found in the Guaicurus Formation. The small size of the Tamengo Formation planktic assemblage could indicate some biological pressure "somehow Lilliput effect related", which could have culminated in complete disappearance of this planktic assemblage in the Guaicurus Formation.

Furthermore, it is not expected much younger age than early Cambrian, Furtunian, for deposition of Guaicurus Formation, due the influence of Brasiliano deformation, which is constrained to 550–520 Ma as one of the latest events in the Brasiliano Orogeny (Alvarenga & Trompete, 1992; Trompette, 1994; Pimentel et al., 1996). which limits the minimum age of the Guaicurus Formation at least to the Cambrian, based on the age of São Vicente Granite 528±4Ma (Trivelli, 2016).

As comented by Gaucher et al. (2003), "the uppermost units of the Corumbá Group (Guaicurus Formation) might reveal the Proterozoic/Cambrian transition as well". Besides in this publication, clear boundary between Ediacaran/Cambrian systems were not provided. According to Boggiani et al. (2010), based on occurrences of *Eoholynia corumbensis,* at least the base of this formation could still be latest Ediacaran. It is herein considered an early Cambrian age for deposition of Guaicurus Formation, based on mass extinction recorded in the uppermost Tamengo/lowermost Guaicurus formations, were only *Multina minima* could survive and co-occur with the sudden appearance of *Eoholynia corumbensis* in the Guaicurus Formation. This characteristic corroborate the hypothesis of a younger assemblage for Guaicurus Formation, due the absence of *Eoholynia corumbensis* in the Tamengo Formation.

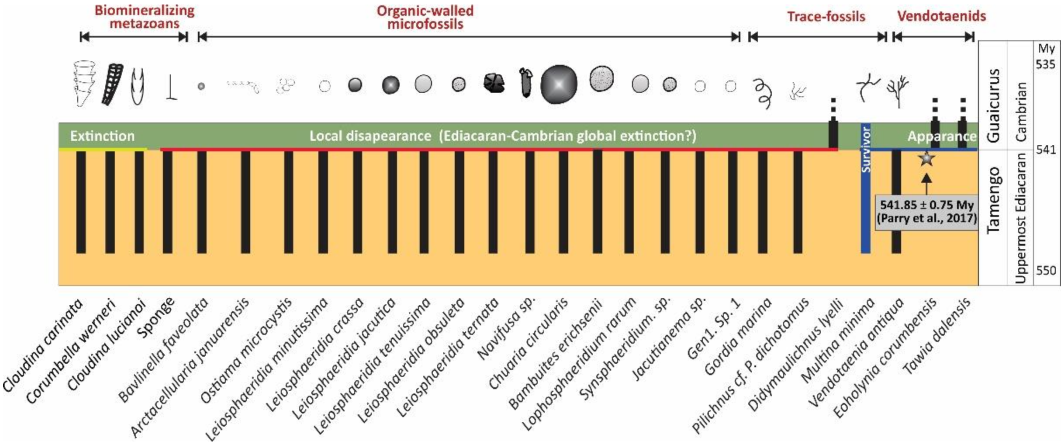


Figure 4. 19. Generalized stratigraphic distribution of the fossil assemblage of Tamengo and Guaicurus formations. Note the greater diversity of species in Tamengo and the red line indicating the local extinction event possibly related to the Ediacaran-Cambrian (E-C) global extinction.

Occurrences of *Cloudina lucianoi*, *Cloudina carinata*, *Cloudina riemkeae*, *Gordia marina*, *Corumbella werneri* and *Namacalathus hermanastes* were plotted in the paleogeographic map showing the reconstruction of Proto-Gondwana in 550 Ma (Warren et al., 2017). Warren et al. (2017) presents a discussion on paleobiogeography in which the occurrences of *Namacalathus hermanastes* in the paleogeographic reconstruction presented in Trindade et al., (2006); Li et al., (2008); Tohver et al., (2012) show that this species has spread through several oceans and interior seas surrounding low latitude paleocontinents. The scenario was complemented with paleogeographic distribution of four additional species: *Cloudina lucianoi*, *Cloudina carinata*, *Cloudina riemkeae*, *Gordia marina*, *Corumbella werneri* (**Figure 4. 20**).

