UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

FÁCIES CARBONÁTICAS DA FORMAÇÃO TERESINA NA
BORDA CENTRO-LESTE DA BACIA DO PARANÁ

Johanna Méndez Duque

Orientador: Prof. Dr. André Oliveira Sawakuchi

DISSERTAÇÃO DE MESTRADO
Programa de Pós-Graduação em Geoquímica e Geotectônica

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LESTE DA BACIA DO PARANÁ”**

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***“I am neither especially clever nor especially gifted,
I am only very, very curious”***
Albert Einstein

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ÍNDICE

Fácies carbonáticas da Formação Teresina na borda centro-leste da Bacia do Paraná

RESUMO.....	1
ABSTRACT.....	3
Apresentação.....	5
1. INTRODUÇÃO.....	6
2. Aspectos geológicos da área de estudo.....	6
2.1 Considerações litoestratigráficas	6
2.2 Contexto tectônico-estrutural	9
3. Área de estudo	12
4. Discussão	13
5. Conclusões.....	15
Referências	15

Tectonic-climate controls on carbonate and evaporite sedimentation in the Teresina Formation, Late Permian of the Paraná Basin, southern Gondwana

ABSTRACT	22
1. Introduction	23
2. Study area	24
3. Geological background	25
4. Material and methods	28
5. Results	28
5.1 Sedimentary Facies.....	28
5.2 Carbonate facies distribution	38
6. Discussion.....	42
6.1 Controls on carbonate and evaporite sedimentation in the Teresina Formation	42
6.2 Implications for the paleogeography of the southwestern Gondwana during the Permian.....	45
7. Conclusions	47

Acknowledgements	47
References	47

Calcite-dolomite lamination and organic nanostructures in stromatolites of the Teresina Formation, Permian of the Paraná Basin

ABSTRACT	54
1. INTRODUCTION	55
2. THE TERESINA FORMATION	55
3. MATERIALS AND METHODS	56
4. RESULTS	57
4.1 Stromatolite beds and associated facies.....	57
4.2 Stromatolite lamination	57
4.3 Microbial filaments	59
5. Discussion.....	64
6. Conclusions	67
ACKNOWLEDGMENTS	67
References	67

ÍNDICE DE FIGURAS

Fácies carbonáticas da Formação Teresina na borda centro-leste da Bacia do Paraná

Figura 1. Localização da Bacia do Paraná. Modificado de Zalán <i>et al.</i> (1991).....	7
Figura 2. Carta estratigráfica da Bacia do Paraná. Modificada de Milani (1997).....	10
Figura 3. Principais elementos estruturais da Bacia do Paraná, segundo Stollhofen <i>et al.</i> (2000). Modificado de Zalán <i>et al.</i> (1990).....	11
Figura 4. Mapa geológico com a localização das estações de campo. Modificado de CPRM (2006).....	12

Tectonic-climate controls on carbonate and evaporite sedimentation in the Teresina Formation, Late Permian of the Paraná Basin, southern Gondwana

Figure 1. A. The Paraná Basin location in South America. B. Location of the study area (blue square) and principal tectonic elements. Modified from Zalán <i>et al.</i> (1991).....	25
---	----

Figure 2. Stratigraphic chart of the Paraná Basin. Modified from Milani <i>et al.</i> (2007). Litostratigraphical formations of each sequence. <i>Rio Ivaí sequence</i> : ALG: Alto Garças, IAP: Iapó, VLM: Vila Maria. <i>Paraná sequence</i> : FUR: Furnas, PGR: Ponta Grossa, JGR: Jaguariaíva Member, TBJ: Tibagi Member, SDM: São Domingos Member. ORT: Ortigueira Diamictite. <i>Gondwana I sequence</i> : LAZ: Lagoa Azul, CMO: Campo Mourão, ITA: Itaraté, AQU: Aquidua, TAC: Campo do Tenete, RSL: Rio do Sul, DRD: Siderópolis, RBN: Rio Bonito, PLM: Palermo, IRT: Irati, SAL: Serra Alta, TRS: Teresina, CBT: Corumbataí, RRT: Rio do Rasto, SCB: Sanga do Cabral, PIR: Pirambóia. <i>Gondwana II</i> : SM: Santa Maria. <i>Gondwana III</i> : BOT: Botucatu, SGL: Serra Geral.....	26
---	----

Figure 3. A) Dolomite crystals in breccia. B) Anhydrite (An) cement filling channels. C) and D) Hopper texture in dolomite indicating possible pseudomorphs of halite. E) Sword-shape gypsum pseudomorphs replaced by calcite. F) Romboedric dolomite crystals. G) Interlamination of wavy calcite (Ca) and dolomite (Do) levels in tabular boundstone facies. Chert nodule (N) interrupting the lamination (parallel polarizers). H) Alternation of sub-millimeter calcite (Ca) and dolomite (Do) levels in tabular boundstone facies (crossed polarizers).....	30
--	----

Figure 4. Columnar sections representative of the carbonate and evaporite facies succession in the studied region.....	32
--	----

Figure 5. A) Stylolites in bioclastic wackstone facies. B) Calcite (Ca) and gypsum (Gy) cements filling a cavity in a fenestral mudstone. C) Chalcedony (Ch) filling intergranular and intragranular porosities in a dissolved ooid (so). Ooids with concave-	
---	--

convex contact showing chemical compaction (mc). D) Authigenic quartz (Aq) with border replaced by calcite (Cc). E) Drusy (Dr) and mega quartz (Mg) filling a bivalve shell. F) Fragmented fish scale by mechanical compaction. G) Ooids with contacts sutured by chemical compaction (Mc). H) Fractures cutting the chert nodule (Ns) and the horizontal vein of calcite. Fragmented fish scale by mechanical compaction (Mc).....34

Figure 6. A) Bed of chert nodules (nodular and enterolithic chert facies). B) Deformed chert nodules. C) and D) Continuous level of chert. D) Bitumen in level of chert. F) Silicified tepee. G) and H) Silicified breccia.....37

Figure 7. A) Barite (Ba) cement attached to the borders of a calcite (Ca) crystal. B) Crystals of barite (Ba) within calcite (Ca). C) Cubic crystals of halite (arrows). D) Barite with strontium (BaS) replacing calcite (Ca).....38

Figure 8. A) and b) Amalgamated bars of oolitic packstone-grainstone facies. C) and D) Cross-stratification in oolitic grainstone. D.a) Rose diagram showing the mean vector of the preferential trend of the cross-stratifications. D.b) Rose diagram showing the values within the confidence interval of 99%. E) Detail of radial ooids.....39

Figure 9. A) Isopach map of the Teresina Formation based on data from wells and columnar sections. B) Map of frequency of occurrences of carbonate facies. Both maps are in meter units.....42

Figure 10. Schematic model of the carbonate ramp depositional system interpreted for the Teresina Formation in the studied region, with the respective facies deposited according the ramp part. Modified from Burchette and Wright (1992). WL: water level, FWB: fair-weather wave base, SWB: storm wave base.....44

Figure 11. A) Reconstruction of West Gondwana during the Late Paleozoic. Modified from Faure and Cole (1999). B) Paleogeographic reconstruction of South Gondwana during the Paleozoic. Modified from Visser and Praekelt (1996). P: Paraná Basin, H: Huab Basin, SA: Serras Australes, KH: Kalahari Basin, K: Karoo Basin, E: Ellsworth Basin.....46

Calcite-dolomite lamination and organic nanostructures in stromatolites of the Teresina Formation, Permian of the Paraná Basin

Figure 1. Geologic map showing the location of the study site. Modified from CPRM (2006).....58

Figure 2. Studied outcrop with the boundaries of the stromatolite bed marked by red lines.....59

Figure 3. Facies succession comprising the studied stromatolite bed.....60

Figure 4. A) Alternation of sub-milimeter levels of calcite (Ca) and dolomite (Do). Crossed polarizers. B), D) and E) Chert nodule interrupting and deforming the carbonate levels. Parallel polarizers. C) Disarticulated ostracode shells (Os) forming

continuous levels. D) and E) Alternate bands of calcite (Ca) and dolomite (Do) under parallel polarizers. E) and G) Blue fluorescent levels corresponding to dolomite bands rich in organic matter (ultraviolet light fluorescence).....61

Figure 5. Polyhedrons formed by extracellular polymeric substances (EPS).....62

Figure 6. Model illustrating stages of the microfabric formation of stromatolites. Modified from Spadafora *et al.* (2010).....62

Figure 7. SEM photomicrographs. A) and B) Tubular filaments of large diameter. C) and D) Biofilm formed by branching large diameter filamentous. The bacteria links the minor filaments. E) and F) Extracellular polymeric substances (EPS) linking bacteria. G) Cross section of a calcified filament, and spherical nanoglobules (sns). H) Moldic porosity of tubular filaments.....63

Figure 8. A. Map of Early Triassic paleogeography. Modified from Baud *et al.* (1989). B) Histogram of normal-marine level bottom stromatolites. S: Silurian. D: Devonian. M: Mississippian. P: Pennsylvanian. P: Late Permian. T: Early Triassic. J: Jurassic. K: Cretaceous. Cz: Cenozoic. Modified from Schubert and Bottjer (1992).....66

RESUMO

A Formação Teresina, Neopermiano da Bacia do Paraná, é uma unidade estratigráfica principalmente terrígena, com algumas ocorrências de fácies carbonáticas, sendo depositada durante a última fase regressiva do mar epicontinental da bacia. O ambiente deposicional da Formação Teresina, especialmente no que se refere às suas fácies carbonáticas, ainda é alvo de debate. As fácies carbonáticas da Formação Teresina e fácies evaporíticas associadas ocorrem em toda a formação, mas são mais freqüentes no norte do Estado do Paraná e no sul do Estado de São Paulo, na porção superior da unidade. Esta região constitui a área de estudo desta dissertação, que visou interpretar os processos sedimentares básicos, assim como fatores tectônicos e climáticos que influenciaram a formação destes depósitos carbonáticos e evaporíticos. Para isto, foram utilizadas informações de poços e realizados levantamentos detalhados de seções colunares, com coleta de amostras para análises petrográficas por microscopia óptica e microscopia eletrônica de varredura (MEV). Foram identificadas e descritas oito fácies carbonáticas e/ou evaporíticas: *mudstone* com conchas de ostracodes, *mudstone* peloidal, *packstone* bioclástico, *wackstone* bioclástico, *boundstone* tabular, *packstone-grainstone* oolítico, brecha de *mudstone-chert* e *chert* enterolítico-nodular. O sistema deposicional foi interpretado como uma rampa carbonática com zona interna alta protegida por barreiras arenosas influenciadas por ondas e correntes associadas. Nas partes mais rasas, os períodos áridos e de intensa evaporação e baixo aporte terrígeno provocariam aumento da salinidade e induziria a deposição das fácies evaporíticas de *chert* enterolítico-nodular e brecha de *mudstone-chert*. A porção intermediária corresponderia à zona protegida da ação das ondas, com águas rasas e baixa energia. Isto permitiria a deposição de sedimentos finos por decantação, que constituem as fácies *mudstone* com conchas de ostracodes e *wackstone* bioclástico. Nesta mesma porção, as condições geoquímicas da água teriam incentivado atividade microbiana, gerando as fácies *mudstone* peloidal e *boundstone* tabular. Bandas ricas em dolomita identificadas em fácies de *boundstone* tabular no norte do Estado do Paraná estariam relacionadas com precipitação mineral induzida por atividade microbiana. Filamentos e nanoestruturas orgânicas observadas podem corresponder a remanescentes fossilizados de *extracellular polymeric substance* (EPS), usados por bactérias redutoras de sulfato nos procesos de precipitação da dolomita-calcita. A ação das ondas causava agitação constante da água, o que originaria a sedimentação das fácies *packstone-grainstone*

oolítico em baixios e das fácies heterolíticas terrígenas em zona distal entre o nível de base das ondas de tempo bom e o nível de base das ondas de tempestade. Mapas de isópacas e de frequência de ocorrência de calcários elaborados a partir da integração dos dados de poços e seções colunares demonstraram aumento da concentração de calcários no flanco norte do Arco de Ponta Grossa (APG). A espessura da formação aumenta em direção ao APG. Em algumas regiões próximas ao APG, as isópacas tornam-se paralelas ao eixo desta estrutura tectônica. Os resultados obtidos sugerem que o Arco de Ponta Grossa atuou como barreira geográfica que restringiu a entrada de águas do oceano vindas do sul e influenciou a deposição das fácies carbonáticas e evaporíticas. A restrição da circulação das águas promoveu o aumento da salinidade na área imediatamente ao norte do arco. Além disso, uma provável zona de convergência de ventos paralela ao Arco de Ponta Grossa e situada ao sul da área de estudo teria dificultado a entrada de massas de ar úmido provenientes do Oceano Panthalassa vindas de sul. Isto favoreceu a instalação de condições áridas na área de estudo. O significado tectônico e climático das fácies carbonáticas e evaporíticas da Formação Teresina podem auxiliar as correlações entre a Bacia do Paraná e bacias na África, tais como as bacias do Huab e Karoo, além de contribuir para reconstruções paleogeográficas do Gondwana no final do Permiano.

Palavras-chave: fácies carbonáticas e evaporíticas, estromatólitos, Formação Teresina, Bacia do Paraná, Permiano, Gondwana.

ABSTRACT

The Teresina Formation, Late Permian of the Paraná Basin, is mainly composed of terrigenous sediments, with some occurrences of carbonate and evaporite facies. It corresponds to the upper portion of the last regressive phase of the Paraná Basin epicontinental sea. The depositional system responsible for the carbonate and evaporite facies of the Teresina Formation is still target of discussion. These facies occur in a huge area of the basin, but they have a greater thickness and are more frequent in the north of the Paraná State and in the southern of the São Paulo State, in the upper portion of the formation. This region constitutes the study area of this dissertation in order to interpret the depositional processes as well as the tectonic and climatic factors acting during the formation of these deposits. The study included the interpretation of data from wells, detailed description of columnar sections, with sampling for petrographical analysis under the optical and scanning electron microscopes (SEM). Eight carbonate and/or evaporite facies were identified: mudstone with ostracod shells, peloidal mudstone, bioclastic wackstone, bioclastic packstone, tabular boundstone, oolitic packstone-grainstone, nodular and enterolithic chert and mudstone-chert breccia. The depositional system was interpreted as a carbonate ramp with a protected zone by growth of oolitic sand bars and sediment transport dominated by wave action and associated currents. In the inner regions, arid periods of intense evaporation and low terrigenous input would increase the salinity, causing the deposition of enterolithic and nodular chert and mudstone-chert breccia facies. The intermediate portion corresponds to a lagoon with shallow and low energy waters, allowing the deposition of fine grained sediments recorded in the mudstone with ostracod shells and bioclastic wackstone facies. In the same portion, the hypersaline conditions of the water would have stimulated microbial activity, promoting the deposition of peloidal mudstone and tabular boundstone facies. Dolomite bands identified in the tabular boundstone facies in the north of the Paraná State are enriched in organic matter and they would be associated to mineral precipitation induced by microbial activity. Organic filaments and nanostructures may correspond to fossilized remains of extracellular polymeric substance (EPS), which are used by sulfate-reducing bacteria in the precipitation of dolomite-calcite. The wave action remobilized bottom sediments, causing constant waters agitation. This induced sedimentation of oolitic packstone-grainstone facies in shoals and the terrigenous heterolithic facies between the fair-weather and storm wave

bases. Maps of isopachs and frequency of occurrences of limestones show concentration of limestones in the north flank of the Ponta Grossa Arch (PGA). The thickness of the formation increases from south to north towards the PGA. In some regions near the PGA, isopachs are parallel to the axis of this tectonic structure. The obtained results suggest that the Ponta Grossa Arch influenced the deposition of the carbonate and evaporite facies of the Teresina Formation, acting as a geographical barrier that restricted the entry of ocean waters from south. This promoted reduced terrigenous input, low water circulation and the increase of salinity in the northern flank of the PGA. Furthermore, a possible winds convergence zone, parallel to the Ponta Grossa Arch, would affected the climatic conditions in the study region during the Late Permian, difficulting the northward migration of wet air masses coming from the Panthalassa Ocean. This favored arid conditions in the study area. The tectonic and climatic significance of the carbonate and evaporite facies of the Teresina Formation have important implications for correlations between the Paraná Basin and basins from Africa, such as the Karoo and Huab basins, as well as for paleogeographic reconstructions of the Gondwana in the Permian.

Key-words: carbonate and evaporite facies, stromatolites, Teresina Formation, Paraná Basin, Permian, Gondwana.

