**UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL**
**INSTITUTO DE GEOCIÊNCIAS**
**PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS**

ETIENE FABBRIN PIRES

# Análises dendrológicas no Cretáceo Inferior das bacias do Araripe e Paraná: determinação de paleoclimas regionais e relação com biomas globais do Mesozóico.

**ORIENTADORA: PROFª. DRª. MARGOT GUERRA SOMMER**

Porto Alegre - 2008

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# ANÁLISES DENDROLÓGICAS NO CRETÁCEO INFERIOR DAS BACIAS DO ARARIPE E PARANÁ: DETERMINAÇÃO DE PALEOCLIMAS REGIONAIS E RELAÇÃO COM BIOMAS GLOBAIS DO MESOZÓICO.

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# RESUMO

A análise de anéis de crescimento de associação de lenhos silicificados, de idade Cretáceo Inferior, provenientes de seqüência pré-rifte da Depressão Afro-Brasileira (Formação Missão Velha, Bacia do Araripe) e da parte norte da Formação Botucatu (Bacia do Paraná) produziu importantes resultados com relação à periodicidade de crescimento arbóreo durante o Berriasiano no Cinturão Equatorial. A análise de diferentes tipos de lenhos da Formação Missão velha (8°S) indicou que, mesmo em altas temperaturas, o clima foi caracterizado por alternância cíclica entre períodos secos e chuvosos. O fator controlador do crescimento foi o suprimento aqüífero originado principalmente por precipitações cíclicas. A alta freqüência de falsos anéis de crescimento foi atribuída a secas ocasionais durante a fase de crescimento e também a danos causados por artrópodes. Os dados dendrológicos indicam um típico clima de savana, contrariando modelos paleoclimáticos que estabelecem condições de deserto subtropical, áridas a semi-áridas para o Cretáceo Inferior na porção sul do Cinturão Equatorial. Esse clima é definido por regimes pluviométricos e de temperatura, com uma longa estação de seca (inverno) e uma estação úmida chuvosa (verão). Conseqüentemente, a associação de lenhos é relacionada ao bioma Verão Úmido, em baixa latitude, caracterizado em modelo paleoclimático previamente estabelecido para a transição Jurássico-Cretáceo. Estas inferências concordam com estudos geológicos estabelecidos para a Depressão Afro-Brasileira que indicam condições úmidas vigentes na parte norte em relação a condições semi-áridas vigorantes na parte sul da bacia. A interação planta-artrópode constitui-se em registro inédito de evidências de fitofagia em associação de lenhos silicificados da Bacia do Araripe. A presença de um complexo sistema de canais, frequentemente preenchidos com coprólitos de formato oval a hexagonal, permitiu inferir atividades de oribatídeos (Isoptera). Peculiaridades da preservação dos lenhos demonstram que o dano foi causado provavelmente por formas herbívoras. Dados dendrológicos associados a resultados obtidos na análise da interação planta-artrópode restringem o intervalo de deposição dos níveis contendo lenhos fósseis na Formação Missão Velha ao intervalo basal do Cretáceo Inferior. Uma associação monotípica de coníferas com afinidade a Pinaceae atuais, preservada na porção norte da Formação Botucatu (18°S) na Bacia do Paraná, constitui evidência de alguma umidade presente nas condições áridas vigorantes no bioma Deserto. Análises dendrológicas nessa associação monotípica indicam que as condições de crescimento eram periódicas, mas altamente estressantes durante o ciclo de vida das plantas. Os parâmetros quantitativos, que controlaram o desenvolvimento dos anéis de crescimento, mais do que uma conseqüência do clima, foram relacionados a caracteres ambientais. Características taxonômicas e fisiológicas foram também decisivas como resposta a restrições ambientais. A associação de coníferas desenvolveu-se durante o clímax de uma fase "*greenhouse*" com aumento na disponibilidade de $CO_2$ atmosférico. A presença de anéis de crescimento como característica comum indica variações cíclicas nas condições de crescimento da planta; todavia zonas típicas de lenho tardio caracterizadas pelo espessamento da parede e redução do lúmen do traqueídeo não foram encontradas. Simulações de paleoclimas do Cretáceo Inferior para esta latitude indicam biomas áridos desérticos associados a condições hiper-áridas durante a fase pré-rifte do Pangéia. A integração dos diferentes dados obtidos na análise das diferentes bacias indica que parâmetros quantitativos utilizados em dendrologia podem estar relacionados com características ambientais, bem como a características intrínsecas da planta. Portanto, anéis de crescimento não são determinados exclusivamente por fatores extrínsecos; características taxonômicas e fisiológicas foram decisivas como resposta a restrições ambientais, especialmente em condições estressantes de crescimento. Considerando-se as análises dendrológicas associadas a dados paleogeográficos e sedimentológicos, detectou-se que condições climáticas áridas e semi-áridas vigentes em regiões peri-equatoriais em ecossistemas desenvolvidos em fase "*greenhouse*" no Cretáceo Inferior não possuem análogos na atualidade, na vigência de estágio "*icehouse*".