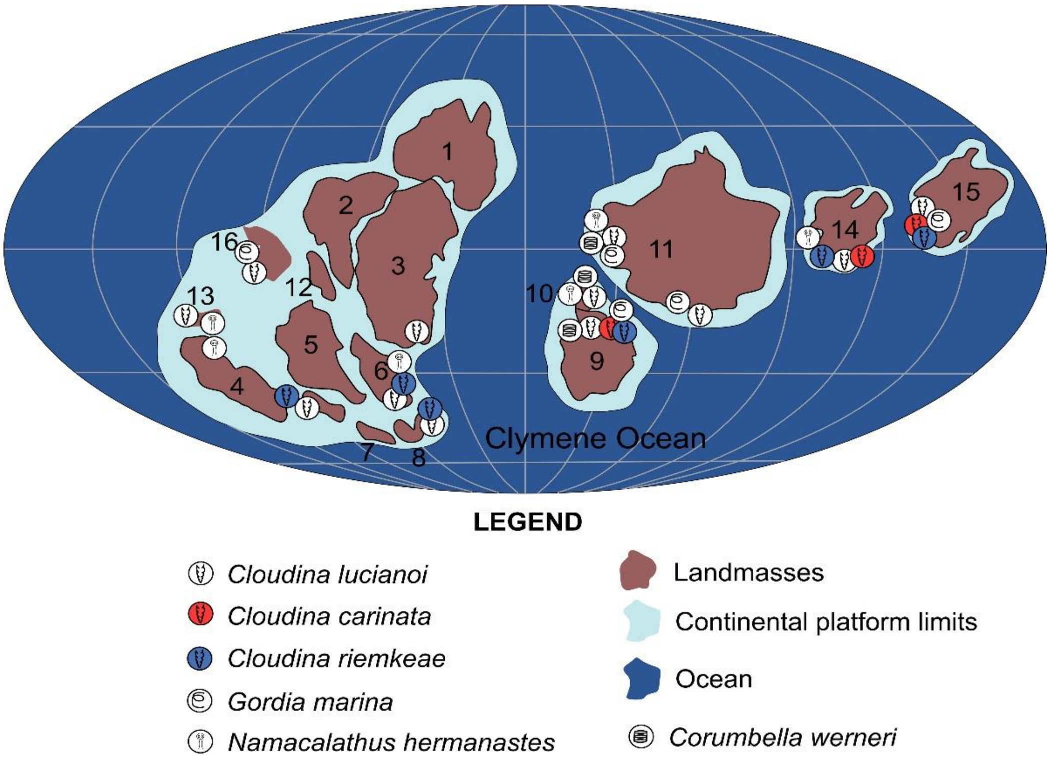


Figure 4. 20. Paleogeographic reconstructions of Gondwana ca. 550 Ma highlighting the *Cloudina lucianoi*, *Cloudina carinata*, *Cloudina riemkeae*, *Gordia marina*, *Corumbella werneri* and *Namacalathus hermanastes*-occurrences. 1 – Australia, 2 – India, 3 – Antarctica, 4 – West Africa, 5 – Congo-São Francisco, 6 – Kalahari, 7 – Paraná, 8 –Rio de la Plata, 9 – Amazonia, 10 – Rio Apa, 11 – Laurentia, 12 – Madagascar, 13 – Arabia-Nubia, 14 – Siberia, 15 – Baltica, 16 – Yangtze Block (South China). The paleogeographic reconstruction is based on Germs (1972), Yochelson and Stump (1977), Hagadorn and Waggoner (2000), Grotzinger et al. (2000), Hofmann and Mountjoy (2001), Amthor et al. (2003), Gaucher et al. (2003), Trindade et al. (2006), Li et al. (2008), Kontorovich et al. (2008), Warren et al. (2011), and Tohver et al. (2012), Merdith et al., (2017) (Modified from Warren et al., 2017).

4.3.1. DISCUSSION ON PALEOECOLOGY AND PALEOENVIRONMENTAL INFERENCES

The update on the paleogeographic map presented in this thesis is related to the use of taxonomy in species level. As it is possible to note at Figure 4. 20, there seems to be a corridor of occurrences of assembled species *Cloudina lucianoi*, *Cloudina carinata*, and *Cloudina riemkeae* in the paleo margins of the paleocontinents South America, West Africa, Baltica and Siberia. In terms of paleolatitude, *Cloudina lucianoi* has the widest distribution among the analized species, occurring since low latitudes to the equator, indicating the highest tolerance to variation in temperature. The occurrences of *Gordia marina* is restricted to high latitudes, indicating to a certain point, colonization of warm water regions.