Apresentação

Esta dissertação inclui texto introdutório, que envolve os objetivos do estudo, contexto geológico da Formação Teresina e a discussão integrada dos resultados, acompanhada das principais conclusões. Os resultados e suas interpretações detalhadas são apresentados na forma de dois artigos anexos. O artigo *Tectonic-climate controls on carbonate and evaporite sedimentation in the Teresina Formation, Late Permian of the Paraná Basin, southern Gondwana* foi submetido para publicação no periódico *Journal of Sedimentary Research*. Este artigo abrange a descrição macroscópica e microscópica e a análise regional da distribuição de facies carbonáticas e evaporíticas da Formação Teresina, os fatores tectônicos e climáticos que condicionaram sua sedimentação e sua relação com a paleogeografia do Gondwana durante o Neopermiano. Esta análise foi feita através da integração de informações de poços, análise petrográfica de amostras e seções colunares levantadas em afloramentos distribuídos na borda leste da Bacia do Paraná, especialmente ao norte do Arco de Ponta Grossa.

O segundo artigo intitulado *Calcite-dolomite lamination and organic nanostructures of the Teresina Formation, Permian of the Paraná Basin* foi submetido para publicação no periódico *Geobiology*. O tema principal deste artigo é a descrição e origem da laminação microbiológica formada pela alternância entre calcita e dolomita e de estruturas orgânicas associadas, identificadas em estromatólitos coletados no norte do Estado do Paraná. Estes estromatólitos constituem a facies carbonática *tabular boundstone* descrita no primeiro artigo.

1. INTRODUÇÃO

A Bacia do Paraná é uma gigantesca bacia de tipo intracratônico, com uma área aproximada de 1.600.000 km², que se localiza no sul do Brasil, nos estados de Mato Grosso, Mato Grosso do Sul, Goiás, Minas Gerais, São Paulo, Paraná, Santa Catarina e Rio Grande do sul; no norte e noroeste do Uruguay; e na Argentina e Paraguay (Fig. 1).

Diversos estudos já foram realizados sobre a Formação Teresina (Fanton *et al.*, 2006; Neregato *et al.*, 2008; Rohn, 2007, Milani *et al.*, 2007, Neves *et al.*, 2010, Holz *et al.*, 2010), mas a maior parte destes trabalhos concentrou-se em aspectos da paleontologia e estratigrafia, de modo que ainda há poucos estudos de detalhe sobre as suas fácies carbonáticas, especialmente os microbialitos. Os estudos sobre as fácies evaporíticas da Formação Teresina também são escassos. Assim, esta dissertação trata das características petrográficas, distribuição regional, geometria e do ambiente deposicional destas fácies. O estudo destes temas serviria para aprofundar o conhecimento acerca dos controles sobre a gênese de fácies carbonáticas e evaporíticas e o seu eventual uso como modelo de reservatórios carbonáticos de petróleo e gás.

Os controles que influenciaram a sedimentação das fácies carbonáticas e evaporíticas da Formação Teresina constituiriam informação importante para o entendimento da evolução da paleogeografia do sul do Gondwana durante o Permiano, além de permitir correlações com as unidades equivalentes em bacias da África.

Os objetivos principais desta dissertação são a caracterização macroscópica e microscópica das fácies carbonáticas e evaporíticas da Formação Teresina e a descrição da distribuição geográfica destas fácies. Os métodos utilizados nesta pesquisa foram a análise petrográfica, a análise de fácies em afloramentos e caracterização da espessura e distribuição espacial das fácies carbonáticas por meio de dados de poços. Isto envolveu a elaboração de colunas estratigráficas de detalhe, análise de paleocorrentes e microscopia óptica e eletrônica de varredura (MEV). Para diferenciar minerais carbonáticos ao microscópio óptico, as seções delgadas foram tingidas com alizarina vermelha e ferricianato de potássio diluído em HCl 1,5% (Dickson, 1966). A descrição detalhada dos métodos empregados no estudo encontra-se nos artigos anexos.

2. Aspectos geológicos da área de estudo

2.1 Considerações litoestratigráficas

O termo **Estrada Nova** foi utilizado pela primeira vez por White (1908), para denominar uma seqüência formada por folhelhos cinza e variegados e arenitos, que aflora na

estrada entre as cidades de Lauro Müller e São Joaquim (SC). Moraes Rego (1930) empregou pela primeira vez o termo **Teresina**, para designar os sedimentos da Formação Estrada Nova encontrados na margem direita do rio Ivaí perto da Cidade de Teresa Cristina (PR).

Figura 1. Localização da Bacia do Paraná. Modificado de Zalán *et al.* (1991).

Maack (1947) sugeriu uma possível correlação da Formação Estrada Nova com as unidades permianas da África do Sul. Gordon Jr (1947) subdividiu a Formação Estrada Nova nos membros Serra Alta (membro inferior) e Teresina (membro superior). O Membro Serra Alta corresponderia aos 30 a 40 m superiores da Formação Irati de White, enquanto que o Membro Teresina incluiria, de acordo com Gordon Jr (1947): *“os folhelhos calcíferos, arenitos finos ou calcários arenosos e calcários oolíticos parcial ou inteiramente silicificados”*.

Neste trabalho, é utilizada a nomenclatura estratigráfica de Schneider *et al.* (1974), que subdivide o Grupo Passa Dois nas formações: Irati, Serra Alta, Teresina e Rio do Rasto, nas porções central e sul da Bacia do Paraná. A norte do lineamento do Rio Tietê, nos estados de São Paulo, Mato Grosso e Goiás, o Grupo Passa Dois está formado pelas formações Irati e Corumbataí.

A partir da década de 1960, foram publicados vários trabalhos sobre a estratigrafia da Bacia do Paraná, entre os quais encontra-se o estudo de Northfleet *et al.* (1969), que faz integração de dados geológicos e apresenta características litológicas, contatos e espessuras das unidades estratigráficas. Destaca-se também o trabalho de Daemon & Quadros (1970), que através da análise palinológica sugerem idades para as unidades que compõem o Grupo Passa Dois.

A Formação Teresina faz parte da porção superior do Grupo Passa Dois e foi definida como uma sucessão sedimentar composta predominantemente por siltitos, com algumas camadas de arenitos, calcários e silexitos.

O sistema deposicional responsável pela sedimentação da Formação Teresina ainda é objeto de discussão, principalmente em relação ao ambiente deposicional, se marinho ou lacustre, e aos processos sedimentológicos que geraram as estruturas sedimentares (Figueiredo Filho, 1972; Lavina, 1991; Rohn, 1994; Elias *et al.*, 2000). Schneider *et al.* (1974), Zaine (1980), Petri & Coimbra (1982) e Sousa *et al.* (1991) interpretam que esta formação se depositou em ambiente marinho raso, com planícies de maré. Holz *et al.* (2010) sugerem que a Formação Teresina é produto de sistema deposicional de costa-afora a planície costeira, influenciado por tormentas.

Segundo Runnegar & Newell (1971), a malacofauna das formações Serra Alta, Teresina e do Membro Serrinha é endêmica. O endemismo dos bivalves e outros invertebrados indicaria a falta de conexão direta entre a Bacia do Paraná e o Oceano Panthalassa (Maranhão, 1995; Simões *et al.*, 1998; Mello, 1999). Já na década de 1954 alguns autores tinham identificado o isolamento da Bacia do Paraná durante a deposição da Formação Teresina. Beurlen (1954, 1955) sugeriu uma bacia de mar intracontinental, de baixa salinidade, com conexão estreita e rasa com o oceano aberto. Rohn (2007) sugeriu um mar epicontinental sem ligação com o Oceano Panthalassa.

No centro-sul do Estado de São Paulo, a Formação Teresina situa-se entre as formações Serra Alta, abaixo, e Pirambóia, acima. O contato entre as formações Teresina e Serra Alta é transicional (Rohn, 2001; Meghioratti, 2006), caracterizado pelo aumento ascendente de rochas heterolíticas cinza e bioturbação. Nos estados do Paraná e Santa

Catarina, o contato entre as formações Teresina e o Membro Serrinha (Formação Rio do Rasto), de acordo com Meglhioratti (2006), é abrupto e corresponderia ao aparecimento de grandes corpos de arenitos com grânulos e intraclastos na base. No Estado de São Paulo, o contato entre o Grupo Passa Dois e a Formação Pirambóia é discordante para Soares (1973) e Caetano-Chang (1993), e concordante, de acordo com Matos (1995), Giannini et al. (2004) e Milani *et al.* (2007).

O equivalente estratigráfico das formações Serra Alta e Teresina é a Formação Corumbataí, a qual está restringida ao norte e nordeste da Bacia do Paraná (Schneider *et al.*, 1974). Porém, de acordo com Ragonha (1984), a fauna de *Xenacanthus* encontrada na Formação Corumbataí se estenderia até o Triássico, idade mais jovem que a comumente atribuída à Formação Teresina, de idade Permiana. A espessura da Formação Teresina é de aproximadamente 280-330 metros na parte central na borda leste da Bacia do Paraná (Holz *et al.*, 2010).

Milani *et al.* (1994, 2007) reconheceram que a Bacia do Paraná foi influenciada por ciclos eustáticos-tectônicos e dividiu o seu preenchimento em seis supersequências: Rio Ivaí (Eo-Ordoviciano – Eosiluriano), Paraná (Devoniano), Gondwana I (Eocarbonífero – Eotriássico), Gondwana II (Triássico), Gondwana III (Neojurássico – Eocretáceo) e Bauru (Cretáceo) (Fig. 2). O Grupo Passa Dois, que pertence à supersequência Gondwana I, registra tendência regressiva e o isolamento progressivo da Bacia do Paraná.

Na Bacia do Paraná foram caracterizados dois sistemas petrolíferos efetivos (Milani & Zalán, 1999, Artur & Soares, 2002), o sistema Ponta Grossa – Itararé e o sistema Irati-Rio Bonito – Pirambóia. A Formação Teresina constitui parte deste último sistema, que é considerado atípico, pela influência de magmatismo básico cretáceo na geração e migração dos hidrocarbonetos (Zalan *et al.*, 1991, Araújo *et al.*, 2000).

2.2 Contexto tectônico-estrutural

Na região de estudo, o Arco de Ponta Grossa (APG) constitui a estrutura tectônica mais importante (Fig. 3). Esta estrutura apresenta direção NW-SE e exerceu um controle tectônico e estratigráfico sobre a bacia pelo menos desde o Devoniano (Northfleet *et al.*, 1969, Ferreira, 1982). Entre o Jurássico e o Eocretáceo, o APG adquiriu sua atual configuração, sendo que as fraturas e falhas de distensão deram acesso ao magma basáltico que originou centenas de diques (Almeida, 1986). Toda a sedimentação da Bacia do Paraná

está influenciada principalmente por elementos tectônicos com direção NW e NE (Zalán *et al.*, 1991).

Figura 2. Carta estratigráfica da Bacia do Paraná. Modificada de Milani (1997).

Outro grupo de estruturas na Bacia do Paraná é representado por estruturas E-W, cuja atividade começaria no Triássico. Estas estruturas são paralelas às zonas de fraturas oceânicas, sugerindo uma relação com a abertura do Oceano Atlântico (Zalán *et al.*, 1991). Sanford & Lange (1960) sugerem que o APG dividia a bacia em duas grandes depressões. De acordo com Fúlfaro (1970), a Bacia do Paraná também teria sido dividida em duas sub-bacias, uma localizada ao sul do APG, a qual abrangia os estados do Paraná, Santa Catarina e sul do Mato Grosso, e outra ao norte do APG, que compreenderia Goiás, o centro-leste de Mato Grosso e a maior parte de São Paulo. Daemon & Aboarrage (1976) interpretam que o APG iniciou sua atividade no Eopermiano, causando hiatos deposicionais, diminuição do aporte sedimentar e a divisão da Bacia do Paraná em duas sub-bacias, uma localizada ao SW e outra ao NW do arco. Ferreira *et al.* (1981) indicam que o Alinhamento de Guapiara, limite

setentrional do APG, teria controlado a sedimentação das duas sub-bacias durante o Permo-Carbonífero. O APG também teria influenciado a sedimentação das fácies fluvio-eólicas registradas na Formação Pirambóia nos estados de São Paulo e Paraná (Giannini et al., 2004). Neste caso, o APG teria atuado como barreira paleogeografica dos paleoventos e controlaria as áreas fontes de sedimentos para os sistemas fluviais.

Figura 3. Principais elementos estruturais da Bacia do Paraná, segundo Stollhofen *et al.* (2000). Modificado de Zalán *et al.* (1990).

3. Área de estudo

Foram selecionadas duas áreas de estudo, visando principalmente os afloramentos com rochas carbonáticas. A primeira área localiza-se no sudoeste do Estado de São Paulo, corresponde aos municípios de Fartura e Taguaí (Fig. 4). Estes municípios se encontram inseridos na Folha Topográfica de Carlópolis (SF-22-Z-C-III-4).

A segunda área localiza-se no noroeste do Estado do Paraná e compreende os municípios de Jacarezinho, Santo Antônio da Platina e Joaquim Távora (Fig. 4), os quais estão inseridos nas folhas topográfica de Santo Antônio da Platina (SF-22-V-II-4), Joaquim Távora (SF-22-W-I-3) e Jacarezinho (SF-22-W-I-1).

Figura 4. Mapa geológico com a localização das estações de campo. Modificado de CPRM (2006).

4. Discussão

Salienta-se que a discussão detalhada dos resultados encontra-se nos artigos anexos. A análise das fácies carbonáticas e evaporíticas da Formação Teresina foi abordada em escalas diferentes, visando a interpretação do sistema deposicional e dos fatores tectônicos e climáticos que afetaram a sedimentação desta unidade geológica. Na escala sub-milimétrica, a microscopia eletrônica de varredura (MEV) demonstrou a presença de minerais evaporíticos nas fácies *mudstone* com conchas de ostracodes e brecha de *mudstone-chert*, como halita e outros minerais que poderiam indicar influência de fluidos salinos na sedimentação, tais como bárita com estrôncio e gipsita. A análise ao MEV também evidenciou a excelente preservação das estruturas orgânicas (biofilmes) na fácies *boundstone* tabular. Bandas de dolomita enriquecidas com matéria orgânica foram identificadas por microscopia de fluorescência por luz ultravioleta, sugerindo origem biogênica para os níveis dolomíticos da fácies *boundstone* tabular.

Na área de estudo, as fácies terrígenas heterolíticas são resultado da alternância entre os processos trativos e de decantação de sedimentos finos por correntes e ondas influenciadas por tormentas. Fácies de nódulos e níveis enterolíticos de silexito (substituição diagenética) foram depositadas por episódios de intensa evaporação e concentração de sais em ambientes de águas rasas com baixo aporte terrígeno. A ação das ondas geram remobilização de grandes quantidades de sedimentos e produzem agitação constante da água, originando as fácies de *packstone-grainstone* oolíticas e *packstone* bioclástico. Fácies de *mudstone* com conchas de ostracodes e *wackstone* seriam originadas por decantação de sedimentos finos em área protegida das ondas induzidas por tormentas. Em águas rasas com periódica exposição subaérea, foram depositadas as fácies de brechas *mudstone-chert*. A atividade microbiana em ambiente protegido com alta salinidade e de águas rasas teria provocado a formação das fácies de *boundstone* tabular e *mudstone* fenestral.

Observou-se na análise regional o incremento na frequência de ocorrência de fácies carbonáticas no flanco norte do Arco de Ponta Grossa, com as maiores frequências na região de estudo. Além disso, o mapa de isópacas gerado a partir de informações de poços demonstrou aumento da espessura da Formação Teresina de sul para norte em direção ao Arco de Ponta Grossa.

A evolução sedimentar da Bacia do Paraná foi fortemente influenciada por estruturas tectônicas, entre as quais destaca-se o Arco de Ponta Grossa. Esta estrutura teria afetado tanto as unidades mais velhas (desde o Devoniano) como as unidades mais recentes que a Formação Teresina. O mapa de isópacas das unidades do Carbonífero (Zalán *et al.*, 1990) demonstra que

a bacia teria se dividido em duas sub-bacias, sendo o limite entre elas o Arco de Ponta Grossa. A Formação Irati (Eopermiano ao Permiano Médio) foi resultado de sedimentação em ambiente restrito e com condições climáticas áridas, permitindo a formação de evaporitos e calcários (Hachiro, 1991; Hachiro, 2000; Milani *et al.*, 2007). Vieira *et al.* (1991) propõem que o Alinhamento de Guapiara (limite norte do Arco de Ponta Grossa) teria atuado como uma barreira tectônica-ecológica-biológica, restringindo a zona do *Stereosternum* e *Brazilosaurus* ao norte e a zona de *Mesosaurus* ao sul do alinhamento. O controle do Arco de Ponta Grossa na sedimentação do Permo-Triássico também foi observado nas fácies eólicas e fluviais da Formação Pirambóia. Giannini *et al.* (2004), por meio de análise de direções de estratificações cruzadas, interpretaram uma zona de convergência de ventos localizada entre os limites sul e norte do Arco de Ponta Grossa. O deslocamento desta zona para o flanco sul do Arco de Ponta Grossa bloquearia a entrada de massas de ar úmido que vinham do Oceano Panthalassa em direção ao norte da Bacia do Paraná. Esta configuração paleogeográfica-paleoclimática seria favorável ao desenvolvimento de zona árida no flanco norte do Arco de Ponta Grossa.