# ABSTRACT

Growth rings analyses on Early Cretaceous silicified coniferous wood assemblage from the pre-rift sequence of Afro-Brazilian Depression (Missão Velha Formation, Araripe Basin - Brazil) and from northern portion of the Botucatu Formation (Paraná Basin - Brazil) have yielded important information about periodicity of arboreal growth during the Berriasian in the Equatorial Belt. Despite warm temperatures, dendrological data from different wood types from Missão Velha Formation (8º S) indicate that the climate was characterized by cyclical alternation of dry and rainy periods. The controlling factor was water supply, originated mainly by cyclical precipitations. The great frequency of false growth rings can be attributed to occasional droughts during the growing period and also to another external factor represented by wood boring arthropod infestation. Dendrological data indicate a typical savanna climate and contrast with palaeoclimatic models that inferred subtropical desert conditions and arid to semi-arid conditions for the Early Cretaceous in the southern equatorial belt. The year-round warm tropical climate is defined by pluviometric and temperature regimes, with a very long dry season (winter) and a wetter, rainy season (summer). Consequently the wood assemblage is linked to a low latitude Summer-Wet biome, well characterized in previous palaeoclimatic model from the Jurassic-Cretaceous transition. The present inferences are in agreement with geological studies for the Afro-Brazilian Depression that indicates humid climatic conditions in the northern part in relation to those semi-arid conditions invigorating at its southern part. The arthropod-plant interaction provides the first relevant data for addressing evidences of phytophagy in an assemblage of coniferous silicified woods in Araripe Basin. A complex boring system, filled sometimes with small, oval to hexagonal coprolites, allowed to infer activities of oribatid termites (Isoptera). Peculiarities from wood preservation show that the damage was probably caused by herbivores, not detritivores. Dendrological data associated to results obtained in arthropod-plant interaction constrains the stratigraphic level of fossil wood occurrence in Missão Velha Formation to the interval Early Cretaceous. Otherwise, a monotypic coniferous wood association, showing affinities with extant Pinaceae, from northern portion of the Botucatu Formation (18°S) in Paraná Basin, is an evidence of some humidity under arid conditions prevailing in a Desert biome. Dendrological analysis for the monotypic wood assemblage indicated that growing conditions were periodic, but most stressed during the life cycle. Quantitative parameters controlling growth ring development should be highly related to environmental characters and not only a single consequence of climate. Taxonomic and physiologic parameters were also decisive as a response to environmental constrains. The conifer assemblage was developed during the climax of a greenhouse phase with increasing atmospheric $CO_2$. The presence of growth rings as a common character indicates cyclical variation in tree growing conditions; nevertheless, typical latewood zone characterized by wall thickening and reduction of lumen size was not found. Simulations of Early Cretaceous climate indicate that arid desert biomes associated to hyper arid conditions may indeed have prevailed at southern lower latitudes during the pre-rift phase of Pangea. Integration of data obtained from different basins indicates that quantitative parameters utilized in dendrology can be highly related to environmental characters and not only a single consequence of climate. Thus growth rings were not determined by extrinsically factors alone; taxonomic and physiologic characters were decisive as a response to environmental constrains, especially in stress growing conditions. Taking into account dendrological analysis associated to palaeogeographic and sedimentological data it can be detected that arid to semi-arid peri-equatorial climatic conditions in Early Cretaceous greenhouse ecosystems have no modern analogs in present icehouse world.

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# TEXTO EXPLICATIVO DA ESTRUTURA DA TESE

O documento aqui apresentado, obrigatório para a obtenção de título de Doutor em Ciências junto ao Programa de Pós-Graduação em Geociências da Universidade Federal do Rio Grande do Sul (PPG-Geo/UFRGS), foi elaborado de acordo com a Resolução nº 093/2007, da Câmara de Pós-Graduação, a qual normatiza a apresentação de teses na forma de artigos publicados e/ou submetidos pelo estudante em periódicos científicos, sendo aqui sintetizados os procedimentos utilizados na estruturação do **Documento Final** submetido à avaliação.

Constam desse documento um **Resumo** e um **Abstract** que sintetizam os objetivos e os resultados obtidos com o desenvolvimento do projeto de pesquisa. A **Introdução** (capítulo 1) corresponde a uma compilação de dados sobre o tema de estudo, incluindo os seguintes itens: **A contribuição da Paleobotânica no delineamento de zonas paleoclimáticas, Zoneamentos paleoclimáticos no Mesozóico, Objetivos, Contexto estratigráfico** (Bacia do Araripe e Bacia do Paraná) e **Material e Métodos**.

O corpo principal da tese é composto pelo capítulo 2, onde são apresentados os artigos submetidos durante a realização do doutorado, nos quais a doutoranda é a primeira autora.

A análise de anéis de crescimento de lenhos fósseis gimnospérmicos provenientes da Formação Missão Velha, Bacia do Araripe (Berriasiano - Cretáceo Inferior) é apresentada como primeira componente do capítulo 2. Este estudo foi submetido ao periódico *Cretaceous Research* com o título "*Palaeoclimatic inferences in the Early Cretaceous – Missão Velha Formation of Araripe Basin (Brazil) – based on dendrological data*".

Evidências que representam registros inéditos de interação inseto-planta na assembléia fossilífera descrita para a Formação Missão Velha, são descritas no trabalho intitulado *"Arthropod-plant interaction in Early Cretaceous (Berriasian) of the Araripe Basin – Brazil"* correspondente ao segundo artigo do capítulo 2 submetido ao periódico *Journal of South American Earth Sciences*.

Finalizando o capítulo 2, são apresentados os resultados obtidos em análises dendrológicas de uma associação de lenhos de grande porte, procedentes de afloramento da

Formação Botucatu intercalado em basaltos da Formação Serra Geral, no norte do estado de Minas Gerais. Esse estudo foi submetido ao periódico *Gondwana Research* sob o título "*Early Cretaceous coniferous wood assemblage from an arid desert biome (Botucatu Formation, Paraná Basin, Brazil): Dendrological parameters and their relation to paleoclimatic data*".