The strategy of dispersion of *Cloudina* species and *Namacalathus* could be similar to modern benthic cnidarians, where the larvae can be transported to long distances (Warren et al., 2017). It could explain why these species are so widespread through almost all paleocontinents during the terminal Ediacaran.

4.4. BIOSTRATIGRAPHIC ESSAY

The first formal biostratigraphic units for the uppermost Ediacaran in Brazil and Paraguay were proposed by Adôrno et al. (2017). These biostratigraphic frameworks are composed of three biozones, from top: 1) *Cloudina lucianoi/Corumbella werneri* Interval Zone; 2) *Corumbella werneri* Range Zone; 3) *Corumbellla werneri/Cloudina lucianoi* Interval Zone (Adôrno et al., 2016b; Adôrno et al., 2017). These three biozones were originally recognized in Brazil and Paraguay sections.

In addition to those three biozones proposed by Adôrno et al. (2017), it is herein presented four new biostratigraphic unities, from the base to the top, respectively named: *Cloudina* Assemblage Superzone, *Bavlinella faveolata - Leiosphaeridia minutissima* Assemblage Subzone, *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone and *Eoholynia corumbensis* Range Zone.

Cloudina Assemblage Superzone presents the widest geographic and stratigraphic distributions, covering all 15 analyzed uppermost Ediacarian sections: Paraguay (three, Warren et al., 2011, 2013, 2017, 2019), Uruguay (one, Gaucher et al., 2003), Argentina (one Gaucher et al., 2005b), Namibia (one Gaucher et al., 2005a), China (one, Zang & Walter, 1992; Chen et al., 2013), Russia (one, Kontorovich et al., 2008, 2009), Canada (one Hofmann & Mountjoy, 2001), the United States of America (one Hagadorn & Waggoner, 2000), Oman (one, Amthor et al., 2003) and herein Brazil (four).

Cloudina Assemblage Superzone is divided into three biozones: *Cloudina lucianoi/Corumbella werneri* Interval Zone; *Corumbella werneri* Range Zone and *Corumbellla werneri/Cloudina lucianoi* Interval Zone (Adôrno et al., 2016b; Adôrno et al., 2017). These three biozones are geographically distributed in sections of Brazil (three sections) and Paraguay (three) (Adôrno et al., 2017). *Bavlinella faveolata - Leiosphaeridia minutissima* Assemblage Subzone is inserted at the base of *Corumbella werneri* Range Zone, distributed in sections from Brazil, Argentina, Uruguay, Namibia and China. *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone is inserted at the upper portion of the *Corumbella werneri/Cloudina lucianoi* Interval Zone, distributed in sections from Brazil, Namibia, China and Siberia. Finally, above other biostratigraphic unities is inserted *Eoholynia corumbensis* Range Zone recognized at the base of Guaicurus Formation, Laginha quarry, lowermost Cambrian.

Considering the criteria presented in Adôrno et al. (2017), the Corcal quarry was chosen as type-locality for all proposed biozones except for *Eoholynia corumbensis* Range Zone, which has the type-locality placed at Laginha quarry. The proposition of all seven biostratigraphic unities follows the recommendations of the International Stratigraphic Code, exploring three kinds of biozones: Interval Zone, Range Zone and Assemblage Zone (Figure 4. 21).

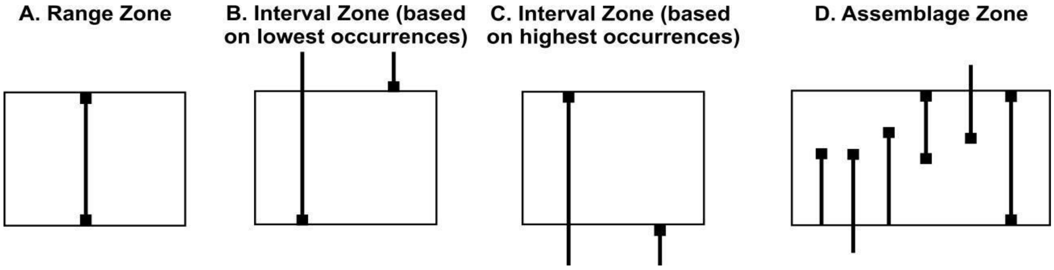


Figure 4. 21. Examples of kinds of biozones used in this biostratigraphic framework (International Stratigraphic Code).