Durante a sedimentação da Formação Teresina, a falta de comunicação com o mar aberto ao sul da Bacia teria induzido a formação de um ambiente com circulação restrita ao norte do Arco de Ponta Grossa, promovendo a deposição das fácies evaporíticas e carbonáticas descritas neste estudo e o endemismo dos bivalves desta unidade e das formações Serra Alta e Corumbataí (Ghilardi & Simões, 2002).

O sul do Gondwana foi afetado por eventos tectônicos importantes, como a Orogenia de San Rafael durante o Permo-Triássico, que produziu depressões e paleoaltos, e a formação de um *rift* entre África e América do Sul (Stollhofen, 1999). O Arco de Ponta Grossa poderia estar relacionado às grandes zonas de falhas de transferência transversais ao eixo do *rift* (Stollhofen *et al.*, 2000), as quais gerariam vários depocentros alinhados entre si. A Formação Teresina na área de estudo poderia ter sido resultado de sedimentação na margem de algum desses depocentros. A Bacia do Huab na África é interpretada como um equivalente marginal da Bacia do Paraná (Horsthemke *et al.*, 1990). A sedimentação da Formação Gai-As da Bacia do Huab, unidade correlacionável à Formação Teresina, também é interpretada como resultado da sedimentação em ambiente fechado com circulação restrita. Esta informação indicaria uma história deposicional semelhante entre as duas formações ao norte do Arco de Ponta Grossa, sugerindo um provável depocentro comum.

5. Conclusões

A sedimentação da Formação Teresina apresenta uma história deposicional diferente ao norte e ao sul do Arco de Ponta Grossa. O isolamento geográfico relacionado à evolução tectônica do sul do Gondwana e uma zona de convergência de ventos provocaram a sedimentação das fácies carbonáticas e evaporíticas da Formação Teresina. O Arco de Ponta Grossa teria atuado como uma grande barreira geográfica, influenciando os ventos, a precipitação, o aporte sedimentar terrígeno, a entrada das águas oceânicas do Panthalassa provenientes do sul e o intercâmbio biológico. Este isolamento promoveu condições climáticas áridas e a produção de corpo d'água hipersalino. Estas condições ecológicas estressantes, além de permitir a sedimentação das fácies carbonáticas e evaporíticas, também proveriam um ambiente propício para a formação de níveis de estromatólitos. Estas novas informações auxiliariam nas correlações entre as unidades permianas das bacias do Paraná e do Huab, colaborando para a interpretação da paleogeografia do sul do Gondwana e da evolução tectônica da borda leste da Bacia do Paraná e sua relação com o *rift* permiano africano.

Referências

- Almeida, F.F.M.** 1986. Distribuição regional e relações tectônicas do magmatismo pós-paleozóico no Brasil. *Revista Brasileira de Geociências*, 16 (suplemento), 15-26.
- Araújo, L.M., Triguís, J.A., Cerqueira, J.R., & Freitas, L.C., da S.** 2000. The atypical Permian Petroleum System of the Paraná Basin, Brazil. In M.R. Mello and B.J. Katz, eds, *Petroleum systems of South Atlantic margins*. AAPG Memoir, 73: 377-402.
- Artur, P.C., & Soares, P.C.** 2002. Paleoestruturas e petróleo na bacia do Paraná, Brasil. *Revista Brasileira de Geociências*, 32(4), 433-448.
- Beurlen, K.** 1954. Horizontes Fossilíferos das Camadas Serra Alta do Paraná. *Div. Geol. Mineral., DNPM, Bol. 152*, 30 p.
- Beurlen, K.** 1955. As Formações Gondwânicas do Sul do Estado do Paraná. *Div. Geol. Mineral., DNPM, Bol. 153*, 52 p.

Caetano-Chang, M.R. 1993. Estado d'arte dos conhecimentos sedimentológicos/estratigráficos das Formações Pirambóia e Botucatu no Estado de São Paulo. In: Sim. Cronoest. da Bacia Do Paraná,1, Rio Claro, SP. Bol. Res. Expandidos. Rio Claro, UNESP-SBG, 84-85.

CPRM – Serviço Geológico do Brasil. 2006. Mapa Geológico de São Paulo. Ministério de Minas e Energia. Secretaria de Geologia, Mineração e Transformação Mineral.

Daemon, R. & Aboarrage, A. 1976. Relatório Integrado dos Projetos Carvão no Extremo Norte de Santa Catarina, Prospecção de Carvão no Paraná I e Carvão no Estado de São Paulo. Relatório Final CPRM, SUREG/SP, 83 p.

Daemon, R.F., & Quadros, L.P. 1970. Bioestratigrafia do Neopaleozóico da Bacia do Paraná. In: Congresso Brasileiro de Geologia, XXIV, Brasília, Sociedade Brasileira de Geologia, 359-412.

Dickson, J.A.D. 1966. Carbonate identification and diagenesis as revealed by staining. *Journal of Sedimentary Petrology*, 36, 491-505.

Elias, A.R.D., Garcia, A.J.V., & Lavina, E.L. 2000. Arcabouço cronoestratigráfico da bacia do Paraná na região centro-oeste do Rio Grande do Sul. *Pesquisas em Geociências*, 27 (2), 31-44.

Fanton, J.C.M., Ricardi-Branco, F., Torres, M., & Rohn, R. 2006. Reinvestigação da conífera permiana *Krauselcaldus* (Formação Teresina, Bacia do Paraná, Brasil): Novas interpretações morfológicas e anatômicas. *Revista Brasileira de Paleontologia*, 9 (22), 221-234.

Ferreira, F. 1982. Integração de dados aeromagnéticos e geológicos: configuração e evolução do Arco de Ponta Grossa. Instituto de Geociências, Universidade de São Paulo, Dissertação de Mestrado, 169 p.

Ferreira, F., Moraes, R., Ferrari, M., & Vianna, R. 1981. Contribuição ao estudo do Alinhamento de Guapiara. In: SBG, Simpósio Regional de Geologia, Curitiba, Anais, 3, p. 226-240.

Figueiredo Filho, P.M. 1972. A faciologia do Grupo Passa Dois no Rio Grande do Sul. Revista Brasileira de Geociências, 2 (4), 216-235.

Fulfaro, V.J. 1970. Evolução tectônica e paleogeográfica da bacia sedimentar do Paraná pelo trend surface analysis. Instituto de Geociências, Universidade de São Paulo, Tese de Doutorado, 112 p.

Giannini, P.C.F., Sawakuchi, A.O., Fernandes, L.A., & Donatti, L.M. 2004. Paleoventos e paleocorrentes subaquosas do Sistema Depositional Pirambóia nos estados de São paulo e Paraná, Bacia do Paraná: estudo baseado em análise estatística de dados azimutais. Revista Brasileira de Geociências, 34 (2), 282-292.

Gordon JR., M. 1947. Classificação das formações Gondwânicas do Paraná, Santa Catarina e Rio Grande do Sul. DNPM – Div. Geol. Min., Notas Prel. Est. 38, 19 p.

Hachiro, J. 1991. Litotipos, associações faciológicas e sistemas deposicionais da Formação Irati no Estado de São paulo. Instituto de Geociências, Universidade de São Paulo, Dissertação de Mestrado, 175 p.

Hachiro, J. 2000. Occurrences of evaporites in the Irati Sub-Group (Late Permian, Paraná Basin). Anais da Academia Brasileira de Ciências, 72 (4), 600.

Holz, M., França, A.B., Souza, P.A., Iannuzzi, R., & Rohn, R. 2010. A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of the Paraná Basin, Brazil, South America. Journal of South American Earth Sciences, 29, 381-399.

Lavina, E.L. 1991. Geologia sedimentar e paleogeografia do Neopermiano e Eotriássico (Intervalo Kazaniano-Scythiano) da Bacia do Paraná. Programa de Pós-Graduação em Geociências, Universidade Federal do Rio Grande do Sul, Tese de Doutorado, 333 p.

Maack, R. 1947. Breves notícias sobre a Geologia dos Estados do Paraná e Santa Catarina. Curitiba. Arquivos de Biologia e Tecnologia, 2, 63-154.

Maranhão, M.S.A.S. 1995. Fósseis das formações Corumbataí e Estrada Nova do Estado de São Paulo: subsídios ao conhecimento paleontológico e bioestratigráfico. Universidade de São Paulo, Instituto de Geociências, Tese de Doutorado, 2v.

Matos, S.L.F. 1995. Contato entre o Grupo Passa Dois e a Formação Pirambóia na borda da bacia do Paraná no Estado de São Paulo. Universidade de São Paulo, Dissertação de Mestrado, 110 p.

Meghioratti, T. 2006. Estratigrafia de seqüências das formações Serra Alta, Teresina e Rio do Rasto (Permiano, Bacia do Paraná) na porção nordeste do Paraná e centro-sul de São Paulo. Rio Claro, Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Dissertação de Mestrado, 169 p.

Mello, L.H.C. 1999. Análise cladística dos bivalves do Grupo Passa Dois (Neopermiano), Bacia do Paraná, Brasil: implicações taxonômicas, evolutivas e paleobiogeográficas. Instituto de Geociências. Universidade de São Paulo. Dissertação de mestrado, 169 p.

Milani, E.L., Melo, J.H.G., Souza, P.A., Fernandes, L.A. & França, A.B., 2007. “Cartas Estratigráficas – Bacia do Paraná”. Boletim de Geociências da Petrobrás 15 (2), 265-287.

Milani, E.J., & Zalán, P.V. 1999. An outline of the geology and petroleum systems of the Paleozoic interior basins of South America. Episodes, 22, 199-205.

Milani, E.J. 1997. Evolução tectono-estratigráfica da Bacia do Paraná e seu relacionamento com a geodinâmica Fanerozóica do Gondwana sul-ocidental. Universidade Federal do Rio Grande do Sul, Instituto de Geociências, Tese de Doutorado, 2v.

Milani, E.L., França, A.B., & Schneider, R.L. 1994. Bacia do Paraná. Boletim de Geociências da Petrobrás, 8 (1), 69-82.

Moraes Rego, L.F. 1930. A Geologia do Petróleo no Estado de São Paulo. Serv. Geol. e Min., 46, 110 p.

Neves, J.P., Rohn, R., & Simões, M.G. 2010. Tafonomia de bivalves em calcários oolíticos da Formação Teresina (Bacia do Paraná, Permiano Médio, Prudentópolis, PR). Revista do Instituto de Geociências – USP, 10 (3), 19-36.

Neregato, R., Souza, P.A. de, & Rohn, R. 2008. Registros Palinológicos inéditos nas Formações Teresina e Rio do Rasto (Permiano, Grupo Passa Dois, Bacia do Paraná): implicações biocronoestratigráficas e paleoambientais. Revista Pesquisas em Geociências, 35 (2), 9-21.

Northfleet, A.A., Medeiros, R.A., & Muhlmann, H. 1969. Reavaliação dos dados geológicos da Bacia do Paraná. Boletim Técnico da Petrobrás, 13 (3), 291-346.

Petri, S., and Coimbra, A.M. 1982. Estruturas sedimentares das formações Irati e Estrada Nova (Permiano) e sua contribuição para elucidação dos seus paleoambientes geradores. 5º Congresso Latinoamericano de Geologia, v.2, Buenos Aires, 353-371.

Ragonha, E.W. 1984. Taxionomia de dentes e espinhos isolados de *Xenacanthodii* (*Choncrichthyes*, *Elasmobranchii*) da Formação Corumbatí. Considerações cronológicas e paleoambietais. Instituto de Geociências, Universidade de São Paulo, Tese de Doutorado, 1v.

Rohn, R. 2007, Meglhioratti, T., & Cordeiro-Silva, A. 2007. Tafonomia de bivalves em testemunhos de furos de sondagem das formações Serra Alta e Teresina (Permiano) no leste da Bacia do Paraná. In: XX Congresso Brasileiro de Paleontologia, Buzios. Anais. Sociedade Brasileira de Paleontologia, 278-279.

Rohn, R. 2001. A estratigrafia da Formação Teresina (Permiano, bacia do Paraná) de acordo com furos de sondagem entre Anhembi (SP) e Ortigueira (PR). Correlação de Sequências Paleozóicas Sul-americanas, 20, 209-218.

Rohn, R. 1994. Evolução ambiental da Bacia do Paraná durante o Neopermiano no leste de Santa Catarina e do Paraná. Instituto de Geociências, Universidade de São Paulo, Tese de Doutorado, 2v.

Runnegar, B., & Newell, N.D. 1971. Caspian-like relict molluscan fauna in the South American Permian. New York, Bulletin of American Museum of Natural History, 146 (1), 5-66.

Sanford, R. & Lange, F. 1960. Basin study approach to oil evaluation of Paraná miogeosyncline South Brazil. Bul. of the Amer. Assoc. Petrol. Geol., 44 (8), 1316-1370.

Schneider, R.L., Mühlmann, H., Tommasi, E., Medeiros, R.A., Daemon, R.F., & Nogueira, A.A. 1974. Revisão estratigráfica da Bacia do Paraná. In: Congresso Brasileiro de Geologia, XXVIII, 1974, Porto Alegre. Anais, Sociedade Brasileira de Geologia, Porto Alegre, vol. 1, 41-66

Simões M.G., Rocha-Campos, A.C., & Anelli, L.E. 1998. Paleoecology and evolution of Permian pelecypod assemblages (Paraná Basin) from Brazil. In: Johnston, P.A. Haggart, J.W. (Eds), Bivalves – An Eon of Evolution – Paleobiological Studies. Honoring Norman D. Newell. University of Calgary Press, Calgary, 443-425.

Soares, P.C. 1973. O Mesozóico Gonduânico no Estado de São Paulo. Departamento de Geologia e Mineralogia da Faculdade de Filosofia, Ciências e Letras de Rio Claro, Rio Claro, Tese de Doutorado, 512 p.

Souza, S.H., Suguio, K., & Castro, J.C. 1991. Sedimentary facies of the Estrada Nova and Corumbataí Formation (Late Paleozoic of the Paraná Basin) in the state of São Paulo, Brazil. In: International Gondwana Symposium, VII, São Paulo, 1988. Proceedings, 161-172

Stollhofen, H., Stanistreet, I.G., Rohn, R., Holzförster, F., & Wanke, A. 2000. The Gai-As Lake System, Northern Namibia and Brazil. In E.H. Gierlowski-Kordesch and K.R. Kelts, eds., Lake basin through space and time: AAPG Studies in Geology, 46, 87-106.

White, I.C. 1908. Relatório final da Comissão de Estudos das Minas de Carvão de Pedra do Brasil. Rio de Janeiro: DNPM, 1988, Parte I, p: 1-300; Parte II, p: 301-617.

Zaine, M.F. 1980. Uma barreira geográfica no Paleozóico Superior na região de Fartura, SP. Instituto de Geociências, Universidade de São Paulo, Dissertação de mestrado, 89 p.

Zalán, P.V., Wolf, S., Conceição, J.C., Astolfi, A.M., Vieira, I.S., Appi, V.T., Zanotto, O.A., & Marques, A. 1991. Tectonics and sedimentation of the Paraná Basin. In: Ulbrich, H.H.G.J., Rocha-Campos, A.C. Gondwana Seven. Instituto de Geociências, Universidade de São Paulo, São Paulo, 83-117.

Zalán, P.V., Wolff, S., Astolfi, M.A.M., Vieira, J.C., Conceição, J., Appi, V.T., Neto, E.V.S., Cerqueira, J.R., & Marques, A. 1990. The Paraná Basin, Brazil, in Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: AAPG Memoir 51, 681-708.