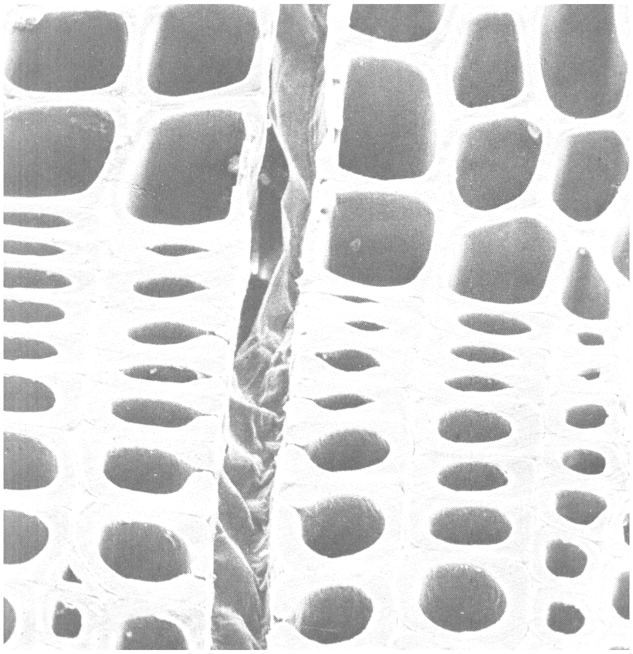
Por fim, é apresentada a **Análise Integradora** (capítulo 3), formulada a partir dos objetivos inicialmente formulados e dos resultados atingidos com o desenvolvimento do projeto de tese. A integração desses resultados possibilitou definir conclusões inéditas a respeito de paleoclimas regionais vigentes durante a deposição das seqüências estudadas, contribuindo para a ratificação de zonas paleoclimáticas globais.

Compõem o capítulo 4, referente aos **Anexos**, as cartas de recebimento dos 3 artigos submetidos para publicação, e dois artigos publicados durante o desenvolvimento do doutorado, focados em seqüência triássica da Bacia do Paraná, que forneceram subsídios importantes para a identificação de padrões diagnósticos de diferentes estágios climáticos.

A **Bibliografia** (capítulo 5) está organizada por ordem alfabética no final deste documento e refere-se exclusivamente aos capítulos 1 e 3.

A **Lista de Figuras e Tabelas**, referente aos capítulos 1 e 3 deste documento, está inserida na página ix.

# 1 - Introdução



# 1 – INTRODUÇÃO

## 1.1. A contribuição da Paleobotânica no delineamento de zonas paleoclimáticas

Embora os sistemas climáticos sejam resultantes da atuação de uma grande diversidade de fatores, incluindo-se, entre outros, o ciclo do carbono, a natureza dos oceanos, os padrões de circulação oceânica, a composição do manto e até a ação de forças extraterrestres, a distribuição e os padrões da vegetação constituem elementos fortemente impactantes nesse processo.

A paleofitogeografia tem se constituído em importante aporte em reconstruções paleoclimáticas. Muitos métodos têm sido utilizados no reconhecimento de unidades vegetacionais globais, destacando-se aqueles que têm como suporte características taxonômicas de formas consideradas guias, padrões ecológicos de determinadas associações e padrões estatísticos de diversidade.

A delineação de diferentes províncias paleoclimáticas foi inicialmente estabelecida a partir de padrões de distribuição de alguns gêneros, considerados guias para a definição de determinados climas (Krasilow, 1972). Embora definindo algumas características climáticas, este método não evidencia gradações na vegetação e no clima, e por outro lado, a extinção temporal de algumas formas guias invalida o esquema, impedindo a compreensão do processo ao longo do tempo. Valkhrameev (1964, 1991) interpreta a evolução climática através da caracterização de grupos de plantas delineados como “phytochoria”. Essa caracterização, todavia, também não é efetiva, pois é eminentemente geográfica e não considera o movimento tectônico das placas, com respeito à latitude. A delimitação de cinturões climáticos paralelos às linhas latitudinais, estabelecida por Valkhrameev (1964, 1991), para o Mesozóico, a partir da concepção de que as modificações climáticas ao longo de continentes eram influenciadas principalmente por gradientes de temperatura latitudinais foi contestada por modelos climáticos definidos por Sloan e Barron (1990). Esses modelos evidenciaram que dada a grande extensão continental, tal zoneamento não ocorre, pois nessa situação geram-se climas sazonalmente mais extremos do que aqueles vigorantes nas áreas marginais.

A utilização de análise multivariada em base de dados paleobotânicos, estabelecidos a partir de identidade genérica e padrões de diversidade da vegetação, associada à determinação de litologias climaticamente sensíveis (e.g. carvões, evaporitos, depósitos de sal) possibilitou o delineamento de zonas climáticas, comparáveis aos biomas definidos por Walter (1985) para floras atuais globais. Dessa forma, a partir de adaptações estabelecidas por Ziegler (1990) ao esquema original de Walter (1985) com objetivo de caracterizar zonas paleoclimáticas, foram estabelecidos dez biomas, os quais, embora definidos de forma muito precisa, constituem categorias suficientemente amplas que permitem, também, a inferência de zonas florísticas em diferentes intervalos no passado geológico. A partir dessa caracterização, mapas paleobiogeográficos de diferentes estágios no tempo geológico têm sido estandardizados, permitindo a compreensão da evolução espacial desses biomas no tempo geológico (Willis e McElwain, 2002; Rees et al., 2000).

Todavia, o resultado mais difundido é aquele disponibilizado por Scotese (2003). Nesse estudo, com base em mapas que demonstram o desenvolvimento de placas tectônicas oceânicas e deriva das massas continentais, são caracterizados distintos paleoclimas vigentes durante a historia geológica da terra nos últimos 100 milhões de anos; é ali plotada a distribuição de rochas, plantas e animais climaticamente sensíveis, que se originam em cinturões climáticos específicos.