A range biozone is a body of rock representing the known stratigraphic and geographic range of occurrence of any selected element or elements of the chosen fossil taxon, or taxa, present in the rock record. Two kinds of range biozone were explored: taxon-range biozone and concurrent range zone. An interval biozone is a body of rock between two specified biostratigraphic surfaces. The features on which biohorizons were defined here are based on lowest occurrences and highest occurrences. An assemblage biozone is a body of rock characterized by a unique association of three or more taxa, the association of which distinguishes it in biostratigraphic character from adjacent strata. An assemblage biozone may be based on a single taxonomic group, for example, trilobites, or on more than one group, such as acritarchs and metazoans, for example (International Stratigraphic Code).

4.4.1. *Cloudina* Assemblage Superzone - new unit

The *Cloudina* Assemblage Superzone is a biostratigraphy unit characterized by the occurrence of species of genera, such as: *Cloudina, Corumbella, Sinotubulites, Conotubus* and *Namacalathus*. The base of *Cloudina* Assemblage Superzone is characterized by the lowermost occurrence of assembled species, and the top is characterized by the uppermost occurrence of assembled species. This superzone has a lower geochronological resolution, and it was proposed as an essay of a correlation tool to be applied especially when the taxonomic studies which are of biomineralizing species are left in open nomenclature. This superzone occurs in all 15 examined sections (Figure 4. 22).

4.4.2. *Cloudina lucianoi*/*Corumbella werneri* Interval Zone (Adôrno et al., 2017)

The base of the *Cloudina lucianoi*/*Corumbella werneri* Interval Zone is characterized by the first occurrence of *Cloudina lucianoi*, and the top of this zone is characterized by the first occurrence of *Corumbella werneri* (Figure 4. 22). This biozone spans only in South America because *Corumbella werneri* has not yet been found in another continent, so this biozone is useful for international correlation between Brazil and Paraguay until now.

4.4.3. *Corumbella werneri* Range Zone (Adôrno et al., 2017)

The base and top of *Corumbella werneri* Range Zone are marked by the first and last occurrences of *Corumbella werneri*, respectively (Figure 4. 22). This biozone spans only in South America because *Corumbella werneri* has not yet been found in another continent, so this biozone is useful for international correlation between Brazil and Paraguay until now.

4.4.4. *Corumbella werneri/Cloudina lucianoi* Interval Zone (Adôrno et al., 2017)

The base of *Corumbella werneri/Cloudina lucianoi* Interval Zone is characterized by the last occurrence of *Corumbella werneri*, and the top of this zone is marked by the extinction of *Cloudina lucianoi* (Figure 4. 22). This biozone spans only in South America as a result of the same reason given for the other two above. Stratigraphic distribution of *Corumbella werneri* in Laginha quarry has not yet been presented, considering the lack of stratigraphic distribution of this species at this locality, so far, this biozone was not recognized at Laginha quarry. Future studies dealing with occurrences and stratigraphic distribution of *Corumbella werneri* might contribute to better understanding of upper Ediacaran biomineralizing metazoans applied to uppermost Ediacaran biostratigraphy.

4.4.5. *Bavlinella faveolata-Leiosphaeridia minutissima Assemblage Subzone* - new unity

Bavlinella faveolata - *Leiosphaeridia minutissima* Assemblage Subzone, *Bf-Lm* – ASZ, is characterized by the assemblage of six species: *Bavlinella faveolata, Leiosphaeridia minutissima, Leiosphaeridia obsuleta* (Naumova, 1949), *Cloudina lucianoi*, *Cloudina riemkeae, Corumbella werneri*. The base of *Bf-Lm* -ASZ is marked by the first occurrence of *Leiosphaeridia minutissima* or the first occurrence of *Cloudina lucianoi* when the first is absent. The top of *Bf-Lm* -ASZ is marked by the first occurrence of *Bavlinella faveolata* (Figure 4. 22). This biozone is a subzone inserted at the base of the *Corubmella werneri* Range Zone.

4.4.6. *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone - new unity

Vendotaenia antiqua-Cloudina lucianoi Concurrent-Range Subzone is characterized by the occurrences of two species: *Vendotaenia antiqua* and *Cloudina lucianoi.* The base of this subzone is marked by the first occurrence of *Vendotaenia antiqua* and the top by the last occurrence of *Cloudina lucianoi.* This subzone occurs at six localities, three in Brazil, Namibia, China and Siberia. In Brazil, these localities are: Ecoparque Cacimba, Corcal quarry and Laginha quarry sections (Figure 4. 22). In Corcal quarry and Ecoparque Cacimba sections, this subzone is recognized at the upper portion of the *Corumbella werneri/Cloudina lucianoi* Interval Zone, uppermost Ediacaran.