ANEXOS

**TECTONIC-CLIMATE CONTROLS ON CARBONATE AND EVAPORITE
SEDIMENTATION IN THE TERESINA FORMATION, LATE PERMIAN OF THE
PARANÁ BASIN, SOUTHERN GONDWANA**

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ABSTRACT

The Teresina Formation, Late Permian of the Paraná Basin, is mainly composed of terrigenous sediments, with some occurrences of carbonate and evaporite facies. It corresponds to the upper portion of the last regressive phase of the Paraná Basin epicontinental sea. The depositional system responsible for the carbonate and evaporite facies of the Teresina Formation is still target of discussion. These facies occur in a huge area of the basin, but they have a greater thickness and are more frequent in the north of the Paraná State and in the southern of the São Paulo State, in the upper portion of the formation. This region constitutes the study area of this dissertation in order to interpret the depositional processes as well as the tectonic and climatic factors acting during the formation of these deposits. The study included the interpretation of data from wells, detailed description of columnar sections, with sampling for petrographical analysis under the optical and scanning electron microscopes (SEM). Eight carbonate and/or evaporite facies were identified: mudstone with ostracod shells, peloidal mudstone, bioclastic wackstone, bioclastic packstone, tabular boundstone, oolitic packstone-grainstone, nodular and enterolithic chert and mudstone-chert breccia. The depositional system was interpreted as a carbonate ramp with a protected zone by growth of oolitic sand bars and sediment transport dominated by wave action and associated currents. In the inner regions, arid periods of intense evaporation and low terrigenous input would increase the salinity, causing the deposition of enterolithic and nodular chert and mudstone-chert breccia facies. The intermediate portion corresponds to a lagoon with shallow and low energy waters, allowing the deposition of fine grained sediments recorded in the mudstone with ostracod shells and bioclastic wackstone facies. In the same portion, the hypersaline conditions of the water would have stimulated microbial activity, promoting the deposition of

peloidal mudstone and tabular boundstone facies. Dolomite bands identified in the tabular boundstone facies in the north of the Paraná State are enriched in organic matter and they would be associated to mineral precipitation induced by microbial activity. The wave action remobilized bottom sediments, causing constant waters agitation. This induced sedimentation of oolitic packstone-grainstone facies in shoals and the terrigenous heterolithic facies between the fair-weather and storm wave bases. Maps of isopachs and frequency of occurrences of limestones show concentration of limestones in the north flank of the Ponta Grossa Arch (PGA). The thickness of the formation increases from south to north towards the PGA. In some regions near the PGA, isopachs are parallel to the axis of this tectonic structure. The obtained results suggest that the Ponta Grossa Arch influenced the deposition of the carbonate and evaporite facies of the Teresina Formation, acting as a geographical barrier that restricted the entry of ocean waters from south. This promoted reduced terrigenous input, low water circulation and the increase of salinity in the northern flank of the PGA. Furthermore, a possible winds convergence zone, parallel to the Ponta Grossa Arch, would affected the climatic conditions in the study region during the Late Permian, difficulting the northward migration of wet air masses coming from the Panthalassa Ocean. This favored arid conditions in the study area. The tectonic and climatic significance of the carbonate and evaporite facies of the Teresina Formation have important implications for correlations between the Paraná Basin and basins from Africa, such as the Karoo and Huab basins, as well as for paleogeographic reconstructions of the Gondwana in the Permian.

Keywords: Gondwana, Paraná Basin, Ponta Grossa Arch, Teresina Formation, carbonate and evaporite facies.

1. Introduction

In the Paraná Basin, the Teresina Formation represents the end of the Permian epicontinental sea in the southwestern Gondwana (Milani *et al.*, 1994; Milani *et al.*, 2007; Rohn, 2007; Holz *et al.*, 2010). This period is highlighted to record a global event of mass extinction (Jia *et al.*, 2012).

In the last decades, most studies about the Teresina Formation have been focused on paleontological aspects (Fanton *et al.*, 2006; Neregato *et al.*, 2008; Rohn, 2007, Neves *et al.*, 2010). Despite its formal definition in 1908, few works emphasized the sedimentological characteristics and the controls on temporal and spatial variability of the sedimentary facies of the Teresina Formation as well as their relation with its paleontological records. In this

context, we stand out the eastern border of the Paraná Basin in the states of São Paulo and Paraná, where the Teresina Formation comprises siliciclastic, carbonate and evaporite facies, representing a mixed depositional system, which is poorly reported in previous studies. It is presented a depositional model for the carbonate and evaporite facies, based on facies and petrographical analyses using wells and outcrops data. The carbonate and evaporite sediments are valuable indicators of environmental conditions, such as salinity, temperature and water depth because, contrary to siliciclastic sediments, carbonate and evaporite sediments are formed within sedimentary basins. Tectonic and climate controls on the spatial distribution of the Teresina Formation carbonate and evaporite facies as well as their relation with correlative stratigraphic units in Africa are discussed in the context of the Gondwana during the Late Permian.

The Huab Basin in Africa is interpreted as a marginal equivalent of the Paraná Basin in the Gondwana (Horsthemke *et al.*, 1990). Thus, the carbonate and evaporite sediments of the Teresina Formation can give valuable information regarding the plaeoclimate and paleorelief of the southwestern Gondwana during the Permian, allowing correlations with the stratigraphical units from the Huab Basin and improving paleogeography reconstructions. Additionally, from Late Permian to Early Triassic, the southwestern of Gondwana was affected by the San Rafael Orogeny (Newell, 1973) and Cabo-La Ventana Orogeny (Milani and Ramos, 1998). These orogenies produced intense volcanism and confinement of epicontinental seas that possibly influenced the sedimentation of the Paraná Basin and the shift between the deposition of terrigenous and carbonate and evaporite facies of the Teresina Formation.

2. Study area

The study area is located at the north of the Ponta Grossa Arch (PGA) axis, one of the most important tectonic structures of the Paraná Basin. The PGA is defined by a dyke swarm and it was possibly active at least since the Devonian (Northfleet *et al.* 1969; Ferreira, 1982, Piccirillo *et al.*, 1990; Strugale *et al.*, 2007). This region is differentiated from other parts of the basin because it concentrates the evaporite and carbonate facies of the Teresina Formation. This study was focused on the northern flank of the PGA in the northeast portion of the Paraná State and the southeast of the São Paulo State. This region comprises great outcrops of the upper part of the Teresina Formation (Fig. 1).

Figure 1. A. The Paraná Basin location in South America. B. Location of the study area (blue square) and principal tectonic elements. Modified from Zalán *et al.* (1991).

3. Geological background

The Teresina Formation is part of the giant cratonic Paraná Basin in central-eastern South America. The sedimentation in this basin would be controlled by tectonic cycles, that promoted a discontinuous depositional history (Milani, 1997; Milani *et al.*, 2007). According to these authors, the stratigraphic succession of the Paraná Basin can be divided into six supersequences: Rio Ivaí (Lower Ordovician to Lower Silurian), Paraná (Devonian), Gondwana I (Early Carboniferous to Early Triassic), Gondwana II (Triassic), Gondwana III (Late Jurassic to Early Cretaceous) and Bauru (Cretaceous). The Teresina Formation belongs to the Passa Dois Group, which corresponds to the upper part of the Gondwana I Supersequence, recording gradual isolation and drying of the Paraná Basin epicontinental sea (Fig. 2).

The Teresina Formation outcrops in the eastern border of the Paraná Basin. This unit consists mainly of heterolithic rocks composed of siltstones interbedded with very fine sandstones (linsen, flaser and wavy lamination) presenting clastic dykes, with minor

occurrences of fish bone-beds and carbonate rocks (mudstone, wackstone, stromatolites and oolitic or ostracods shells grainstone and packstone). The depositional system represented in the Teresina Formation is under discussion. Some authors interpret this unit as result of sedimentation in a tidal flat depositional system (Schneider *et al.*, 1974; Petri and Coimbra, 1982; Gianninni *et al.*, 2004), while others suggest a coastal plain to storm-influenced offshore setting (Holz *et al.*, 2010).

Figure 2. Stratigraphic chart of the Paraná Basin. Modified from Milani *et al.* (2007). Litoestratigraphical formations of each sequence. *Rio Ivaí sequence*: ALG: Alto Garças, IAP: Iapó, VLM: Vila Maria. *Paraná sequence*: FUR: Furnas, PGR: Ponta Grossa, JGR: Jaguariaíva Member, TBJ: Tibagi Member, SDM: São Domingos Member, ORT: Ortigueira Diamictite. *Gondwana I sequence*: LAZ: Lagoa Azul, CMO: Campo Mourão, ITA: Itaraté, AQU: Aquiduaana, TAC: Campo do Tenente, RSL: Rio do Sul, DRD: Siderópolis, RBN: Rio Bonito, PLM: Palermo, IRT: Irati, SAL: Serra Alta, TRS: Teresina, CBT: Corumbataí, RRT: Rio do Rasto, SCB: Sanga do Cabral, PIR: Pirambóia. *Gondwana II*: SM: Santa Maria. *Gondwana III*: BOT: Botucatu, SGL: Serra Geral.

Regarding the fossil content, endemic bivalves dominate this unit (Simões *et al.*, 1998), with some authors considering them as non-typical freshwater mollusks (Ghilardi and Simões, 2002). Others common fossils are ostracods, which Almeida and Do Carmo (2005) considered as marine and cosmopolitan in the northern part of the basin, whereas Sohn and

Rocha-Campos (1990) suggested a freshwater environment. About the age, Rohn (2001) suggests an age near the Cisuralian – Guadalupian limit (Middle Permian). U/Pb dating obtained from zircon grains from ash-fall beds of the Teresina Formation indicates an age of 267 ± 1.7 Ma (Rocha-Campos *et al.*, 2009). Holz *et al.* (2010) indicated an age of Late Kungurian – Rodian (Early to Middle Permian). However, an age of 267.1 ± 3.4 Ma obtained in ash beds of the Rio Bonito Formation lying below, implies a younger age for the Teresina Formation (Matos *et al.*, 2001). Milani *et al.* (2007) assigned an age in the Guadalupian (Late Permian) for the Teresina Formation. The Corumbataí Formation is part of the upper portion of the Passa Dois Group. It is considered as equivalent to the Serra Alta and Teresina formations in the northeastern portion of the Paraná Basin (Milani *et al.*, 2007). Daemon and Quadros (1970) assigned an age in the Kazanian to Tatarian (Late Permian) for the Corumbataí Formation, based on biostratigraphic studies. Valencio *et al.* (1975) indicated an age of Tatarian based on magnetic data. Ragonha (1984) compared *Xenacanthus moorei* fossils of the Corumbataí Formation with occurrences in Germany, United States, India and England, and suggested a Triassic age. The contact between the Teresina Formation and the underlying Serra Alta Formation is transitional (Holz *et al.*, 2010), while the contact with the overlying Rio do Rasto and Pirambóia formations was considered as abrupt by Meglhioratti (2005), but for others authors it is concordant and gradational (Vieira, 1973; Riccomini *et al.*, 1984). For Milani *et al.* (2007), the contact with the overlying units would be hiatus-free.

The stratigraphy of the Paraná Basin was possibly controlled by large tectonic structures, such as the Guapiara and Tietê lineaments and the Ponta Grossa Arch (PGA). The PGA has a NW-SE trend, which is one of the most important tectonic discontinuities affecting the sedimentation within the Paraná Basin. During the deposition of the Ponta Grossa Formation (Devonian), the PGA separated the Paraná Basin into two sub-basins, according to isopach maps of the later formations (Zalán *et al.*, 1990). The PGA would also influenced the paleowinds acting in the eolian depositional system recorded in the Permian-Triassic Pirambóia Formation (Giannini *et al.*, 2004).

Regarding the Paraná Basin petroleum systems, the Teresina Formation occurs between the source rocks and reservoirs of the Irati-Pirambóia petroleum system (Zalán *et al.*, 1990; Milani and Zalán, 1999, Araújo *et al.*, 2000; Araujo *et al.*, 2005). The carbonate facies of the Teresina Formation as potential reservoirs of the Irati-Pirambóia petroleum system have been not studied in detail. Araújo *et al.* (2000) argued that fine grained and cemented facies of the Teresina Formation can be important seals within the Irati-Pirambóia petroleum system, favoring the development of overpressure conditions.

4. Material and Methods

The study of the carbonate and evaporite facies of the Teresina Formation was carried out in different scales: micrometric to millimetric (scanning electron and optical microscopy analyses), centimetric to metric (facies analysis and stratigraphic sections in outcrops) and kilometric (regional distribution and thickness of sedimentary facies compiled from wells). Data from eleven outcrop sections with facies analysis and sampling were used to build a depositional model for the carbonate and evaporite facies. Data from 43 wells were also used for mapping of the carbonate facies distribution and thickness using Geographic Information System software. This allows the characterization of the spatial distribution, isopachs and the frequency of occurrence of carbonate facies. The sedimentary facies were defined on the basis of their geometry, sedimentary structures, grain size, sorting, packing, albiochemical grains, matrix as well as textures associated with eodiagenetic processes. Paleocurrent analysis was performed to provide information about the directions of sediment transport. Seventy two thin sections were made for petrographical analysis under the optical microscope and scanning electron microscope (SEM). This analysis aimed to characterize the morphology of fine grained depositional components, authigenic minerals and porosity. The thin sections were stained with alizarine red and potassium ferricyanide diluted in 1.5% HCl to differentiate carbonate minerals (Dickson, 1966). The thin sections were classified according to Dunham's classification of carbonates (Dunham, 1969). The terminology for fossil microbialite of Grey (1989) was used to classify and describe the stromatolite facies. Porosity was described according to the proposal of Choquette and Pray (1970) and Pittman (1971). SEM analysis were carried out on carbon-coated polished thin sections.

5. Results

5.1 Sedimentary Facies

Carbonate facies are concentrated in the upper portion of the Teresina Formation. Eight carbonate and evaporite facies were recognized within the eleven studied stratigraphic sections. These facies occur intercalated with terrigenous sandy and muddy facies, which occur as centimeter to meter tabular layers (from 20 cm to 4 m thickness), frequently presenting ripple cross lamination, with concave-convex truncations and containing centimeter length intraclasts of underlying lithologies. The heterolithic facies are interpreted as result of alternation between traction and suspension sediment transport. The terrigenous facies are mainly associated with bioclastic packstones and oolitic packstones-grainstones (Fig. 4). The observed facies are described as follows.

Mudstone with ostracod shells

This facies comprises centimeter thick tabular layers (up to 10 cm thick). It is composed of micrite with less than 7% of ostracod shells. These bioclasts are mainly fragmented, with up to 1 mm length. Chert nodules (up to 10 cm diameter) and levels (up to 7 cm thickness) and, occasionally, mudstone-chert breccia facies are intercalated with this facies. The carbonate is dominated by calcite. Calcite and dolomite with chevron texture in cubic crystals (Fig.3C,D) are interpreted as halite pseudomorphs (1 to 5 μm diameter). Calcite occurs as sword-shaped crystals, interpreted as replacing gypsum (Fig.3C,E). Dolomite occurs as rhombohedral crystals with hypidiomorphic texture. The sizes of rhombohedral crystals range between 20 and 200 μm and they can be sparse or concentrated as crystals mosaics (Fig.3F). These crystals can form submillimeter levels close to chert nodules or levels or occur intercalated with these levels (Fig.3F). Scanning electron microscopy analysis shows micrometric cubic crystals of halite (Fig.7C). Autigenic quartz was identified as bipiramidal crystals with length from 50 to 100 μm . The hopper texture suggests an original salt precipitate, which forms by evaporation of shallow waters and dissolution of the halite crystal. This arrangement is characteristic of shallow water saline environments (Tucker, 2001). The autigenic quartz is often found in carbonates affected by saline or hypersaline pore waters (Flügel, 2004). The presence of evaporite minerals, autigenic quartz, chert nodules and levels would indicate arid periods suitable for chemical precipitation. The intercalation of this facies (Fig. 4) with breccias indicates periodic subaerial exposure. This facies was deposited by suspension of micritic mud in shallow waters from arid or semi-arid area close to shoreline.

Peloidal mudstone

This facies comprises centimetric tabular layers (up to 10 cm thick). It is composed mostly of peloids, with up to 2 mm diameter. This facies presents fenestrae cavities (birdseyes), with lengths between 20 μm and 2 mm. The space between peloids is filled with blocky calcite, gypsum or chalcedony (Fig. 5B), which can be connected vertically and horizontally. This facies is associated with the chert nodules (diameters between 2 to 10 cm) and breccias facies.

Figure. 3. A) Dolomite crystals in breccia. B) Anhydrite (An) cement filling channels. C) and D) Hopper texture in dolomite indicating possible pseudomorphs of halite. E) Sword-shape gypsum pseudomorphs replaced by calcite. F) Romboedric dolomite crystals. G) Interlamination of wavy calcite (Ca) and dolomite (Do) levels in tabular boundstone facies. Chert nodule (N) interrupting the lamination (parallel polarizers). H) Alternation of sub-millimeter calcite (Ca) and dolomite (Do) levels in tabular boundstone facies (crossed polarizers).

The fenestrae texture is a common feature of shallow water muddy carbonates deposited under the action of microbial mats (Tucker and Wright, 1990). The cavities may be formed by gas entrapment within the sediment and desiccation (Tucker, 2001). Peloids can be a product of mud grazing by benthic fauna. The intercalation with breccias facies indicates periodic subaerial exposure.

Bioclastic wackestone

This facies occurs as tabular layers, centimeter to decimeter thick (up to 30 cm thickness). The bioclasts are dominated by ostracod shells up to 1 mm length, but also include fish remains and bivalve shells. Stylolites were identified at both the micro and macroscopic scales (Fig. 5A). This facies is frequently associated with the mudstone with ostracod shells and chert nodules facies. This facies was deposited in a muddy flat, probably in a protected area, as result of sedimentation in shallow waters periodically subaerial exposed.

Bioclastic packstone

This facies includes lenses, centimeter to decimeter thick (up to 20 cm thick), moderately sorted, frequently associated with heterolithic and oolitic packstones-grainstones facies. Bioclasts are mostly ostracods and bivalves shells, up to 2 cm length, which represent between 75% and 90% of the volume of the rock. Generally, the bioclasts are disarticulated and fragmented, without orientation. The main cement is fine to medium grained sparry calcite. This facies occurs generally deposited upon erosional bases, indicating probable deposition during or after storm events. The degree of shell fragmentation suggests high energy water conditions.