Além de parâmetros relativos à fisionomia foliar, a presença de anéis de crescimento em plantas foi utilizada desde o século XIX como critério qualitativo de sazonalidade paleoclimática (Witham, 1831; Miller, 1858; Seward, 1892). A adaptação de técnicas dendroclimatológicas quantitativas utilizadas em lenhos holocênicos (Fritts, 1976) no estudo de material fóssil foi estabelecida por Creber (1977), Creber e Chaloner (1984a,b, 1985) e passou a ser aplicada na obtenção de dados paleoclimáticos quantitativos em lignotafofloras (Creber e Francis 1999). Dessa forma, a espessura media dos anéis de crescimento tem sido utilizada como indicadora de condições climáticas para o desenvolvimento da planta (e.g. Francis, 1984; Francis e Hill, 1996; Francis e Pole, 2002). Por outro lado, a sensibilidade média, que mede a variabilidade na espessura dos anéis de crescimento ano a ano, é utilizada para indicar instabilidade ambiental e grau de stress ecológico (Jefferson, 1982; Francis, 1984,1986; Falcon-Lang e Cantril, 2001,2002; Falcon-

Lang et al., 2004). A porcentagem de lenho tardio em cada anel é utilizada para indicar sazonalidade abruptamente demarcada ou, alternativamente, condições favoráveis ao longo do final da estação de crescimento (Parrish e Spicer, 1988; Keller e Hendrix, 1997). Esses critérios foram utilizados como evidências climáticas importantes por Frakes et al. (1992) na definição de modelos climáticos para o Fanerozóico. A validade de tais parâmetros tem sido, todavia, questionada por Brison et al. (2001) e Falcon-Lang (2001), para os quais os fatores intrínsecos (genéticos, taxonômicos) influenciam características quantitativas nos anéis de crescimento em plantas atuais, refletindo-se essa limitação nos resultados obtidos em lenhos fósseis. Os resultados obtidos no presente estudo demonstraram que a eficiência dos parâmetros paleclimáticos obtidos a partir de dados dendrológicos é dependente não só de fatores abióticos, mas também de fatores bióticos intrínsecos.

## 1.2. Zoneamentos paleoclimáticos no Mesozóico

Durante o Mesozóico, a configuração continental modificou-se profundamente, desde um padrão constituído eminentemente por duas extensas massas continentais (Laurásia e Gonduana), separadas por um oceano equatorial (Thetys), para um padrão de múltiplos continentes, estendendo-se por diferentes latitudes e separados por diversos oceanos.

O clima vigente durante o Cretáceo, abordado no presente estudo, foi classicamente considerado como muito quente, com baixos gradientes de temperatura, condições temperadas em altas latitudes, deposição extensiva de evaporitos e registro de organismos fósseis considerados intolerantes ao frio desde o equador até os pólos (Hallam, 1985). Todavia, um grande número de evidências, que incluem dados sedimentológicos, paleontológicos, geoquímicos e aqueles resultantes de modelagem climática, indicaram que esta concepção é simplista e que na realidade, algumas regiões foram frias nesse intervalo, por muito tempo aceito como um dos mais quentes da história da terra.

No inicio do Mesozóico, durante o Triássico, ocorreu a máxima expansão do supercontinente Pangéia, que derivou significativamente ao norte circundado por um imenso oceano (Panthalassa). O Gonduana, nesse intervalo, transitava de estágio climático icehouse para a vigência de um estágio climático greenhouse instalado plenamente a partir do Triássico Médio (Kidder e Worsley, 2004). As fases iniciais da fragmentação da Pangéia, assinaladas pela abertura de riftes, iniciam-se no Jurássico.

A partir do mapeamento da distribuição de biomas em mapas paleogeográficos do Mesozóico Inferior (Triássico e Jurássico), Ziegler et al. (1993) concluem pela inclusão das floras desse intervalo em três amplos biomas: subtropical seco (dry subtropical), temperado úmido (warm temperate) e temperado ameno (cool temperate). Esse zoneamento é semelhante ao que havia sido estabelecido anteriormente por Krassilov (1981), que se contrapõe ao que estabelece Valkhrameev (1991), o qual relaciona esses biomas respectivamente aos cinturões tropical (equatorial), subtropical e temperado quente. Esta escala, segundo Ziegler et al. (1993), infere climas globais excessivamente quentes, sugerindo que a temperatura em baixas latitudes seria superior aos 60ºC.

Análises dendrológicas realizadas em uma associação gimnospérmica monoespecífica, determinada como *Sommerxylon spiralosus* (família Taxaceae) (Pires e Guerra-Sommer, 2004), em seqüências depositadas em baixas latitudes (48°S), no Neo-Triássico (Carniano- Noriano), sul da Bacia do Paraná (Pires et al., 2005), indicaram a vigência de amplos ciclos sazonais. O período de crescimento arbóreo em cada ciclo climático (anual ou não) era extenso e relativamente uniforme, porém interrompido por secas ocasionais, dada à quantidade expressiva de falsos anéis de crescimento. Por outro lado, o período de restrição do crescimento era rápido. A restrição nas precipitações constituiu-se no fator inibidor do crescimento dessas plantas em cada ciclo**.** De acordo com estas características, o clima vigente seria definido ciclicamente por amplas fases de crescimento lento, que evoluíram para fases de acentuada restrição, culminando com sua estagnação. Este padrão climático, em eco-regiões continentais atuais é encontrado nos domínios seco até úmido-temperado, em climas subtropicais até temperados.

Por outro lado, estudos dendrológicos na Antártida (Transantartic Mountains) nesse intervalo evidenciaram que os padrões de crescimento arbóreo em áreas polares era limitado por ciclos distintos de luminosidade e não por disponibilidade hídrica e temperatura, como ocorre nas florestas modernas de altas latitudes (Taylor e Ryberg, 2007).