4.4.7. *Eoholynia corumbensis* Range Zone - new unity

The base and top of *Eoholynia corumbensis* Range Zone are characterized by the first and last occurrences of *Eoholynia corumbensis*. The type-locality of this biozone is Laginha quarry section, lowermost Cambrian (Figure 4. 22). Considering five studied sections in Brazil, this biozone is restricted to Laginha quarry, the sole locality which also outcrops Guaicurus Formation. New occurrences of *Eoholynia corumbensis* would improve the analysis of stratigraphic distribution, as well as, to evaluate its significance of this biozone for the lowermost Cambrian.

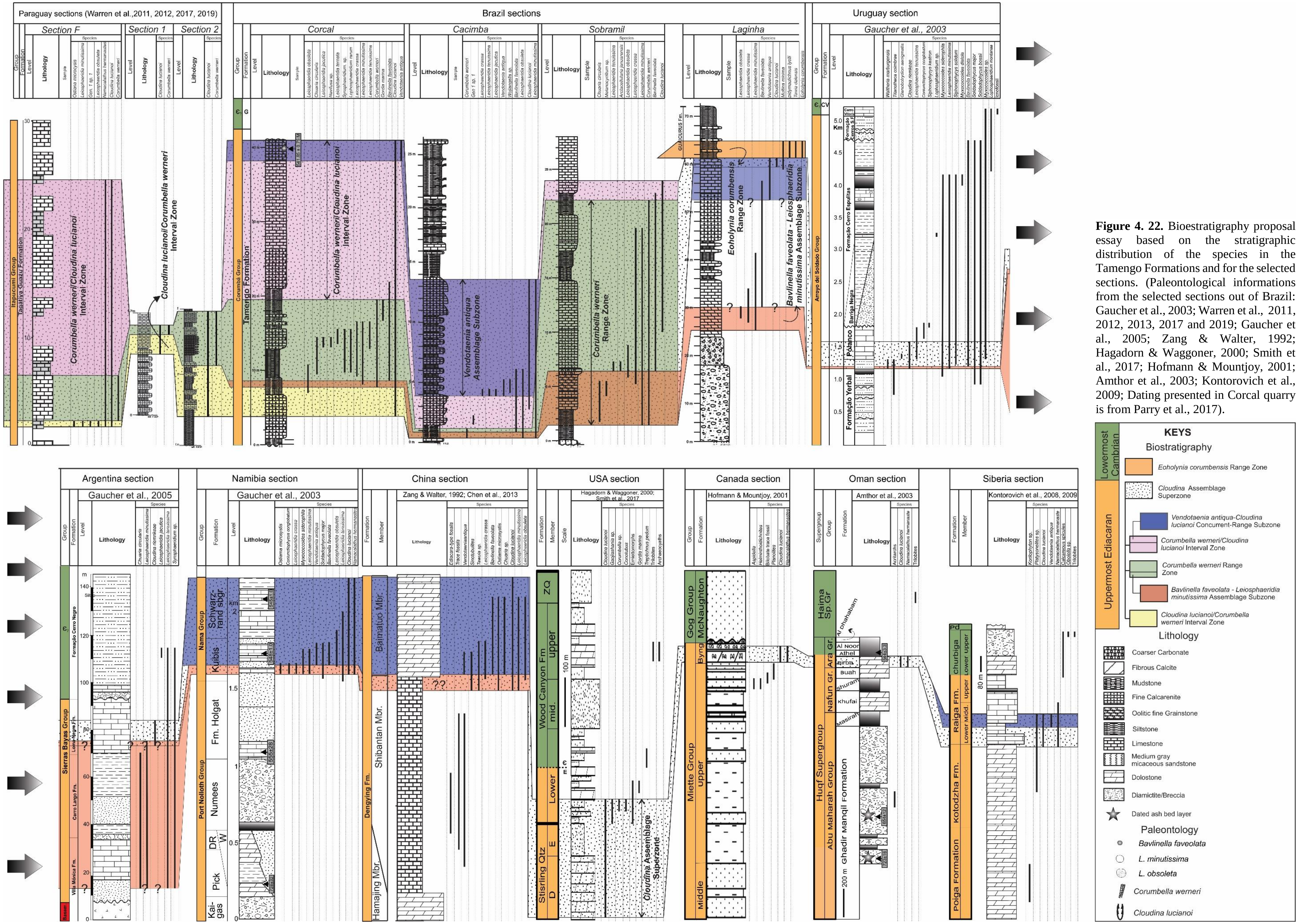


Figure 4. 22. Bioestratigraphy proposal essay based on the stratigraphic distribution of the species in the Tamengo Formations and for the selected sections. (Paleontological informations from the selected sections out of Brazil: Gaucher et al., 2003; Warren et al., 2011, 2012, 2013, 2017 and 2019; Gaucher et al., 2005; Zang & Walter, 1992; Hagadorn & Waggoner, 2000; Smith et al., 2017; Hofmann & Mountjoy, 2001; Amthor et al., 2003; Kontorovich et al., 2009; Dating presented in Corcal quarry is from Parry et al., 2017).

4.2.1. DISCUSSION ON BIOSTRATIGRAPHY RECORD

All seven proposed biozones presented herein are based on the first and last appearance datum. For the five studied sections in Brazil, the information regarding the fossil occurrences was obtained during the field works. For the sections of Namibia, China and Paraguay the information of the occurrences are compilations of the bibliography information added to data from new samples preparations. For the sections of Argentina, Uruguay, USA, Canadá, Oman, and Siberia, the information of the occurrences came from the bibliographic compilation.

The biostratigraphic framework presented herein represents a work in progress and it is expected to be tested in order to evaluate its validity and potential for relative dating the Ediacaran-Cambrian boundary in South America and also to be useful for international correlation. Ash beds have been identified at the lower and upper portion of the Tamengo Formation allowing to define the age of the beginning and end of deposition of Tamengo Formation (Babinski et al., 2008; Parry et al., 2017). The identification of new ash beds from upper Corumbá Group could be helpful for calibrating the geochronology of these biozones. This data allied with further studies on paleontological characterization for Guaicurus Formation would certainly improve the chronobiostratigraphic framework for the Ediacaran/Cambrian boundary in South America.