Tabular boundstone

This facies is represented by a tabular biostrome of uniform thickness (47 cm) and flat to wavy-lamination. The lamination comprises the alternation between bands of calcite and dolomite micrite or microsparite, with 100 μ m to 2 mm thick (Fig. 3G,H).

Figure 4. Columnar sections representative of the carbonate and evaporite facies succession in the studied region.

Lamination types include wrinkled, lenticular, discontinuous and irregularly variable. Bioclasts are represented by ostracod disarticulated shells, that occur as isolated or forming thin and continuous sub-milimetric, well-sorted laminae (300 μm thick). Shell fragments are mostly replaced by sparry calcite. Quartz can occur as scattered grains or as concentrations associated with dolomite laminae. In the calcite laminae, quartz grains does not exceed 10% by volume. Chert nodules are sparse, with diameter up to 2 cm. The low diversity of bioclasts shows ecologically stressful conditions, as high salinity or high concentration of specific ions. The concentration of ostracod shells in submillimeter levels suggests trapping and fixing of these particles by the microbial activity. This facies is interpreted as microbial mats developed under low-moderate energy conditions. The flat lamination and morphology would indicate areas partially protected with low intensity of wave action and proximity to the shoreline (Hoffman, 1976). This facies is interpreted as product of deposition in a shallow water environment, frequently flooded promoting the development of microbial mat. Disrupted lamination is interpreted as the result of desiccation due to sporadic subaerial exposure. These features occur at the top of the bed, indicating gradual shallowing deposition under conditions of arid climate and hypersalinity.

Oolitic packstone and grainstone

Oolitic packstone and grainstone occur as cross-stratified tabular beds or amalgamated lenses of thickness between 0.2 m (Santo Antonio da Platina site) and 3 m (Fartura site). This facies is intercalated with sandstones, bioclastic packstones and heterolithic facies (Fig. 8). Ooids are composed of calcite or dolomite, being poorly sorted, fine to coarse grained (with diameters between 50 μm and 1 mm), ovoid or spherical shape, with, 80% of them presenting radial structure. Terrigenous grains represent up to 10% of the rock and are dominated by quartz with minor amounts of feldspar. Ooids are formed by coating of terrigenous grains and shell fragments. Bioclasts comprise approximately 8% of the rock, being represented by fish remains and minor amounts of ostracod shells. Grains are closely packed. The proportion of dolomitic ooids varies between 30% and 45% in Santo Antônio da Platina and between 20 and 35% in Fartura. In the oolitic grainstone and packstone facies, the primary porosity was occluded by sparry calcite. Some ooids present intraparticle portions filled by microcrystalline quartz and chalcedony, suggesting total or partial dissolution before cementation.

Figure. 5. A) Stylolites in bioclastic wackstone facies. B) Calcite (Ca) and gypsum (Gy) cements filling a cavity in a fenestral mudstone. C) Chalcedony (Ch) filling intergranular and intragranular porosities in a dissolved ooid (so). Ooids with concave-convex contact showing chemical compaction (mc). D) Authigenic quartz (Aq) with border replaced by calcite (Cc). E) Drusy (Dr) and mega quartz (Mg) filling a bivalve shell. F) Fragmented fish scale by mechanical compaction. G) Ooids with contacts sutured by chemical compaction (Mc). H) Fractures cutting the chert nodule (Ns) and the horizontal vein of calcite. Fragmented fish scale by mechanical compaction (Mc).

The interparticle space is filled with micrite matrix or spar calcite and chalcedony cement. Silicification occurs in the oolitic layers as parallel bands or following the cross stratification. Mechanical and chemical compaction are evidenced respectively by fractured bioclasts and sutured contacts ooids (Fig. 5C,G,F). This suggests an early compaction before interparticle cementation, producing significant loss of primary porosity and dewatering. Near Fartura site, fifty-four measurements of cross-bedding dip directions were made in large bars of oolitic grainstone facies. Descriptive statistics of cross-bedding dip directions present a mean vector of N342°, with a confidence interval (99%) between 329° and 354°, standard error of mean of 6.1° and a circular standard deviation of 45.5°, indicating that the bars migrated to directions from N to NNW (Fig. 8).

Low faunal diversity as well as the small size and fragmentation of the ostracod shells in this facies suggest high water energy. Most of the observed ooids have radial-fibrous fabric, which are generated in hypersaline environments (Flügel, 2004). The oolitic grainstones are interpreted as deposited in medium-high energy settings in shallow waters, with constant wave and/or current agitation. When this facies occurs as centimetric lenses, they are frequently upon erosive bases, indicating reworking, possibly by storm-waves. The high degree of fragmentation of the bioclasts also indicates reworking.

Nodular and enterolithic chert

The layers are up to 16 cm thick and nodules up to 10 cm length. This facies is composed principally of microcrystalline and chalcedony quartz, with crystals of irregular, subrounded and rounded shapes. Frequently, this facies is associated with mudstones and wackstones facies. Layers may present enterolithic structure (Fig. 6A,B,C) and structures similar to tepees (Fig. 6F). Petrographic analysis revealed the presence of length-slow chalcedony in the enterolithic layers. The chert nodules and layers are interpreted as replaced evaporites. The enterolithic structure of these levels may represent deformation and collapse of evaporite laminae.

The overlying lithology is deformed and fill space between fragments. The tepee structures suggest desiccation process. The presence of length-slow chalcedony within enterolithic layers is strongly suggestive of a high salinity depositional or early diagenetic environment (Tucker, 2001; Folk and Pittman, 1971). This facies is produced by sediment settling in shallow and low-energy waters, with periods of intense evaporation and precipitation of evaporite minerals.

Mudstone-chert breccia

Breccias occur as millimetric to centimetric laminae (1 mm to 3 cm thick), mainly associated with the wackestone and mudstone facies. The breccias consist of angular to subrounded fragments of chert with a major lengths between submillimeter to 1 cm (Fig. 6H). According to the nomenclature of Morrow (1982), these breccias may be classified as crackle to mosaic breccias.

The clasts are closely fitted in the central part and loosely towards the ends, being sometimes spatially independent. Contacts between clasts are ragged, microfragment armouring, jagged, solution rounded and pitted. The breccias is matrix-supported. The space between clasts is filled chiefly by micrite and secondary by calcite and dolomite spar cements (Fig. 6H). Dolomite crystals are concentrated mainly in the upper portion of the breccia, with 10 to 200 μm length (Fig. 3A).

The analysis under scanning electron microscope reveals the presence of gypsum and autigenic barite with strontium. Barite and gypsum occur as isolated and euhedral crystals, as cement filling the space between calcite crystals and chert nodules, replacing calcite and dolomite or as aggregated masses (Fig. 7A,B). Petrographic analysis revealed fractures within the nodules filled with anhydrite (Fig. 3B). Autigenic quartz was identified as bypyramidal crystals of 50 to 300 μm long and frequently associated with blocky calcite cement and chalcedony (Fig. 5D).

In some sections, desiccation cracks were observed in the muddy sediments below chert nodules. The overlying lithology is deformed and fills space between chert fragments. The evaporite minerals such as gypsum and anhydrite may be dissolved, creating solution-collapse breccias and increasing porosity. This facies was deposited by settling of fine sediments in suspension in shallow and quiet waters, with periods of subaerial exposure producing dissolution of evaporite minerals.

Figure 6. A) Bed of chert nodules (nodular and enterolithic chert facies). B) Deformed chert nodules. C) and D) Continuous level of chert. D) Bitumen in level of chert. F) Silicified tepee. G) and H) Silicified breccia.

Figure 7. A) Barite (Ba) cement attached to the borders of a calcite (Ca) crystal. B) Crystals of barite (Ba) within calcite (Ca). C) Cubic crystals of halite (arrows). D) Barite with strontium (BaS) replacing calcite (Ca).

5.2 Carbonate facies distribution

Data from wells and outcrops of the Teresina Formation were analysed to map the spatial distribution of the carbonate facies. We should stand out that the available information for the wells is concentrated to the south of the PGA, difficulting a precise evaluation of small scale variation in carbonate facies distribution. However, this dataset was valuable to highlight major patterns of carbonate facies distribution.

The isopachs of the Teresina Formation decrease close to the PGA with the isopach lines becoming almost parallel in the NW direction (Fig. 9A). This indicates a depocenter southward the PGA, however, the frequency of occurrence and thickness of the carbonate layers increase in the north flank of PGA (Fig. 9B). It was observed that the greatest lithologic contrasts of the carbonate facies of the Teresina Formation occur to the north and south of the APG. The largest thickness and the most frequent occurrences of carbonate layers are in the southwestern São Paulo State and northern Paraná State.

Figure 8. A) and b) Amalgamated bars of oolitic packstone-grainstone facies. C) and D) Cross-stratification in oolitic grainstone. D.a) Rose diagram showing the mean vector of the preferential trend of the cross-stratifications. D.b) Rose diagram showing the values within the confidence interval of 99%. E) Detail of radial ooids.

Figure 9. A) Isopach map of the Teresina Formation based on data from wells and columnar sections. B) Map of frequency of occurrences of carbonate facies. Both maps are in meter units.

6. Discussion

6.1 Controls on carbonate and evaporite sedimentation in the Teresina Formation

The depositional systems of the Paraná Basin are dominated by terrigenous sediments. Carbonate and evaporite sediments are restricted in time and space, being present only during the Permian, since the deposition of the Irati Formation (Hachiro, 1996). The carbonate and evaporite facies of the Teresina Formation record a shift for a condition of low terrigenous input in a shallow depositional environment during the end of Permian. Identified features in the study region such as collapse breccias, evaporite minerals and their pseudomorphs, silicified or calcitized nodules interpreted as replacement of evaporites, presence of quartzine, authigenic idiomorphic quartz crystals, as well as the low diversity but abundant skeletal grains are suggestive of saline and hypersaline depositional conditions (Flügel, 2004). Also, stromatolites with flat morphology, presence of *Lycopodiopsis* fragments with low sedimentary transport (De Faria *et al.*, 2009) and desiccation cracks are others evidences suggestive of shallow and restrict depositional environment. The heterolithic silty-sandy facies and fragmented stems and leafs of *Lycopodiopsis* were probably deposited by storm events, as De Faria *et al.* (2009) suggested for silicified stems of *Lycopodiopsis derbyi* from

the Teresina and Corumbataí formations in the region northward the PGA. This vegetal fossil is an indicator of arid conditions (De Faria *et al.*, 2009).

The carbonate and evaporite facies of the Teresina Formation would record sedimentary environments of low-energy ramp protected by oolitic sand bars, with frequent hypersaline conditions and under the influence of waves and associated currents (Fig. 10). The spatial and stratigraphical distribution of the carbonate and evaporite facies indicates a restricted area with lower terrigenous input that was isolated progressively from open waters. In periods of high runoff, the water level raised and the storms and strong winds provoked increase of the terrigenous input and remobilization of bottom sediments. The entries of sea water were restricted and were controlled by the PGA. The protected areas behind the oolitic bars promoted the deposition of fine sediments, allowing the formation of muddy flats where the mudstone with ostracod shells, peloidal mudstones and tabular boundstones facies were deposited. During periods of intense evaporation, nodular and enterolithic sulphates and mudstone-sulphate breccia facies were deposited in an onshore sabkha exposed to dissolution processes. These evaporites sulphates were replaced by chert during diagenesis. The bioclastic wackstones and oolitic packstone-grainstone were deposited in offshore zones directly influenced by waves. During the storm events, coarser sediments were transported to distal parts. The sedimentation of these facies was between the fairweather and the storm wave base. The deposition of proximal and distal sediments alternates during fair and storm weather periods, respectively. During storm episodes, the sabkha is flooded and the lime mud is transported and deposited on it, forming a mud surface. When the water level decreased, the intense evaporation produced dessication cracks and evaporite minerals precipitation.

Others authors have been observed evidences of enclosed environment in the Teresina Formation in the studied area. Ghilardi and Simões (2002) consider that the endemism of bivalves of the Serra Alta, Teresina and Corumbataí formations is promoted by the gradual geographic isolation of the Paraná Basin. Rohn (1994) indicates that after the deposition of the Irati Formation, the basin becoming similar to a large closed lake (sea-lake), with low amounts of rainfall influencing changes in water level and salinity. The Corumbataí Formation, which is the Teresina Formation equivalent unit, is located to the north of the Tietê Lineament. Its sedimentation is predominantly terrigenous, without significant carbonate facies deposition. This could mean larger amounts of pluviosity and run off in the northern portion of the Paraná Basin during the Late Permian, with the carbonate and evaporite sedimentation concentrated in the region to the south of the Tietê Lineament and to the north of the PGA axis.

Figure 10. Schematic model of the carbonate ramp depositional system interpreted for the Teresina Formation in the studied region, with the respective facies deposited according to the ramp part. Modified from Burchette and Wright (1992). WL: water level, FWB: fair-weather wave base, SWB: storm wave base.

Petri and Fúlfaro (1983) suggest a restricted communication with the open or epeiric sea to the southwest of the basin. Other authors have identified that the environmental conditions of the Teresina Formation in the studied region corresponding to the marginal shallow water may be predominately hypersaline (Rohn, 1994; Matos, 1995). The influence of the PGA on the sedimentation of the Paraná Basin during the Permian had been proposed in previous works. Sandford and Lange (1960) proposed that the basin was divided by the PGA into two major depressions. Fúlfaro (1971) identified two sub-basins located northward and southward the PGA. Aeromagnetic studies carried by Ferreira *et al.* (1981) and Ferreira (1982) show that the Guapiara Fault, the northern limit of the PGA controlled the sedimentation in the Paraná Basin during the Carboniferous and Permian periods. The PGA became uplifted during the deposition of the upper parts of the Passa Dois Group (Stollhofen *et al.*, 2000). The PGA had influenced the deposition of geologic units older than the Teresina Formation in the Paraná Basin, as the Irati Formation (Middle Permian – Late Permian, Milani *et al.*, 2007). Hachiro (1991) and Milani *et al.* (2007) recognized conditions able to the development of carbonate facies in the Irati Formation only northward the PGA. Hachiro (2000) interpreted the occurrences of evaporites northward the PGA in the Irati Formation as result of a restricted environment and dry climate during the Late Permian. Vieira *et al.* (1991) proposed that the northern limit of the PGA (Guapiara Fault) acted as a tectonic –ecologic barrier during the sedimentation of the Irati Formation, with the *Stereosternum* and *Brazilosaurus* zone situated northward of the Guapiara Fault and the *Mesosaurus* zone southward of it. Williams (1995) suggested that the PGA had uplifted during the sedimentation of the Morro Pelado Member of Rio do Rasto Formation, which

during the sedimentation of the Morro Pelado Member of Rio do Rasto Formation, which overlies the Teresina Formation. Giannini *et al.* (2004) analyzed cross-stratifications dip directions of eolian and fluvial facies of the Pirambóia Formation (Permian and/or Triassic), which cover the Teresina Formation in most of the studied area. These authors interpreted a wind convergence zone located between the south and north limits of the PGA. Northward the PGA, the paleowinds came from the N and NE while southward the PGA, the paleowinds came from W and SW. This convergence zone had influenced and differentiated the climate in the south and north of the PGA. The migration of the winds convergence zone to the south would block the northward and eastward advance of wet air masses from the Panthalassa Ocean, favoring dry conditions in the studied region.

6.2 Implications for the paleogeography of the southwestern Gondwana during the Permian

Summons *et al.* (2008) suggest that the Paraná Basin, the Falkland Islands, the Kalahari Basin (southern Namibia), and the Karoo Basin (South Africa) probably formed a huge cratonic basin in the southwest portion of the Gondwana. This basin was apparently isolated from the world oceans as it has been corroborated by the observed endemic fauna. During the Permo-Triassic times, the southern margin of the Gondwana was affected by the Gondwanide Orogeny, producing deformation, metamorphism and magmatic-arc activity (Trouw and De Wit, 1999). During this time, the collisional event that originates the San Rafael Orogeny probably influenced the structural framework of the Paraná Basin, producing changes in its depositional settings and source areas through the generation of local depressions and highs. In this context, Milani (2000) observed the inversion of the on-lap trend in the supersequence Gondwana I, which comprise the Teresina Formation.

According to Stollhofen (1999), a rift valley depression linked to the opening of the South Atlantic between Africa and South America was affected by extensional events since the Late Carboniferous. During the deposition of the Irati Formation, this depression extended from the west of South Africa to the northern Brazil. According to this author, later the Corumbataí Formation was deposited in the rift west margin. The rift was controlled by a long-lived north-northwest trending tectonic zonation, inducing the formation of transfer fault zones transversal to the rift valley axis and promoting the formation of various depocenters that were linked during water highstands. The PGA may be one of these fault zones perpendicular to the main rift trend (Stollhofen *et al.*, 2000). Thus, the carbonate and evaporite facies of the Teresina Formation would be deposited in a tectonic-controlled

facies deposited in alluvial systems from the Pirambóia Formation in the northern flank of the PGA agrees with its tectonic activity during the Permo-Triassic (Giannini *et al.*, 2004).