Rees et al. (2000) apresentam novos dados a respeito da paleoclimatologia do Jurássico, utilizando variações na morfologia foliar em plantas não angiospérmicas como caráter determinante. Um espectro climático foi então construído, associando esses dados e informações fornecidas por litologias climaticamente sensíveis. Cinco grandes biomas são reconhecidos para o intervalo Jurássico: i. sazonalmente quente (verões quentes ou subtropical); ii. deserto; iii. sazonalmente seco (inverno úmido); iv. temperado quente; v. temperado ameno. Os limites latitudinais mantiveram-se praticamente constantes, evidenciando-se, porém, sutil movimentação continental. Alterações climáticas muito expressivas não são identificadas por Rees et al. (2000) durante toda a extensão do período. Na figura 1 estão caracterizados os diferentes biomas globais vigentes no limite o Jurássico Superior – Cretáceo Inferior.

Analisando lenhos permineralizados e *charcoal* provenientes de seqüências depositadas durante o intervalo Jurássico Inferior-Médio (Pliesbachiano-Bathoniano), Morgans (1999) registrou um clima do tipo mediterrâneo, com aumento temporal de sazonalidade climática. O autor estabeleceu a evolução do crescimento arbóreo, uma vez que lenhos bathonianos apresentaram características mais extremas (como anéis de crescimento mais estreitos, presença de falsos anéis). A disponibilidade hídrica foi o fator limitante do crescimento, sendo uma conseqüência do baixo nível do mar e da vigência de clima seco.

Estudando uma associação de evaporitos no sul da Inglaterra, Francis (1984) registrou uma associação de lenhos fósseis procedentes de seqüências estratigráficas relacionadas à ambiente deposicional associado a um pântano hipersalino depositado no intervalo Jurássico Superior. O padrão dos anéis de crescimento, estreitos e variáveis em espessura, indicou que as condições para o crescimento das árvores foram marginais ao pântano e altamente irregulares ano a ano.

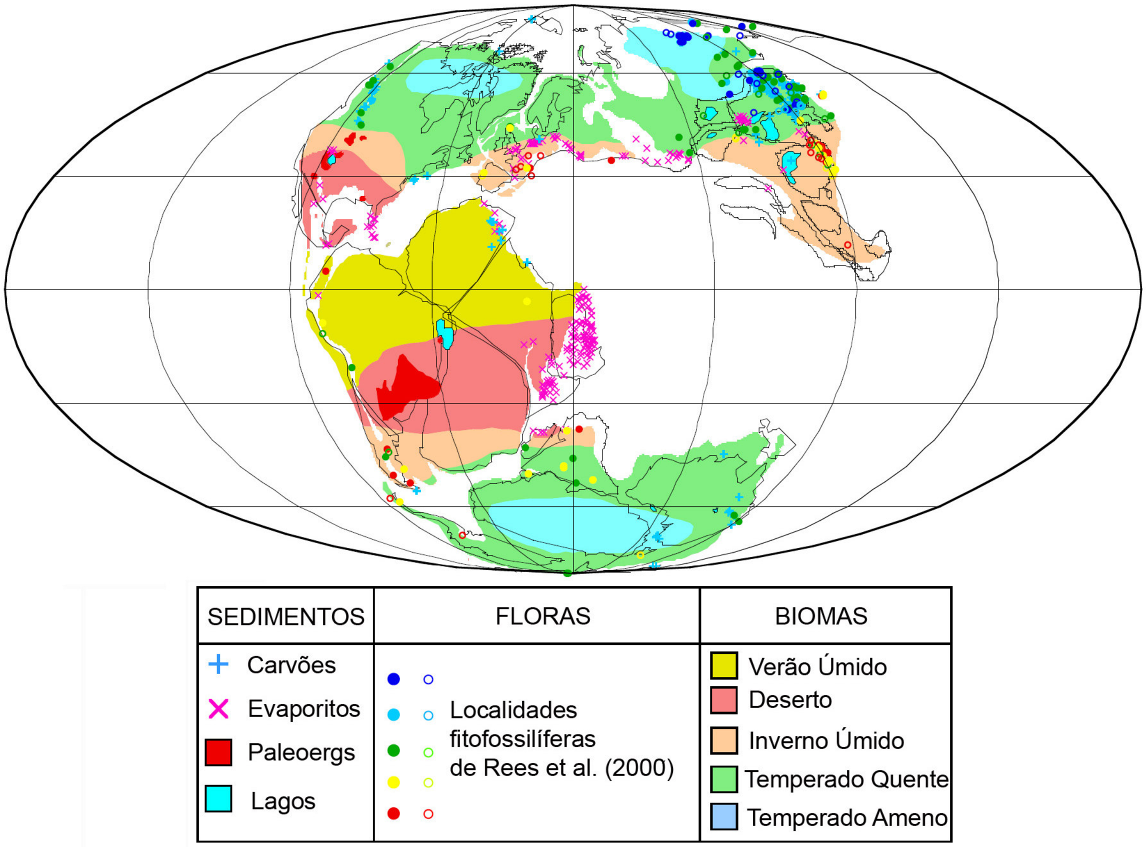


Figura 1: Biomas globais vigentes no limite o Jurássico Superior – Cretáceo Inferior (modificado de Rees et al., 2000).

Keller e Hendrix (1997) analisaram uma floresta petrificada de excelente preservação localizada no deserto de Gobi, sul da Mongólia, em paleolatitude de 46º N, datada como Jurássico Superior. As características dendrológicas da associação indicaram a vigência de um paleoclima monsonal, onde o crescimento arbóreo era constante durante a estação de crescimento, mas cessava abruptamente sob condições desfavoráveis. A disponibilidade hídrica era o fator controlador do crescimento.

No intervalo Jurássico Superior-Cretáceo Inferior, o qual corresponde ao segmento abordado especificamente no presente estudo, a separação entre Gonduana e Laurásia progrediu, e um amplo oceano que se desenvolvia entre esses dois continentes (Scotese, 2003). O nível eustático dos mares era alto, inundando extensas áreas da Laurásia e gerando o desenvolvimento de mares epicontinentais. No Gonduana, depósitos marinhos formaram-se apenas na margem oeste, ao longo de um estreito corredor na região dos Andes, ocorrendo, no interior do continente, exclusivamente sedimentação continental.