CHAPTER – 5: CONCLUSIONS

The fossil assemblage recovered from the Tamengo and Guaicurus formations is composed of twenty-six species. Twenty-two have occurrences restricted to Tamengo Formation and three species are restricted to Guaicurus Formation. Only *Multina minima* Uchman, 2001 has occurrences in both Tamengo and Guaicurus formations.

From the total twenty-three species of Tamengo Formation, three were epibenthic biomineralizing sessile: *Cloudina lucianoi* (Beurlen & Sommer, 1957), *Cloudina carinata* Cortijo et al., 2010, *Corumbella werneri* Hahn et al., 1982 and an indeterminate species of poriferous. Three ichnospecies represent activity of vagile benthic organisms: *Multina* *minima* Uchman, 2001, *Gordia marina* Emmons, 1844 and *Pilichnus cf. P. dichotomus* Uchman, 1999. *Multina minima* were endobiot organisms while *Gordia marina* and *Pilichnus cf. P. dichotomus* were vagile epibiont on water-sediment interface. In addition, sixteen species probably derived from planktic organisms were recovered. Fifteen species of small sphaeromorphs organic-walled microfossils that possibly represented marine planktic: *Arctacellularia januarensis* Denezine, 2018 *nomem nudum, Leiosphaeridia ternata* (Timofeev, 1966)*, Leiosphaeridia crassa* (Naumova, 1949)*, Leiosphaeridia jacutica* (Timofeev, 1966)*, Leiosphaeridia minutissima* (Naumova, 1949)*, Leiosphaeridia tenuissima* Eisenack, 1958, *Leiosphaeridia obsuleta* (Naumova, 1949)*, Bavlinella faveolata* Vidal, 1976, *Bambuites erichsenii* Sommer, 1971, *Synsphaeridium* sp.*, Jacutianema* sp.*, Lophosphaeridium* sp.*, Ostiama microcystis* Hermann in Timofeev et al., 1976*, Navifusa* sp. and Gen1. sp. 1; and one species of permineralized microfossils *Chuaria circularis* Walcott, 1899. The sessile epibionts prokaryotic-colony *Vendotaenia antiqua* was previously reported in Cerradinho and Bocaina formations, and herein their latest occurrences and extinction are recorded in the mass extinction event recorded in uppermost Tamengo Formation.