The Huab Basin in west Africa is interpreted as a Gondwana marginal equivalent of the Paraná Basin (Horsthemke *et al.*, 1990) (Fig. 11). The Gai-As Formation of the Huab Basin has an age of 265 ± 2.5 Ma (Holzforster, 2002) while the Teresina Formation was assigned an age of 267 ± 1.7 Ma (Rocha-Campos *et al.*, 2009). The Teresina Formation would be equivalent to Gai-As Formation, which was deposited in a rift lake system. Horsthemke (1992) interpreted the limestones layers with evaporitic minerals (halite and gypsum) founded in the Gai-As and the Doros Formation, which overlies the Gai-As Formation, as formed in alkaline-saline lake environment. The sedimentation of the Teresina Formation would have been influenced by tectonic and climate controls, which also acted on the correlate units of the Huab Basin. The similarity between the lithologies and environmental conditions of the Gai-As and Teresina formations suggest a common subsidence zone under arid conditions.

Figure 11. A) Reconstruction of West Gondwana during the Late Paleozoic. Modified from Faure and Cole (1999). B) Paleogeographic reconstruction of South Gondwana during the Paleozoic. Modified from Visser and Praekelt (1996). P: Paraná Basin, H: Huab Basin, SA: Serras Australes, KH: Kalahari Basin, K: Karoo Basin, E: Ellsworth Basin.

According to the paleogeographic zonation proposed by Chumakov and Zharkov (2003), the study region would be within the southern arid belt of low-middle latitudes, where lacustrine-alluvial sediments prevailed, frequently associated with gypsum-bearing sabkha-

lacustrine-alluvial sediments prevailed, frequently associated with gypsum-bearing sabkha-related and eolian depositional systems. Its flora characterized hot and arid climate (for instance, *Lycopodiopsis*), with humid seasons in some areas. The Argentine-Brazilian flora was of desert type (Wnuk, 1996).

7. Conclusions

During the Permian, the deposition of the carbonate and evaporite facies of the Teresina Formation would result from the combined influence of a wind convergence zone and the geographic isolation linked to the tectonic evolution of the southwest Gondwana. The Ponta Grossa Arch influenced the climate conditions of the Permian-Triassic formations of the Paraná Basin, acting as a geographical barrier controlling the winds, run-off, entry of sea waters from south and biological exchange. These features dictate the development of a high salinity water body and arid conditions in the studied region. A probable wind convergence zone located parallel to the Ponta Grossa Arch influenced the periodic sedimentation of carbonate and evaporite facies of the Teresina Formation. The migration of this wind convergence zone to the south would promote arid conditions in the studied zone. The comparison between the Teresina Formation and the Gai-As and Doros formations from the Huab Basin provides valuable information about the possible evolution of a Permian rift zone in the Brazilian and African parts of the southwestern Gondwana.

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References

Almeida, C.M., and Do Carmo, D.A., 2005. Taxonomia e paleoecologia de ostracodes da Bacia do Paraná, Estado de Goiás, Brasil, Boletim de Resumos do Congresso Brasileiro de Paleontologia, 19, Aracajú.

- Araújo, L.M., Triguís, J.A., Cerqueira, J.R., and Freitas, L.C., da S., 2000.** The atypical Permian Petroleum System of the Paraná Basin, Brazil. In M.R. Mello and B.J. Katz, eds, Petroleum systems of South Atlantic margins. AAPG Memoir, 73, 377-402.
- Burchette, T.P., and Wright, V.P., 1992.** Carbonate ramp depositional systems. *Sedimentary Geology*, 79, 3-57.
- Choquette, P.W., and Pray J., 1970.** Geologic nomenclature and classification of porosity in sedimentary carbonates. AAPG Bulletin, 54, 207-250.
- Chumakov, N.M., and Zharkov, M.A., 2003.** Climate during the Permian-Triassic Biosphere Reorganizations. *Stratigraphy and Geological Correlation*, 11, (4), 361-375.
- Daemon, R.F., and Quadros, L.P., 1970.** Bioestratigrafia do Neopaleozóico da Bacia do Paraná. In: Congresso Brasileiro de Geologia, XXIV, Brasília, Sociedade Brasileira de Geologia, 359-412.
- De Faria, R.S., Ricardi-Branco, F., Giannini, P.C.F., Swakuchi, A.O., and Del Bem, L.E.V., 2009.** *Lycopodiopsis derbyi* Renault from the Corumbataí Formation in the state of São Paulo (Guadalupian of Paraná Basin, Southern Brazil): New data from compressed silicified stems. *Review of Palaeobotany and Palynology*, 158, 180-192.
- Dickson, J.A.D., 1966.** Carbonate identification and diagenesis as revealed by staining. *Journal of Sedimentary Petrology*, 36, 491-505.
- Dunham, R., 1969.** Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (Ed), *Classification of Carbonate Rocks*. Am. Assoc. Pet. Geol., Mem 1, 108-121.
- Fanton, J.C.M., Ricardi-Branco, F., Torres, M., and Rohn, R., 2006.** Reinvestigação da conífera permiana *Krauselcaldus* (Formação Teresina, Bacia do Paraná, Brasil): Novas interpretações morfológicas e anatômicas. *Revista Brasileira de Paleontologia*, 9 (22), 221-234.
- **Faure, K., and Cole, D., 1999.** Geochemical evidence for lacustrine microbial blooms in the vast Permian Main Karoo, Paraná, Falkland Islands and Huab basins of southwestern Gondwana. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 152 (3), 189-213.
- Ferreira, F., Moraes, R., Ferrari, M., and Vianna, R., 1981.** Contribuição ao estudo do Alinhamento de Guapiara. In: SBG, Simpósio Regional de Geologia, Curitiba, Anais, 3, p. 226-240.
- Ferreira, F., 1982.** Integração de dados aeromagnéticos e geológicos: configuração e evolução do Arco de Ponta Grossa. Instituto de Geociências, Universidade de São Paulo, Unpublished M. Sc. Dissertation, 169 p.
- Flügel, E., 2004.** *Microfacies of Carbonate Rocks*. Springer, 976 p.

- Folk, R.L., and Pittman, J.S., 1971.** Length-slow chalcedony: a new testament for vanished evaporites. *Journal of Sedimentary Petrology*, 41, 1045-1058.
- Fulfaro, V.J., 1970.** Evolução tectônica e paleogeográfica da bacia sedimentar do Paraná pelo trend surface analysis. Instituto de Geociências, Universidade de São Paulo, Unpublished Ph.D. Thesis, 112 p.
- Ghilardi, R.P., and Simões, M.G., 2002.** Foram os Bivalves do Grupo Passa Dois (Exclusive Formação Rio do Rasto), Neopermiano, invertebrados tipicamente dulcícolas?. *Pesquisas em Geociências*, 29 (1), 3-13.
- Giannini, P.C.F. , Sawakuchi, A.O., Fernandes, L.A., and Donatti, L.M., 2004.** Paleoventos e paleocorrentes subaquosas do Sistema Depositional Pirambóia nos estados de São paulo e Paraná, Bacia do Paraná: estudo baseado em análise estatística de dados azimutais. *Revista Brasileira de Geociências*, 34 (2), 282-292.
- Grey, K., 1989.** Handbook for the study of stromatolites and associated structures. *Stromatolite Newsletter*, 14, 82-171.
- Hachiro, J., 1991.** Litotipos, associações faciológicas e sistemas deposicionais da Formação Irati no Estado de São paulo. Instituto de Geociências, Universidade de São Paulo, Unpublished M.Sc. Dissertation, 175 p.
- Hachiro, J., 2000.** Occurrences of evaporites in the Irati Sub-Group (Late Permian, Paraná Basin). *Anais da Academia Brasileira de Ciências*, 72 (4), 600.
- Hoffman, P., 1976.** Enviromental diversity of middle Precambrian stromatolites. In: Walter, M.R., ed. *Stromatolites*, Elsevier Sci. Publ. Co., Amsterdam, 599-611.
- Holz, M., França, A.B., Souza, P.A., Iannuzzi, R., and Rohn, R., 2010.** A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of the Paraná Basin, Brazil, South America. *Journal of South American Earth Sciences*, 29, 381-399.
- Holzforster, F., 2002.** Sedimentology, stratigraphy and synsedimentary tectonics of the Karoo Supergroup, N-Namibia. *Beringeria*, 30,1-144
- Horsthemke, E., 1992.** Fazies der Karoosedimente in der Huabregion, Damaraland, NW-Namibia. *Göttinger Arbeiten Geologie Paläontologie*, 55, 1-102.
- Horsthemke, E. Ledendecker, S., and Porada, H., 1990.** Depositional environments and stratigraphic correlation of the Karoo Sequence in northwestern Damaraland. *Comm. Geol. Surv. Namibia*, 6, 63-73.
- Jia, C., Huang, J., Kershaw, S., Luo, G., Farabegoli, E., Perri, M.C., Chen, L., Bai, X., and Xie, S., 2012.** Microbial response to limited nutrients in shallow water immediately after the end-Permian mass extinction, *Geobiology*, 10, 60-71.

- Matos, S.L.F., Yamamoto, J.K., Riccomini, C., Hachiro, J., and Tassinari, C.C.G., 2001.** Absolute Dating of Permian Ash-fall in the Rio Bonito Formation, Paraná Basin, Brazil. *Gondwana Research*, 4 (3), 421-426.
- Matos, S.L.F., 1995.** O contato entre o Grupo Passa Dois e a Formação Pirambóia na borda leste da Bacia do Paraná no Estado de São Paulo. Instituto de Geociências, Universidade de São Paulo, São Paulo, Unpublished M. Sc. Dissertation, 110 p.
- Meghlhioratti, T., 2006.** Estratigrafia de seqüências das formações Serra Alta, Teresina e Rio do Rasto (Permiano, Bacia do Paraná) na porção nordeste do Paraná e centro-sul de São Paulo. Rio Claro, Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Unpublished M.Sc. Dissertation, 169 p.
- Milani, E.L., Melo, J.H.G., Souza, P.A., Fernandes, L.A. and França, A.B., 2007.** “Cartas Estratigráficas – Bacia do Paraná”. *Boletim de Geociências da Petrobrás*, 15 (2), 265-287.
- Milani, E.J., 2000.** Geodinamica Fanerozóica do Gondwana sul-ocidental e a evolução geológica da Bacia do Paraná. *Geologia do Rio Grande do Sul. CIGO/UFRGS*, 275 – 302.
- Milani, E.J., and Zalán, P.V., 1999.** An outline of the geology and petroleum systems of the Paleozoic interior basins of South America, *Episodes*, 22, 199-205.
- Milani, E.J., and Ramos, V.A., 1998.** Orogenias Paleozóicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. *Revista Brasileira de Geociências*, 28 (4), 473-484.
- Milani, E.J., 1997.** Evolução tectono-estratigráfica da Bacia do Paraná e seu relacionamento com a geodinâmica fanerozóica do Gondwana sul-ocidental. Universidade Federal do Rio Grande do Sul. Unpublished Ph. D.
- Milani, E.J., França, A.B., and Schneider, R.I., 1994.** Bacia do Paraná. *Boletim de Geociências da Petrobrás*, 8 (2), 69-82.
- Morrow, D.W., 1982.** Descriptive field classification of sedimentary and diagenetic breccia fabrics in carbonate rocks. *Bull. Can. Petrol. Geol.*, 30, 227-229.
- Neregato, R., Souza, P.A. de, and Rohn, R., 2008.** Registros Palinológicos Inéditos nas Formações Teresina e Rio do Rasto (Permiano, Grupo Passa Dois, Bacia do Paraná) Implicações Biocronoestratigráficas e Paleoambientais. *Revista Pesquisas em Geociências*, 35 (2), 9-21.
- Neves, J.P., Rohn, R., and Simões, M.G., 2010.** Tafonomia de Biválvios em Calcários Oolíticos da Formação Teresina (Bacia do Paraná, Permiano Médio, Prudentópolis, PR). *Revista Geociências USP*, 10 (3), 19-36.

- Newell, N.D.**, 1973. The very last moment of the Paleozoic Era. In: The Permian and Triassic systems and their mutual boundary. Logan, A. and Hills, L.V., eds, Memoir of Canadian Society of Petrology Geologists, 2, 1-10.
- Northfleet, A.A., Medeiros, R.A., and Muhlmann, H.**, 1969. Reavaliação dos dados geológicos da Bacia do Paraná. Boletim Técnico da Petrobrás, 13 (3), 291-346.
- Petri, S., and Coimbra, A.M.**, 1982. Estruturas sedimentares das formações Irati e Estrada Nova (Permiano) e sua contribuição para elucidação dos seus paleoambientes geradores. 5º Congresso Latinoamericano de Geologia, v.2, Buenos Aires, 353-371.
- Petri, S., and Fúlfaro, V.J.**, 1983. Geologia do Brasil (Fanerozóico). São Paulo, Ed. São Paulo University, 631 p.
- Piccirillo, E.N., Bellieni, G., Cavazzini, G., Comin-Chiaramonti, R., Petrini, R., Melfi, A.J., Pinese, J.P.R., Zantadeschi, R., and De Min, A.**, 1990. Lower Cretaceous tholeiitic dyke swarms from the Ponta Grossa Arch (southeast Brazil): Petrology, Sr-Nd isotopes and genetic relationships with the Paraná flood volcanics. Chemical Geology, 89, 19-48.
- Pittman, E.D.**, 1971. Microporosity in carbonate rocks. AAPG Bulletin, 55, 1873-1878.
- Ragonha, E.W.**, 1984. Taxionomia de dentes e espinhos isolados de Xenacanthodii (Choncrichthyes, Elasmobranchii) da Formação Corumbati. Considerações cronológicas e paleoambientais. Instituto de Geociências, Universidade de São Paulo, Unpublished Ph.D. Thesis, 1v
- Riccomini, C., Filho, A.G., and Almeida, F.F.M.**, 1984. Considerações sobre a estratigrafia do Permo-Triássico na região da Serra do Cadeado, Paraná. Congresso Brasileiro de Geologia, 33, Rio de Janeiro, Anais, 2, 754-764.
- Rocha-Campos, A.C., Basei, M.A. and Santos, P.R.**, 2009. Depósitos de cinza vulcânica no Neopaleozóico da Bacia do Paraná: datação radiométrica (SHRIMP) e possíveis implicações cronoestratigráficas e paleoambientais. Boletim de Resumos da Reunião Anual da Sociedade Brasileira de Paleontologia- Núcleo SP, 8.
- Rohn, R. 2007, Meghioratti, T., and Cordeiro-Silva, A.**, 2007. Tafonomia de bivalves em testemunhos de furos de sondagem das formações Serra Alta e Teresina (Permiano) no leste da Bacia do Paraná. In: XX Congresso Brasileiro de Paleontologia, Buzios. Anais. Sociedade Brasileira de Paleontologia, 278-279
- Rohn, R.**, 2001. A estratigrafia da Formação Teresina (Permiano, bacia do Paraná) de acordo com furos de sondagem entre Anhembi (SP) e Ortigueira (PR). Correlação de Sequências Paleozóicas Sul-americanas, 20, 209-218.

Rohn, R., 1994. Evolução ambiental da Bacia do Paraná durante o Neopermiano no leste de Santa Catarina e do Paraná. Instituto de Geociências, Universidade de São Paulo, Unpublished Ph.D. Thesis, 2v.

Sanford, R. and Lange, F., 1960. Basin study approach to oil evaluation of Paraná miogeosyncline South Brazil. *Bul. of the Amer. Assoc. Petrol. Geol.*, 44 (8), 1316-1370.

Schneider, R.L., Mühlmann, H., Tommasi, E., Medeiros, R.A., Daemon, R.F., and Nogueira, A.A., 1974. Revisão estratigráfica da Bacia do Paraná. In: Congresso Brasileiro de Geologia, XXVIII, 1974, Porto Alegre. *Anais, Sociedade Brasileira de Geologia, Porto Alegre*, vol. 1, 41–66.

Simões M.G., Rocha-Campos, A.C., and Anelli, L.E., 1998. Paleoecology and evolution of Permian pelecypod assemblages (Paraná Basin) from Brazil. In: Johnston, P.A. Haggart, J.W. (Eds), *Bivalves – An Eon of Evolution – Paleobiological Studies. Honoring Norman D. Newell*. University of Calgary Press, Calgary, 443-425.

Sohn, I.G., and Rocha-Campos, A.C., 1990. Late Paleozoic (Gondwana) ostracodes in the Corumbataí Formation, Paraná Basin, Brazil. *Journal of Paleontology*, 64 (1), 116-128.

Stollhofen, H., 1999. Karoo Synrift-sedimentation und ihre tektonische Kontrolle am entstehenden Kontinentairand Namibias. *Zeitschrift der Deutschen Geologischen Gesellschaft*, 149, 519-632.

Stollhofen, H., Stanistreet, I.G., Rohn, R., Holzförster, F., and Wanke, A., 2000. The Gai-As Lake System, Northern Namibia and Brazil. In E.H. Gierlowski-Kordesch and K.R. Kelts, eds., *Lake basin thorough space and time: AAPG Studies in Geology*, 46, 87-106.