Nesse intervalo, a fragmentação do Gondwana intensificou-se. Bacias rifte formam-se nas porções nordeste da América do Sul, enquanto que na bacia intracratônica do Paraná acumulou-se um espesso depósito de dunas eólicas, designado como Formação Botucatu. A presença de uma importante associação de lenhos permineralizados de grande porte, inclusa em sedimentos da Formação Botucatu na porção noroeste da bacia, na região de Uberlândia, Minas Gerais, constitui evidencia intrigante, pois configura disponibilidade hídrica, mesmo que efêmera, e sazonalidade do crescimento em plantas no horizonte estudado.

Gérards et al. (2007) realizaram análises quantitativas e qualitativas dos anéis de crescimento de uma associação de lenhos fósseis do Cretáceo Inferior, proveniente da Bacia de Mons (Bélgica), com paleolatitude de 30-35ºN. Os altos coeficientes de sensibilidade média indicaram condições instáveis de crescimento, corroborando com a inferência de um clima tropical, com estações seca e úmida, bem delimitadas.

Jefferson (1982) através de análise de anéis de crescimento evidenciou a vigência de clima sazonal em médias latitudes (ilha Alexandre – Antarctica). Falcon-Lang e Cantrill (2000) também registraram padrões anatômicos similares para lenhos fósseis provenientes da mesma localidade estudada por Jefferson (1982), porém de idade albiana.

As condições especiais que levaram a geração de anéis de crescimento tanto em plantas localizadas próximo aos paleopolos quanto em plantas tropicais no Cretáceo Inferior, são geralmente interpretadas segundo a presença de altas quantidades de dióxido de carbono na atmosfera, condição comum em todo o globo em um estágio "greenhouse" (Chaloner and McElwain, 1997).

A grande área continental correspondente à África e América do Sul está incluída por Chumakov (1995) no cinturão Tropical-Equatorial Quente-Árido durante a vigência do Cretáceo Inferior (Berriasiano). Esse cinturão se constitui em uma das oito zonas climáticas distribuídas de pólo a pólo. Os mapas paleoclimáticos de Scotese (2003) definidos de forma mais ampla para todo o Neocomiano, também incluem essa grande massa continental no cinturão climático árido. Reconstituições paleogeográficas da Depressão Afro-Brasileira – ABD (Ponte, l972) da qual a Formação Missão Velha seria um fragmento remanescente, indicam a presença de faixas estreitas de terras baixas, paralelas às margens continentais do Brasil e da África do Sul (Ziegler et al., 1987; Golonka et al., 1994). Da Rosa e Garcia (2000) dividem a bacia em duas regiões, com base em análises de paleocorrentes, proveniência, diagênese e paleontologia. A abundância de lenhos permineralizados sugere para esses autores, o desenvolvimento de uma floresta de coníferas na margem norte, mais úmida, isolada da porção sul, onde prevaleciam condições áridas a semi-áridas, evidenciadas pela presença de extensivas fácies eólicas.

Tendo em vista a relação entre dados dendrológicos, paleoclimas regionais e zoneamentos climáticos globais, a análise comparativa entre padrões de anel de crescimento de lenhos fósseis procedentes de afloramentos da Formação Missão Velha relacionada à fase pré-rifte da Bacia do Araripe e da Formação Botucatu na Bacia do Paraná, permite estabelecer os objetivos que se seguem.

## 1.3. Objetivos

- Identificar padrões de desenvolvimento qualitativo e quantitativo de anéis de crescimento em lenhos de gimnospermas fósseis do Cretáceo Inferior, procedentes da Formação Missão Velha (Bacia do Araripe) e Formação Botucatu (Bacia do Paraná).
- Estabelecer inferências paleoclimáticas de caráter regional com base nos dados dendrológicos.
- Verificar a coerência entre os resultados obtidos na análise dendrológica de associações lignoflorísticas procedentes das diferentes bacias com evidências paleogeográficas e estratigráficas.
- Averiguar a congruência entre a assinatura paleoclimática obtida com dados dendroclimatológicos obtidos nas diferentes bacias com os biomas globais estabelecidos para o intervalo estudado.
- Verificar a validade do método estatístico em dendrologia como indicador paleoclimático.
- Identificar padrões de interação planta- artrópode, definindo resultados de caráter paleoclimático e, se possível bioestratigráfico.
- Relacionar os resultados dendroclimáticos com zoneamento paleoclimático compatível, tentando também refinar dados estratigráficos vigentes para o intervalo estudado (Jurássico Superior - Cretáceo Inferior).

## 1.4. Contexto estratigráfico

### 1.4.1. Bacia do Araripe

A sucessão sedimentar das bacias interiores do Nordeste do Brasil (Araripe, Rio do Peixe, Recôncavo/Tucano/Jatobá, Iguatu) tem sido subdivida em três seqüências: pré-rift, rift ou syn-rift, e pós-rift. Estas seqüências contêm o registro dos estágios de separação da América do Sul e África, durante a fragmentação do Gondwana. O registro sedimentar ocorrente nas seqüências pré-rift das bacias interiores do Nordeste, é remanescente de uma grande e rasa bacia sedimentar denominada Depressão Afro-Brasileira - ABD (Fig. 2), definida originalmente por Ponte (1972).