Four species represent the benthic fossil assemblage for Guaicurus Formation: *Eoholynia corumbensis* Gaucher et al., 2003, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979)*, Multina minima* and *Didymaulichnus lyelli* (Rouault, 1850). From the total, three species have occurrences restricted to this formation: *Eoholynia corumbensis*, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) and *Didymaulichnus lyelli*, only *Multina minima* has shared occurrences with Tamengo Formation. It is worthy of note that, Tamengo Formation yielded the greatest diversity of species for terminal Ediacaran Corumbá Group.

A dramatic change was recorded in the fossil assemblage from Tamengo to Guaicurus formations with disappearance of almost 95% of the species from Tamengo to Guaicurus formations. The mass extinction event recorded in the uppermost Tamengo

Formation is materialized by the elimination of three epibenthic biomineralizing metazoan: *Cloudina lucianoi*, *Cloudina carinata* and *Corumbella werneri*. Other nineteen epibenthic and planktic species disappeared in the uppermost Tamengo Formation. The contact between Tamengo and Guaicurus Formation is concordant and it is marked by the appearance of three new species: *Eoholynia corumbensis*, *Tawuia dalensis* Hofmann, 1979 in (Hofmann & Aitken, 1979) and *Didymaulichnus lyelli*. Only *Multina minima* survived the mass extinction event that occurred across Ediacaran to Cambrian boundary. This local mass extinction is herein correlated to the uppermost Ediacaran-Cambrian extinction event, which together with the dating of the ash bed in the upper Tamengo Formation, reinforce the hypothesis of lowermost Cambrian age for the Guaucurus Formation. The small size of the Tamengo Formation planktic assemblage could indicate some biological pressure "somehow Lilliput effect related", which could have culminated in complete disappearance of this planktic assemblage in the Guaicurus Formation. Furthermore, it is not expected much younger age for Guaicurus Formation, due the presence of Brasiliano deformation, which is constrained to 550–520 Ma as one of the latest events in the Brasiliano Orogeny (Pimentel et al., 1996; Trompette, 1994) which limits the minimum age of the Guaicurus Formation at least to the Cambrian, based on the age of São Vicente Granite 528±4Ma (Trivelli, 2016).

In addition, a change in the depositional paleoenvironment from Tamengo to Guaicurus formations was also observed. The Tamengo Formation was deposited in a favorable paleoenvironment for deposition of carbonates, which was episodically interrupted by immature siliciclastic supply. The Guaicurus Formation on the other hand, is a result of an uninterrupted immature siliciclastic supply.

Moreover, five species of organic-walled microfossils were recovered and identified from samples of the Dengying Formation, China: *Bavlinella faveolata*, *Leiosphaeridia minutissima*, *Leiosphaeridia crassa*, *Leiosphaeridia obsuleta* (Naumova, 1949) and *Ostiama microcystis*; Nine species from samples from Nama Group, Namibia:

Bavlinella faveolata, *Ostiama microcystis*, *Leiosphaeridia crassa*, *Leiosphaeridia obsuleta* (Naumova, 1949), *Leiosphaeridia tenuissima*, *Leiosphaeridia minutissima*, *Soldadophycus major*, *Coniunctiophycus conglobatum* and *Myxococcoides siderophila*. Four species in the Tagatiya Guazu Formation, Paraguay: *Ostiama microcystis*, *Leiosphaeridia obsuleta* (Naumova, 1949) and *Leiosphaeridia minutissima* and Gen. 1 sp. 1. The micropaleontological result for these sections complemented the scarce record of species of organic-walled microfossils from the uppermost Ediacaran.

Based on the stratigraphic and geographic distribution of the studied fossil assemblage, seven biozones were proposed, from bottom to top: *Cloudina* Assemblage Superzone that is distributed in all 15 analyzed sections in Brazil, Paraguay, Uruguay, Argentina, United States, Canada, Namibia, Oman, Russia and China. Inserted in this superzone, there are three biozones, distributed in sections of Brazil and Paraguay: *Cloudina lucianoi/Corumbella werneri* Interval Zone; *Corumbella werneri* Range Zone; and *Corumbellla werneri/Cloudina lucianoi* Interval Zone. It was possible to propose two subzones: *Bavlinella faveolata - Leiosphaeridia minutissima* Assemblage Subzone inserted in the base of *Corumbella werneri* Range Zone and *Vendotaenia antiqua-Cloudina lucianoi* Concurrent-Range Subzone at the upper portion of the *Corumbella werneri/Cloudina lucianoi* Interval Zone. The first subzone spans across Brazil, Argentina, Uruguay, Namibia and China, and the second across Brazil, Namibia, China and Siberia. Finally, *Eoholynia corumbensis* Range Zone was proposed for the base of Guaicurus Formation at Laginha quarry, lowermost Cambrian. The geographic distribution of this biozone is apparently restricted to Laginha quarry locality, so far.