Stollhofen, H., Stanistreet, I.G., Bangert, B., and Grill, H., 2000. Tuffs, tectonism and glacially related sea level changes, Carboniferous-permian, Southern Namibia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 161, 167 – 180.

Strugale, M., Rostirolla, S.P., Mancini, F., Portela Filho, C.V., Ferreira, F.J.F., and Freitas, R.C., 2007. Structural framework and Mesozoic-Cenozoic evolution of Ponta Grossa Arch, Paraná Basin, southern Brazil. *Journal of South American Earth Sciences*, 24, 203-227.

→ **Summons, R.E., Hope, J.M., Swart, R., and Walter, M.R.**, 2008. Origin of Nama Basin bitumen seeps: Petroleum derived from a Permian lacustrine source rock traversing southwestern Gondwana. *Organic Geochemistry*, 39, 589-607

Trouw, R.A.J., and De Wit, M., 1999. Relation between the Gondwanide Orogen and contemporaneous intracratonic deformation. *Journal of African Earth Sciences*, 28 (1), 203-213.

Tucker, M.E., and Wright, V.P., 1990. *Carbonate Sedimentology*. Blackwell Science, 482 p.

Tucker, M.E., 2001. Sedimentary petrology. Blackwell Science. 262 p.

Valencio, D.A., Rocha-Campos, A.C., and Pacca, I.G., 1975. Paleomagnetism of some sedimentary rocks of the Late Paleozoic Tubarão and Passa Dois Groups from the Paraná Basin, Brazil. *Revista Brasileira de Geociências*, 5, 186-197.

Vieira, P.C., Mezzalana, S., and Ferreira, F.J.F., 1991. Mesossaurídeo (*Stereosternum tumidum*) e crustáceo (*Liocaris huenei*) no Membro Assistência da Formação Irati (P) nos municípios de Jataí e Montevidiu, Estado de Goiás. *Revista Brasileira de Geociências*, 21 (3), 224-235.

Vieira, A.J., 1973. Geologia do centro e Nordeste do Paraná e Centro Sul de São Paulo. Congresso Brasileiro de Geologia, 27, Aracaju, Anais, 3, 259-277.

Visser, J.N.J., and Praekelt, H.E., 1996. Subduction, megashear systems and late Paleozoic basin development in the African segment of Gondwana. *Geologische Rundschau*, 805, 632-646.

Williams, K.E., 1995. Tectonic subsidence analysis and Paleozoic paleogeography of Gondwana, in A.J. Tankard, R. Suárez Soruco, and H.J. Welsink, eds., *Petroleum Basins of South America : AAPG Memoir* 62, 79-100.

Wnuck, C., 1996. The Development of Floristic Provinciality during the Middle and Late Paleozoic. *Palaeobotany, Palynology*, 90, 5-40.

Zalán, P.V., Wolf, S., Conceição, J.C., Astolfi, A.M., Vieira, I.S., Appi, V.T., Zanotto, O.A., and Marques, A., 1991. Tectonics and sedimentation of the Paraná Basin. In: Ulbrich, H.H.G.J., Rocha-Campos, A.C. *Gondwana Seven*. Instituto de Geociências, Universidade de São Paulo, São Paulo, 83-117.

Zalán, P.V., Wolff, S., Astolfi, M.A.M., Vieira, J.C., Conceição, J., Appi, V.T., Neto, E.V.S., Cerqueira, J.R., and Marques, A., 1990. The Paraná Basin, Brazil, in Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., *Interior Cratonic Basins: AAPG Memoir*, 51, 681-708.

Calcite-dolomite lamination and organic nanostructures in stromatolites of the Teresina Formation, Permian of the Paraná Basin

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ABSTRACT

Stromatolites layers of the Teresina Formation (Late Permian) was identified in the eastern border of the Paraná Basin at north of the Paraná State (Brazil). These stromatolites stand out due to its calcite-dolomite lamination and well preserved organic structures. The genesis of these stromatolites and their calcite-dolomite lamination are discussed in the context of the Permian-Triassic Boundary Microbialites (PTBMs). The dolomite bands are enriched in organic matter as identified by fluorescence microscopy. The precipitation of dolomite would be linked to mineral precipitation induced by biological processes. The organic structures identified were filamentous and nanoglobules, forming biofilms. All these organic structures are known as extracellular polymeric substances (EPS) and are the principal source of energy for metabolic processes of sulphate-reducing bacteria. Polyhedra of EPS showing initial stages of growth of the stromatolites were observed. The biofilms would correspond to thin laminae of calcite-dolomite precipitated. The high degree of preservation of the remains of degraded EPS is related to early calcification processes. Hypersaline conditions promoted stressful environmental conditions and microbial activity, inhibiting favorable conditions for development of other organisms and fauna diversification. The low content of terrigenous grains indicates that the dominant mechanism for stromatolite formation is biologically induced mineral precipitation.

Keywords: stromatolites, Late Permian, Teresina Formation, bacterial biofilms, dolomite.

1. INTRODUCTION

Stromatolites are considered the most ancient biological feature and the major constituent of fossil record, being the earliest evidence of the emergence of life on Earth (Seckbach, 2010). They are the result of the trapping, binding and precipitation of sediment by the extracellular polymeric matrix (EPS) produced by the organisms-biofilms (Krumbein, 1994). Biofilms are defined as a collection of microorganisms and their extracellular products bound to a solid surface (Neu, 1994).

Stromatolites are widely used as paleoenvironmental indicators. Its development is controlled by physical and chemical factors, such as temperature, salinity, water depth, wave and tidal energy and dissolved oxygen concentration. Stromatolites are common sedimentary features in proterozoic carbonate rocks, which is attributed to the absence of competing carbonate-skeletal organisms (Knoll, 1993). During the Phanerozoic, the generation of stromatolites is favored in environments with hypersaline waters, whose conditions difficult the growing of carbonate-skeletal organisms. Well preserved structures of the stromatolites microbial components are rare.

The Teresina Formation (White, 1908; Milani *et al.*, 2007; Holz *et al.*, 2010), Late Permian of the Paraná Basin, is highlighted by the presence of calcite-dolomite stromatolite layers with impressive well preserved microscopic organic structures. The Teresina Formation stromatolites developed in the context of the Permian-Triassic Boundary Microbialites (PTBMs), which are thin (0.05-15 m thick) microbialites associated with shelly faunas and whose growing was favored by global environmental changes responsible for the end-Permian mass extinction (Kershaw *et al.*, 2012). The PTBMs are mainly reported in low latitudes of the Tethys sea. The objective of this paper is to describe the structures preserved in stromatolites layers of the Teresina Formation and discuss their ecological significance for the Gondwana epicontinental seas during the Late Permian.

2. THE TERESINA FORMATION

The Teresina Formation (Passa Dois Group) outcrops along the eastern edge of the Paraná Basin (Milani *et al.*, 2007). This unit is composed of tabular decimeter to meter thick layers of heterolithic laminated siltstones and fine-grained sandstones, limestones (oolitic and bioclastic grainstones and packstones, wackestones and stromatolites). The proportion and thickness of carbonate facies are greater northward the Ponta Grossa Arch axis, where it was developed a carbonate-evaporite ramp depositional system recorded in the upper portion of

the Teresina Formation (Mendez and Sawakuchi, submitted). The studied outcrop occurs in the northern flank of the Ponta Grossa Arch, at the north of the Paraná State, in the municipality of Santo Antônio da Platina (Fig. 1).

Rohn (2001) suggests an age near the Cisuralian – Guadalupian limit (Middle Permian) for the Teresina Formation. Some plant fossils identified are *Lycopodiopsis*, which have been assigned an age of Cisuralian and Guadalupian for the Teresina and Corumbataí formations (De Faria *et al.*, 2009). Holz *et al.* (2010) indicated an older age of Late Kungurian – Rodian (Early to Middle Permian). However, the endemic fossil assemblage of the Teresina Formation difficulties its precise chronostratigraphical position. Rocha-Campos *et al.* (2009) obtained an U/Pb age of 267 ± 1.7 Ma (Late Permian) from zircon grains from ash-fall beds of the Teresina Formation. The fossil content is represented mainly by bivalves, which are endemic to the Paraná Basin (Simoes *et al.*, 1998), and occur commonly in carbonate facies.

The influence of marine conditions is not well defined yet. Almeida and Do Carmo (2005) considered some ostracods as marine. But Sohn and Rocha-Campos (1990) suggested freshwater environment. Others bioclasts are fish remains (scales, teeth and dental plates) and rare amphibian teeth, occurring in bone beds or scattered (Holz *et al.*, 2010). Other authors have recognized the presence of Permian stromatolites in the Teresina and Corumbataí formations. Rohn (2001), Rohn *et al.* (2003) and Meglhioratti (2006) registered stromatolitic levels in the Teresina Formation. Rohn and Fairchild (1986) observed microbial communities colonizing bivalve shells. Fairchild *et al.* (1991) identified columnar stromatolites and Maranhão (1995) described silicified domal and stratiform stromatolites. Stromatolites in the Corumbataí Formation were described by Soares (1972) and Suguio *et al.* (1985).

3. MATERIALS AND METHODS

The sedimentary facies associated with the studied stromatolites were described, with the facies assemblage being presented through a columnar section. Samples of the stromatolite layers were collected for petrographical studies. The thin sections were stained with alizarine red and potassium ferricyanide diluted in 1.5% HCl to differentiate calcite and dolomite minerals under a light polarized microscope. Thin sections were also analysed with fluorescence microscopy to identify content and distribution of organic matter (Perrette *et al.*, 2005). Scanning electron microscopy (SEM) analysis was made on freshly broken surfaces, with the samples being gold-coated to study the stromatolite textures. The classification of stromatolite morphology is based on the nomenclature proposed by Grey (1989).

4. RESULTS

4.1 Stromatolite beds and associated facies

The studied stromatolite layer has a uniform thickness of 47 cm (Fig 2). It is a tabular lithostrome with laminations spacing very closed. The lamination types are wrinkled, lenticular, discontinuous and irregularly variable (Grey, 1989). The discontinuous and irregular lamination can be caused by desiccation promoted by sporadic subaerial exposure. Its morphology is undulatory and non-columnar. The stromatolite facies is associated with heterolithic sandstones facies, which occur as tabular layer, with centimeter to meter thickness (up to 4 m), presenting concave-convex truncament and ripple-marks (Fig. 3). The heterolithic facies is interpreted as deposited under the action of storm waves and associated currents in a ramp between the fair-weather wave base and storm wave base. During these storm episodes, large amounts of sediments are remobilized and deposited from suspension (silt and clay) and traction (sand) loads. Bioclastic packstones occur intercalated in the heterolithic laminated sandstones.

4.2 Stromatolite lamination

Petrographic analysis reveals that stromatolite lamination occurs as submillimetric to millimetric alternations of calcite and dolomite bands (Fig. 4A,B,D,F). Terrigenous components (up to 15%) are mainly quartz, feldspar and muscovite, occurring as scattered grains or concentrated in the dolomite levels. The siliciclastic grains (up to 40 μm diameter) are concentrated in dolomite levels. Chert nodules with diameters between 3 cm and 200 μm are sparse and deform the lamination, suggesting their genesis before significant mechanical compaction. The groundmass is micrite. Toward the top level, blocky spar calcite and chalcedony occur as cements filling microfractures and channels, with 10 to 400 μm length and 10 to 100 μm thick, interrupting and deforming the lamination. The proportion of calcite to dolomite varies from 30:70 to 40:60.

Figure 1. Geologic map showing the location of the study site. Modified from CPRM (2006)

The identified microfauna is composed of well sorted fragments of disarticulated ostracod shells, occurring isolated or forming thin and continuous sub-millimetric laminae (up to 200 μm thick). The shell fragments are mainly replaced by spar calcite and occasionally by chalcedony. These bioclast occur mostly in dolomite levels.

The petrographic analysis under the ultraviolet light indicates that the lamination comprises the alternation of blue fluorescent and non-fluorescent levels. The fluorescent levels correspond to the dolomite bands, indicating their high content of organic matter (Fig. 4).

Figure 2. Studied outcrop with the boundaries of the stromatolite bed marked by red lines.

4.3 Microbial filaments

Organic structures occur as a filamentous matrix within the stromatolite lamination. It is formed by branching filaments, with similar diameter and straight and tubular shape, forming a high density matrix (Fig.7). The major filaments have diameters between 5 and 2 μm while the diameter of the minor ones varies from 1 to 0.4 μm . These filaments are linked to probable spherical coccoid structures, with diameter of 2 μm , defining a polyhedral array.

The observed filaments are interpreted as biofilms, which were defined by Rosenberg (1989) as heterogeneous matrices of microorganisms held together and tightly bound to underlying surfaces by extracellular polymeric substances (EPS).

The spherical structures would correspond to EPS linking bacterial filaments (figs. 7E, 7). The cylindrical filaments in cross section have a diameter of 2 μm (Fig. 7G) branching mainly to 90°. The tubular molds are within the rock and they have the same diameters of the filaments (Fig. 7H). This indicates that the rock laminae would represent a bacterial mat whose mold preservation was proportionated by early silicification process.

Spadafora *et al.* (2010) proposed a model to explain the process of mineral precipitation on a microbial mat (Fig. 6), where the bacterial metabolism and EPS degradation induce the precipitation of carbonate with an ovoidal shape composed of polyhedron crystals of Ca-dolomite and/or high-Mg calcite. The agglutination of spherical nanoglobules (Fig. 7G) forms these polyhedrons. According this model, the observed polyhedral was in an initial development stage.

Figure 3. Facies succession comprising the studied stromatolite bed

Figure 4. A) Alternation of sub-millimeter levels of calcite (Ca) and dolomite (Do). Crossed polarizers. B), D) and E) Chert nodule interrupting and deforming the carbonate levels. Parallel polarizers. C) Disarticulated ostracode shells (Os) forming continuous levels. D) and E) Alternate bands of calcite (Ca) and dolomite (Do) under parallel polarizers. E) and G) Blue fluorescent levels corresponding to dolomite bands rich in organic matter (ultraviolet light fluorescence).

Figure 5. Polyhedrons formed by extracellular polymeric substances (EPS).

Figure 6. Model illustrating stages of the microfabric formation of stromatolites. Modified from Spadafora *et al.* (2010).

Figure 7. SEM photomicrographs. A) and B) Tubular filaments of large diameter. C) and D) Biofilm formed by branching large diameter filamentous. The bacteria links the minor filaments. E) and F) Extracellular polymeric substances (EPS) linking bacteria. G) Cross section of a calcified filament, and spherical nanoglobules (sns). H) Moldic porosity of tubular filaments.

Discussion

The shape and lamination type of the stromatolites are directly linked to the water energy of the depositional environment (Logan *et al.*, 1974). Many authors also recognized that the morphology of the stromatolites is related to the water energy and therefore to their proximity to the coastline (Donaldson and Taylor, 1972; Donaldson, 1976; Grotzinger, 1989). Stromatolite morphology changes from flat to columnar and domal shapes in the offshore direction (Yamamoto *et al.*, 2011). Thus, the flat morphology of the analyzed stromatolite would correspond to an environment of shallow waters with low action of waves and currents.

The environments of formation of the stromatolites are characterized by high chemical gradients, abundance of phototrophic microorganisms and the separation of microbial populations in different layers (Riding and Awramik, 2000). In the studied region, it was identified centimeter nodules and enterolithic layers of chert, that are interpreted as evaporite deposits replaced by silica during the diagenesis. These deposits indicate that the Teresina Formation stromatolites evolved in an environment of high salinities and intense evaporation.

The well preserved lamination occurs at the base of the studied stromatolite level. Towards the top, the lamination is destroyed progressively by microchannels and fractures. This indicates that the water level decreased gradually, producing desiccation cracks by air exposure. The geochemical data of the carbonate rocks from the Teresina Formation are indicative of high salinities, showing evaporitic conditions during its deposition (Suguio *et al.*, 1974, Stollhofen *et al.*, 2000). Thus, hypersaline shallow waters favored the development of microbial mats in the Teresina Formation. This would be similar to microbial mats developed due to hypersaline conditions during the Miocene in the Mediterranean region, which records periods of intense evaporation as result of the isolation of the Mediterranean Sea from the world ocean (Oliveri *et al.*, 2010).

In the petrographic analysis, the only fossils observed in the studied stromatolite bed were ostracods shells. This low faunistic diversity could mean that environmental conditions were stressful during microbial mat development and only ostracods could adapt to this stressful environment. The abrupt contact between the stromatolite level and underlying

heterolithic facies deposited in relatively deeper water suggests a sudden drop of water level. The presence of most ostracods species is limited by seasonal variations in water temperature (Forester, 1985) and hydrochemistry (Forester and Brouwers, 1985). As well as stromatolites, ostracods can be valuable diagnostic indicators of water composition in ancient lakes. For example, some species only occur in SO₄ rich waters, and others in water with high concentration of Cl⁻ (Forester, 1986). The presence of ostracods associated with evaporation can indicate high contents of SO₄ in the water, favoring the development of microbial communities of sulphate reduction bacteria.