A Bacia do Araripe (Fig. 2) é a mais extensa dessas bacias, com aproximadamente 243 km de comprimento por 83 km de largura, com uma área de 12.200 $km^2$ . Diferentes concepções sobre a evolução geológica e a caracterização estratigráfica dessa unidade são reavaliadas por Arai et al. (2004) a partir do paradigma da estratigrafia de seqüências, sendo propostas 4 seqüências sedimentares: 1. Sedimentação Regional, depositada em intervalo de tempo ainda não definido (Ordoviciano Superior–Siluriano Inferior ou Eocretáceo); 2. Sedimentação pré-rift (Andar Dom João), Neojurássico a Eocretáceo; 3. Sedimentação rift, Neocomiano; 4. Sedimentação Regional do Grupo Araripe, de idade Aptiano-Albiano (Fig. 3).

O intervalo estratigráfico abordado no presente estudo inclui-se na segunda seqüência sedimentar (Fig. 3) e representa a fase pré-rift, correspondendo às formações Brejo Santo e Missão Velha, coevas e equivalentes respectivamente às formações Aliança e Sergi (Bacias do Recôncavo-Tucano-Jatobá, Camamu e Almada) e às formações Bananeiras e Serraria (Bacia de Sergipe-Alagoas - Arai et al., 2004). A Formação Brejo Santo, composta por arenitos muito finos, siltitos e argilitos com intercalações de margas, tem sido datada no Andar Dom João, através da associação de ostracodes (Arai et al., 2004). O conteúdo fossilífero da Formação Brejo Santo inclui peixes, ossos de quelônios, dinossauros, crocodíleos e lacertílios, além de icnofósseis, conchostráceos e coprólitos (Gallo-da-Silva e Azevedo, 1996; Viana et al., 2002). A Formação Missão Velha, de idade Jurássico (Thitoniano) – Cretáceo (Barresiano) é constituída por arenitos friáveis, de granulação média a fina, com intercalações de argila e níveis conglomeráticos. Nesta formação, bem como nas unidades correlatas (Formações Sergi e Serraria), ocorre a presença de muitos lenhos silicificados (Arai et al., 2004).

O termo Formação Missão Velha foi introduzido por Beurlen (1962), atribuindo-o ao "Arenito Inferior" de Small (1913), definido como todo pacote sedimentar compreendido entre as atuais Formações Brejo Santo e Rio da Batateira. Segundo Arai (2006) esta denominação foi inadequadamente referida a distintas unidades estratigráficas.. Dessa forma, no presente trabalho, é aceita a proposição de Arai (2004) e Arai et al. (2006) representada na figura 4, segundo a qual termo Formação Missão Velha representa exclusivamente a unidade homóloga à Formação Sergi (andar Dom João), conforme as preposições de Ponte e Appi (1990) e Assine (1992) .

O afloramento Grota Funda (coordenadas UTM: 7º02'-7º49' S/38º30'-40º55'W), localidade da qual provém os lenhos fósseis aqui estudados, localiza-se aproximadamente 6 quilômetros a leste da cidade de Missão Velha - CE (Fig. 2), e corresponde à uma exposição erosiva, com cerca de 4 m de altura e 30 de comprimento, localizado na BR 293 relacionado litoestratigraficamente à Formação Missão Velha. O afloramento é caracterizado pela exposição de fácies fluvial e eólica, compostas por uma sucessão de arenitos médios com estratificação cruzada e intercalações conglomeráticas (Fig. 4 a). Os lenhos silicificados ocorrem abundantemente no afloramento, rolados ou inclusos no arenito, sem orientação preferencial. Lenhos de grande porte (Fig. 4 b) com 1 metro de diâmetro e ate 2 metros de altura foram anteriormente resgatados desse sítio, encontrando-se atualmente no setor de Paleontologia da UFRJ.