Future studies involving taxonomy and stratigraphic distribution of the uppermost Ediacaran fossil assemblage would be of great importance for advances in biostratigraphy. Special attention must be given to the occurrences of *Cloudina* sp. reported in the Sete Lagoas Formation, Bambuí Group, mainly aiming at stratigraphic positioning and precise taxonomic positioning for those occurrences. Furthermore, studies on biology especially in the areas of phylogeny and morphology compared with metazoan, in addition to in-depth studies on the microbiota of the uppermost Ediacaran, should be encouraged. Chemical analysis of the skeleton of calcifying metazoans must be done, in order to determine if the original chemistry remains preserved, and if so it could be useful to reconstruct the paleoenvironmental conditions. Future work on the identification of new levels of volcanic ash, and geochemical characterization of the ashes already identified at the Corcal quarry must be done. The Laginha quarry section must be studied in more detail, aiming to discover new biomineralizing metazoans occurrences such as *Cloudina lucianoi*, *Cloudina carinata* and *Corumbella werneri* presenting their stratigraphic distribution. Additional locations with Guaicurus Formation are crucial to be studied in order to evaluate validity of the biostratigraphic framework and dating the Ediacaran-Cambrian boundary in South America.

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APPENDIX

Appendix 1: Scientific production from this research.

Authors	Year	Complete article (Journal and DOI)	Title
Walde et al.	2015	Annales de Paléontologie 101 (2015) 213–224 <http://dx.doi.org/10.1016/j.annpal.2015.07.002>	New aspects of Neoproterozoic-Cambrian transition in the Corumbá region (state of Mato Grosso do Sul, Brazil)
Adôrno et al.	2017	Precambrian Research 301 (2017) 19–35 <http://dx.doi.org/10.1016/j.precamres.2017.08.023>	*Cloudina lucianoi* (Beurlen & Sommer, 1957), Tamengo Formation, Ediacaran, Brazil: Taxonomy, analysis of stratigraphic distribution and biostratigraphy
Adôrno et al.	2018	Precambrian Research 317 (2018) 271–274 <http://dx.doi.org/10.1016/j.precamres.2017.08.023>	Reply to comment on Adôrno et al. (2017) "*Cloudina lucianoi* (Beurlen & Sommer, 1957), Tamengo Formation, Ediacaran, Brazil: Taxonomy, Analysis of Stratigraphic Distribution and Biostratigraphy"
Fazio et al.	2019	Journal of South American Earth Sciences 90 (2019) 487–503 <https://doi.org/10.1016/j.jsames.2018.11.025>	Mineralogical and chemical composition of Ediacaran-Cambrian politic rocks of The Tamengo and Guaicurus formations, (Corumbá Group - MS, Brazil): Stratigraphic positioning and paleoenvironmental interpretations
Authors	**Year**	**Scientific meeting**	**Title**
Adôrno et al.	2015	XIV Simpósio de geologia do Centro-Oeste	Implicações estratigráficas das ocorrências de Espécies do Gênero *Cloudina* no Brasil
Adôrno et al.	2016	35th International Geological Congress Capetown, Session: The dawn of animals, abstr., paper 4131.	Three-dimensional *Cloudina* specimens extraction from limestone of the Nama Group, Namibia.
Adôrno et al.	2016	35th International Geological Congress, Capetown, Session: The dawn of animals, abstr., paper 4144.	Biostratigraphy of Neoproterozoic strata based on invertebrate species from South America.
Adôrno et al.	2018	International Conference on Ediacaran and Cambrian Sciences Xi'an China.	Taxonomic remarks and stratigraphic implication of *Cloudina* species in Neoproterozoic strata
Erdtmann et al.	2018	International Conference on Ediacaran and Cambrian Sciences Xi'an China.	The multiple (?) Ediacaran/Cambrian boundary hiatus: possible causes and consequences.

Appendix 2: Adôrno et al. (in preparation): Taxonomy and stratigraphic distribution of fossil assemblage from Tamengo and Guaicurus formations, Corumbá Group, Ediacaran-Cambrian boundary in the Midwest of Brazil.

Taxonomy and stratigraphic distribution of the fossil assemblage from Tamengo and Guaicurus formations, Corumbá Group, Ediacaran-Cambrian boundary in the Midwest of Brazil