The dolomite origin in stromatolite still is a debate subject still especially regarding if its origin is primary by direct precipitation from sea water or secondary by diagenesis. In the last decades, some works have demonstrated that the precipitation of dolomite is induced by microbial activity (Vasconcelos *et al.*, 1995). Oliveri *et al.* (2010) proposed that the precipitation of dolomite would be linked to bacterial sulphate reduction, which can remove the sulphate and release Mg²⁺. As well as pyrite and NH₃ are produced bacterially, increasing the pH and promoting alkalization of the environment would induce the dolomite precipitation. Organic matter such EPS is used in this process by the bacteria as energy source.

Robarts and Zohary (1987) proposed that the warm water promotes the cyanobacterial growth. In periods of greater evaporation due to warmer climate, the concentration of sulfates increases and therefore, the food source for this type of bacteria increases, favoring the precipitation of dolomite. Thus, the dolomite levels of the studied stromatolite would represent periods of warmer and arid climate with intense evaporation and microbial activity. This would explain the higher concentration of organic matter in the dolomite levels relative to the calcite levels. van Lith *et al.* (2002) suggest that sulphate reduction and elevated salinity are the main causes of dolomite precipitation in Lagoa Vermelha and Brejo do Espinho lagoons (Brazil). The well preserved biofilms in the stromatolites of the Teresina Formation would be caused by the calcification of the EPS. According to the microbial calcification model, this process is metabolically induced and is essential to the preservation, distribution and abundance of stromatolites in time and space (Riding, 2000). However, the organic nanostructures observed in the Teresina Formation could correspond to biofilms developed in rock microfractures and cavities. The high degree of preservation of the biofilms may suggest organic structures younger than the Late Permian. The Early Cretaceous hydrothermal event (Nomura *et al.*, submitted), could promote growth of microbial communities within fractures of the Teresina Formation.

The low content of terrigenous grains indicates a low clastic supply during the formation of stromatolites in the Teresina Formation. The concentration of the terrigenous grains and ostracod shells in dolomite levels, probably, was produced by microbial activity through trapping and binding processes by EPS.

Burns *et al.* (2000) suggest a relation between the global environmental changes and dolomite formation during the Phanerozoic, taking into account the declining abundance of dolomite. According the information available, the age of the Teresina Formation may range from Early Permian to Triassic. The Permian-Triassic stands out due to the occurrence of a global mass extinction event, whose causes are still debated (*sensu* Fügel, 2004). According to Schubert and Bottjer (1992), the occurrences of stromatolites increased during the Late Permian and Trisassic (Fig. 8). Kearsey *et al.* (2009) based on stable isotope analysis inferred increasing of the sea surface temperature in the Late Permian. Disaster forms are opportunistic taxa, typically of long stratigraphic range, which normally occur in marginal and environmentally unstable settings but become abundant and environmentally widespread during times of biotic crisis (*sensu* Fischer and Arthur, 1977). The stromatolites of the Teresina Formation probably could be related to the Permo-Triassic extinction, which is characterized by the expansion of the microbialites in nearshore ramp, platform interior and slope settings (Mata and Bottjer, 2012).

Figure 8. A. Map of Early Triassic paleogeography. Modified from Baud *et al.* (1989). B) Histogram of normal-marine level bottom stromatolites. S: Silurian. D: Devonian. M: Mississippian. P: Pennsylvanian. P: Late Permian. T: Early Triassic. J: Jurassic. K: Cretaceous. Cz: Cenozoic. Modified from Schubert and Bottjer (1992).

Conclusions

Stromatolites of the Teresina Formation in the study region would indicate stressful environmental conditions such as elevated salinity and evaporation caused by rising temperatures and/or less runoff. The stromatolite morphology is suggestive of proximity to the shoreline in low energy setting with restricted terrigenous input. The high degree of preservation of the organic nanostructures is related to early calcification of EPS. The dolomite precipitation would occur during warmer periods with intense microbial activity. The dolomite precipitation was result of biologically induced mineral precipitation. The stromatolites of the Teresina Formation could be linked to disaster forms associated with mass extinction events. Thus, the Teresina Formation would record PTBMs in the southwestern Gondwana.

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References

- Almeida, C.M., and Do Carmo, D.A.,** 2005. Taxonomia e paleoecologia de ostracodes da Bacia do Paraná, Estado de Goiás, Brasil, Boletim de Resumos do Congresso Brasileiro de Paleontologia, 19, Aracajú.
- Baud, A., Mordeckai, M., and Holser, W.T.,** 1989. Permian-Triassic of the Tethys: Carbon isotope studies: Geologische Rundschau, 78, 649-677.
- Burns, S.J., Mckenzie, J.A. and Vasconcelos, C.,** 2000. Dolomite formation and biogeochemical cycles in the Phanerozoic. Sedimentology, 47, 49-61.
- de Faria, R.S., Ricardi-Branco, F., Giannini, P.C.F., Sawakuchi, A.O., and Del Bem, L.E.V.,** 2009. Lycopodiopsis derbyi Renault from the Corumbataí Formation in the state of São Paulo (Guadalupian of Paraná Basin, Southern Brazil): New data from compressed silicified stems. Review of Palaeobotany and Palynology, 158, 180-192.
- Donaldson, J.A.,** 1976. Paleoecology of *Conophyton* and associated stromatolites in the Precambrian Dismal Lakes and Rae Groups, Canada. In: Walter, M.R., eds, Stromatolites, Elsevier, Amsterdam, 523-534.

- Donaldson, J.A., and Taylor, A.H., 1972.** Conical – columnar stromatolites and subtidal environment. *American Association Petroleum Geologists Bulletin*, 56, 614 p.
- CPRM – Serviço Geológico do Brasil., 2006.** Mapa Geológico de São Paulo. Ministério de Minas e Energia. Secretaria de Geologia, Mineração e Transformação Mineral
- Fairchild, T.R., Hiruma, S.T., and Mello & Sousa, S.H. de., 1991.** Nova ocorrência de estromatólitos na Formação Estrada Nova (Permiano Superior), Fartura, SP. In: Congresso Brasileiro de Paleontologia, 12º, São Paulo, SP, Boletim de Resumos, Sociedade Brasileira de Paleontologia, p. 14.
- Fischer, A.G., and Arthur, M.A., 1977.** Secular variations in the pelagic realm, in Cook, H.E., and Enos, P., eds., *Deep-water carbonate environments: Society of Economic Paleontologists and Mineralogists Special Publications* 25, 19-51.
- Flügel, E., 2004.** *Microfacies of Carbonate Rocks*. Springer. 976 p.
- Forester, R.M., 1985.** *Limnocythere bradburyi* n. sp: A modern ostracode from central Mexico and a possible Quaternary paleoclimatic indicator. *Journal of Paleontology*, 59, 8-20.
- Forester, R.M., and Brouwers, E.M., 1985.** Hydrochemical parameters governing the occurrence of estuarine and marginal estuarine ostracodes: An example from south-central Alaska; *Journal of Paleontology*, 59, 344-369.
- Grey, K., (1989).** Handbook for the study of stromatolites and associated structures. In: *Stromatolite Newsletter*, 14, 82-171.
- Grotzinger, J.P., 1989.** Facies and evolution of Precambrian carbonate depositional systems: Emergence of the modern platform archetype. In: Crevelo, P.D., Wilson, J.L., Sarg, J.F., Read, J.F., eds, *Controls on carbonate platforms and basin development*, Special Publication of Society of Economic Paleontologists and Mineralogists, Tulsa, 44, 79-106.
- Holz, M., França, A.B., Souza, P.A., Iannuzzi, R., and Rohn, R., 2010.** A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of the Paraná Basin, Brazil, South America. *Journal of South American Earth Sciences*, 29, 381-399.
- Kearsey, T., Twitchett, R., Price, G.D., and Grimes S.T., 2009.** Isotope excursions and palaeotemperature estimates from the Permian/Triassic boundary in the Southern Alps (Italy). *Palaeogeography, Palaeoclimatology, Palaeocology*, 279, 29-40.
- Kershaw, S., Crasquin, S., Li, Y., Collin, P.-Y., Forel, M.-B., Mu, X., Baud, A., Wang, Y., Xie, S., Maurer, F., Guo, L., 2012.** Microbialites and global environmental change across the Permian-Triassic boundary: a synthesis. *Geobiology*, 10, 25-47.

- Knoll, A.H., Fairchild, I.J., and Swett, K., 1993.** Calcified Microbes in Neoproterozoic Carbonates: Implications for Our Understanding of the Proterozoic/Cambrian Transition. *Palaios*, 8 (6), 512-525.
- Krumbein, W.E., 1994.** The Year of the Slime. In: Krumbein, W.E., Paterson, D., Stal, I.J. (eds) *Biostabilization of sediments. Bibliotheks und Information system der Carl von Ossietzky Universitat. Ondenburg*, 1-7.
- Logan, B.W., Hoffman, P., and Gebelein, C.D., 1974.** Algal matas cryptalgal fabrics and structures, Harmelin Pool, Western Australia. *AMer. Assoc. Petrol. Geol. Mem.* 13, p: 38-84.
- Maranhão, M.S.A.S., 1995.** Fósseis das formações Corumbataí e Estrada Nova do Estado de São Paulo: subsídios ao conhecimento paleontológico e bioestratigráfico. Universidade de São Paulo, Instituto de Geociências, Unpublished Ph.D. Thesis, 2v.
- Mata, S.A., and Bottjer, D.J., 2012.** Microbes and mass extinctions: paleoenvironmental distribution of microbialites during times of biotic crisis. *Geobiology*, 10, 3-24.
- Meghlhioratti, T., 2006.** Estratigrafia de sequencias das formacoes Serra Alta, Teresina e Rio do Rasto (Permiano, Bacia do Paraná) na porção nordeste do Paraná e centro-sul de São Paulo, Rio Claro, Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, M.Sc. Dissertation, 133 p.
- Méndez-Duque, J., and Sawakuchi, A.O.,** Tectonic-climate controls on carbonate and evaporite sedimentation in the Teresina Formation, Late Permian of the Paraná Basin, southern Gondwana. *Journal of sedimentary Research. (Submitted)*.
- Milani, E.L., Melo, J.H.G., Souza, P.A., Fernandes, L.A. and França, A.B., 2007.** “Cartas Estratigráficas – Bacia do Paraná”. *Boletim de Geociências da Petrobrás* 15 (2), 265-287.
- Neu, T.R., 1994.** Biofilms and microbial mats. In: Krumbein, W.E., Paterson, D.M., Stal L.J. (eds) *Biostabilization of sediments. Bibliotheks und Information system der Carl von Ossietzky Universitat. Ondenburg*, 9-15.
- Nomura S.F., Sawakuchi, A.O., Bello, R.M.S., Méndez, J.D., Oliveira, A.F., Fuzikawa, K., Giannini, P.C.F., and Dantas, M.S.S.,** Paleotemperatures and paleofluids of the Teresina Formation in the eastern border of Paraná Basin (Southern, Brazil): implications for the generation and migration of hydrocarbons in basins affected by magmatism. *Marine and Petroleum Geology. (Submitted)*.
- Oliveri, E., Neri, R., Bellanca, A., and Riding, R., 2010.** Carbonate stromatolites from a Messinian hypersaline setting in the Caltanissetta Basin, Sicily; petrographic evidence of microbial activity and related stable isotope and rare earth element signatures. *Sedimentology*, 57, 142-161.

- Perrette, Y., Delannoy, J.J., Desmet, M., Lignier, V., and Destombes, J.L., 2005.** Speleothem organic matter content imaging. The use of a Fluorescence Index to characterize the maximum emission wavelength. *Chemical Geology*, 214, 193 -208.
- Riding, R., & Awramik, S., 2000.** *Microbial Sediments*. Springer
- Riding, R., 2000.** Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. *Sedimentology*, 47, Supplement 1, 179-214.
- Robarts, R., and Zohary, T., 1987.** Temperature effects on photosynthetic capacity, respiration, and growth rates of bloom-forming cyanobacteria. *New Zeland Journal of Marine and Freshwater Research*, 21, 391-399.
- Rocha-Campos, A.C., Basei, M.A. and Santos, P.R., 2009.** Depósitos de cinza vulcânica no Neopaleozóico da Bacia do Paraná: datação radiométrica (SHRIMP) e possíveis implicações cronoestratigráficas e paleoambientais. *Boletim de Resumos da Reunião Anual da Sociedade Brasileira de Paleontologia- Núcleo SP*, 8.
- Rohn, R., 2001.** A estratigrafia da Formação Teresina (Permiano, bacia do Paraná) de acordo com furos de sondagem entre Anhembi (SP) e Ortigueira (PR). *Correlação de Seqüências Paleozóicas Sul-americanas*, 20, 209-218.
- Rohn, R., and Fairchild, T.R., 1986.** Estromatólitos Permianos em Calcário Coquinóide do Grupo Passa Dois, Nordeste do Paraná. *Anais da Academia Brasileira de Ciências*, v. 58 (3), 433-444.
- Rohn, R., Lourenço, A.T., and Meghioratti, T., 2003.** As formações Serra Alta, Teresina e Rio do Rasto no furo de sondagem SP-23-PR (Permiano, Grupo Passa Dois, Borda Leste da Bacia do Paraná), In: *Congresso Brasileiro de P&D em Petróleo & Gás*, 2, Rio de Janeiro, 6 p., Resumos, p. 40.
- Rosenberg, E., 1989.** Biofilms on water-soluble substrates. In: Characklis, W.G., and Wilderer, P.A., eds., *Structure and Function of Biofilms*: Chichester, U.K., Wiley, 59-72.
- Seckback, J., 2010.** Stromatolites: interaction of Microbes with Sediments. In: Tewari, V., and Seckbach, J., eds, *Stromatolites: Interaction of Microbes with Sediments: Cellular Origin, Life in Extreme Habitats and Astrobiology*, 18, 9.
- Simões M.G., Rocha-Campos, A.C., and Anelli, L.E., 1998.** Paleoecology and evolution of Permian pelecypod assemblages (Paraná Basin) from Brazil. In: Johnston, P.A. Haggart, J.W. (Eds), *Bivalves – An Eon of Evolution – Paleobiological Studies. Honoring Norman D. Newell*. University of Calgary Press, Calgary, 443-425.
- Soares, P.C., 1972.** Estruturas estromatolíticas do Permiano no Estado de São Paulo. *Res. Com., 26º Congr. Bras. Geol., S.B.G*, 1: 249, Belém.

- Sohn, I.G., and Rocha-Campos, A.C.,** 1990. Late Paleozoic (Gondwana) ostracodes in the Corumbataí Formation, Paraná Basin, Brazil. *Journal of Paleontology*, 64 (1), 116-128.
- Spadafora, A., Perri, E., Mckenzie, J., and Vasconcelos, C.,** 2010. Microbial biomineralization processes forming modern Ca:Mg carbonate stromatolites. *Sedimentology*, 57, 27-40.
- Stollhofen, H., Stanistreet, I.G., Bangert, B., and Grill, H.,** 2000. Tuffs, tectonism and glacially related sea level changes, Carboniferous-Permian, Southern Namibia, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 161, 167-180.
- Suguio, K., Salati, E., and Barcelos, J.H.,** 1974. Calcários oolíticos de Taguai (SP) e seu possível significado paleoambiental na deposição da Formação Estrada Nova. *Revista Brasileira de Geociências*, São Paulo, 4, 142-166.
- Suguio, K., Fairchild, T.R., and Mello e Sousa, S.H. de.,** 1985. Novas descobertas de estromatólitos na Formação Corumbataí (Permiano) em Santa Rosa do Viterbo (SP) e seus significados paleoambientais. *In: Simpósio Regional de Geologia*, 5º, Rio Claro, SP, Boletim de Resumos, Sociedade Brasileira de Geologia, p. 12.
- Schubert, J.K., and Bottjer, D.J.,** 1992. Early Triassic stromatolites as post-mass extinction disaster forms. *Geology*, 20: 883-886.
- van Lith, Y., Vasconcelos, C., Warthmann, R., Martins, J.C.F., and McKenzie, J.A.,** 2002. Bacterial sulfate reduction and salinity: two controls on dolomite precipitation in Lagoa Vermelha and Brejo do Espinho (Brazil): *Hydrobiologia*, 485, 35-49.
- Vasconcelos, C., McKenzie, J.A., Bernasconi, S., Grujic, D. and Tien, A.J.,** (1995). Microbial mediation as a possible mechanism for dolomite formation. *Nature*, 377, 220-222.
- White, I.C.,** 1908. Relatório final da Comissão de Estudos das Minas de Carvão de Pedra do Brasil. Rio de Janeiro: DNPM, 1988, Parte I, p: 1-300; Parte II, 301-617.
- Yamamoto, At., Lee, K.C., and Isozaki, Y.,** 2011. Lower Cretaceous stromatolites in far east Asia: Examples in Japan and Korea. *In: Tewari, V., and Seckbach, J., eds, Stromatolites: Interaction of Microbes with Sediments: Cellular Origin, Life in Extreme Habitats and Astrobiology*, 18, 275-287.