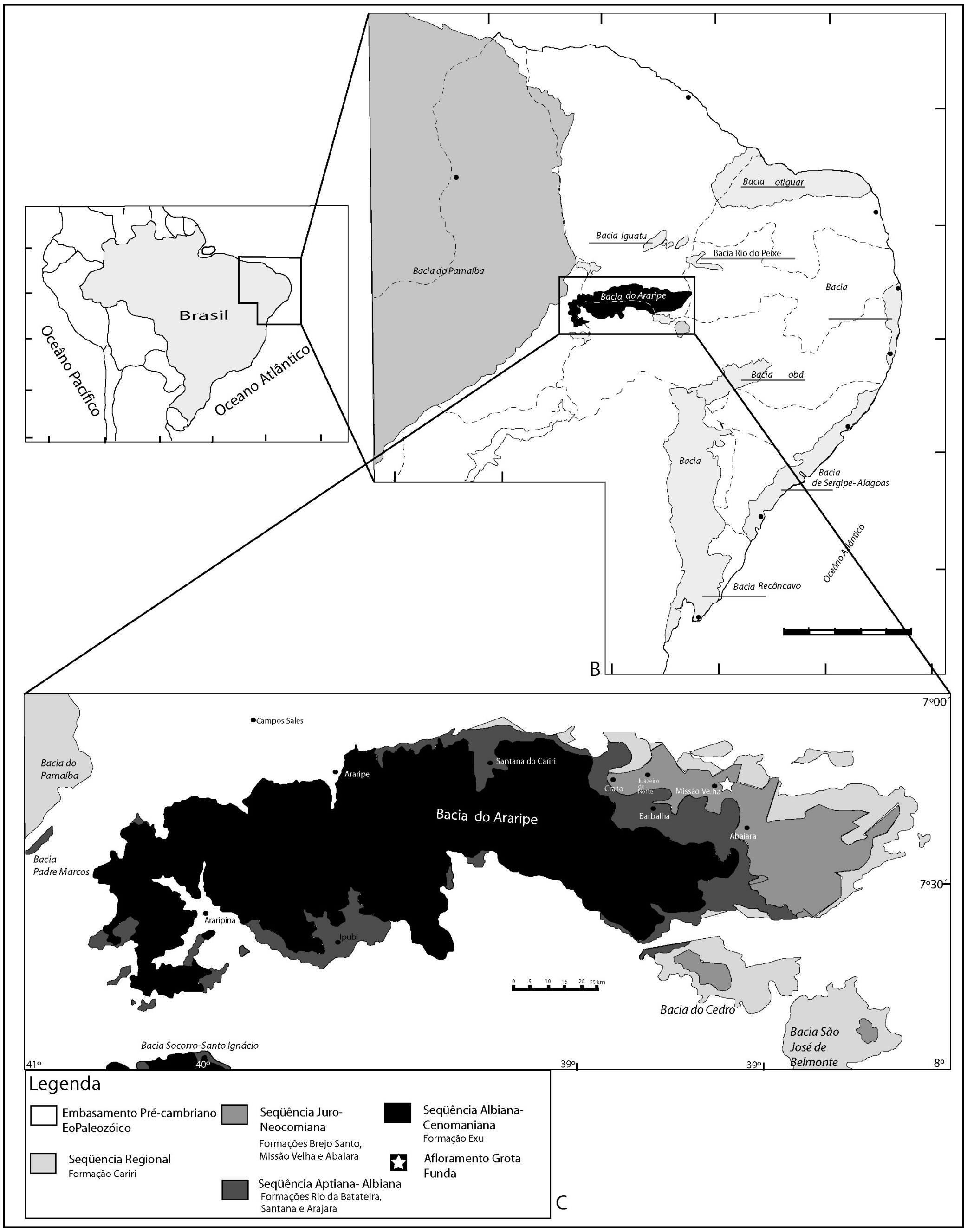


Figura 2: Localização da Bacia do Araripe**, a:** mapa do Brasil; **b:** mapa da Região Nordeste do Brasil, demonstrando a localização da Bacia do Araripe (em preto) e das bacias interiores do Nordeste do Brasil; **c:** mapa geológico da Bacia do Araripe (modificado de Assine, 1992).

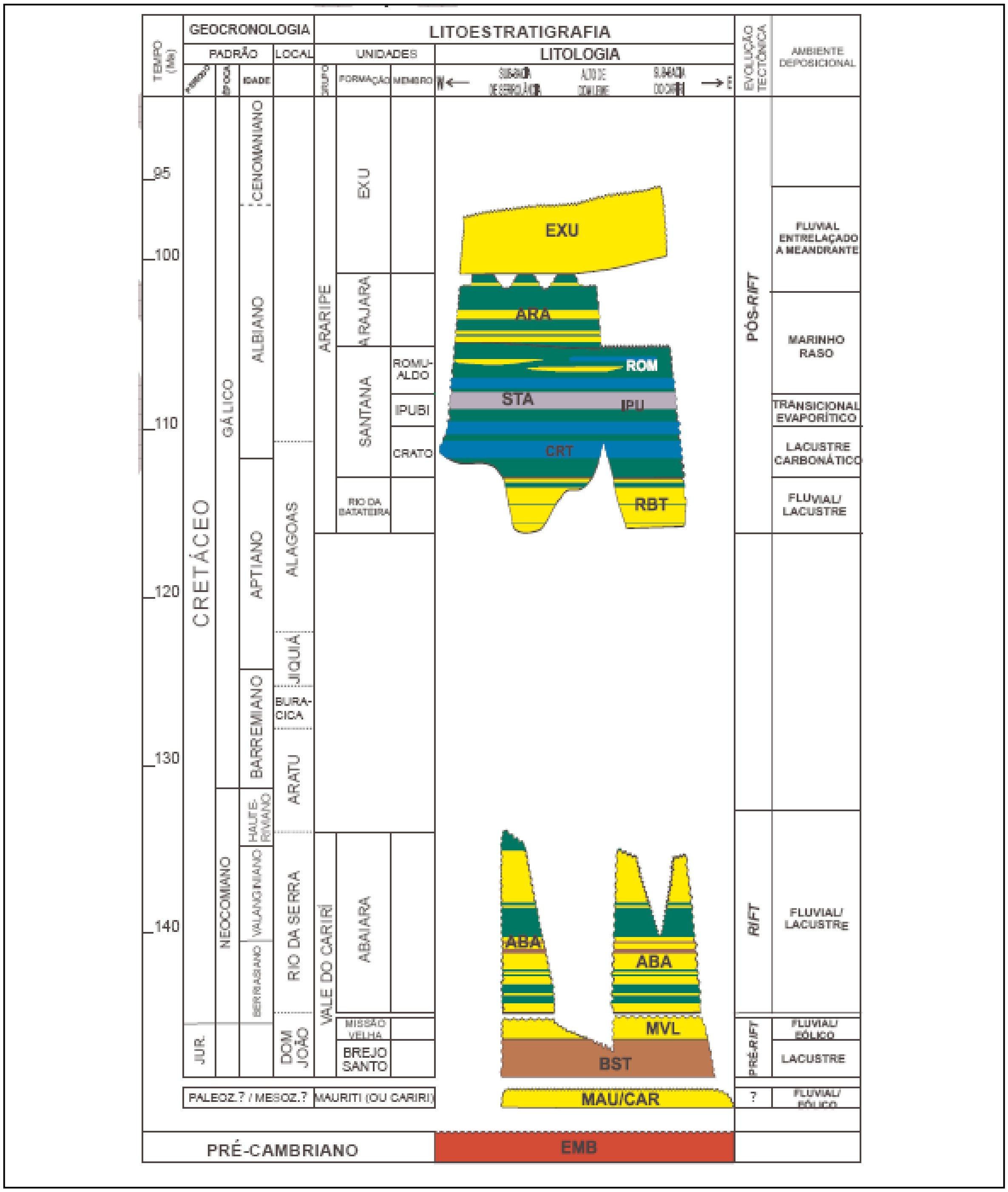


Figura 3: Carta estratigráfica simplificada da Bacia do Araripe (modificada de Arai et al., 2004).

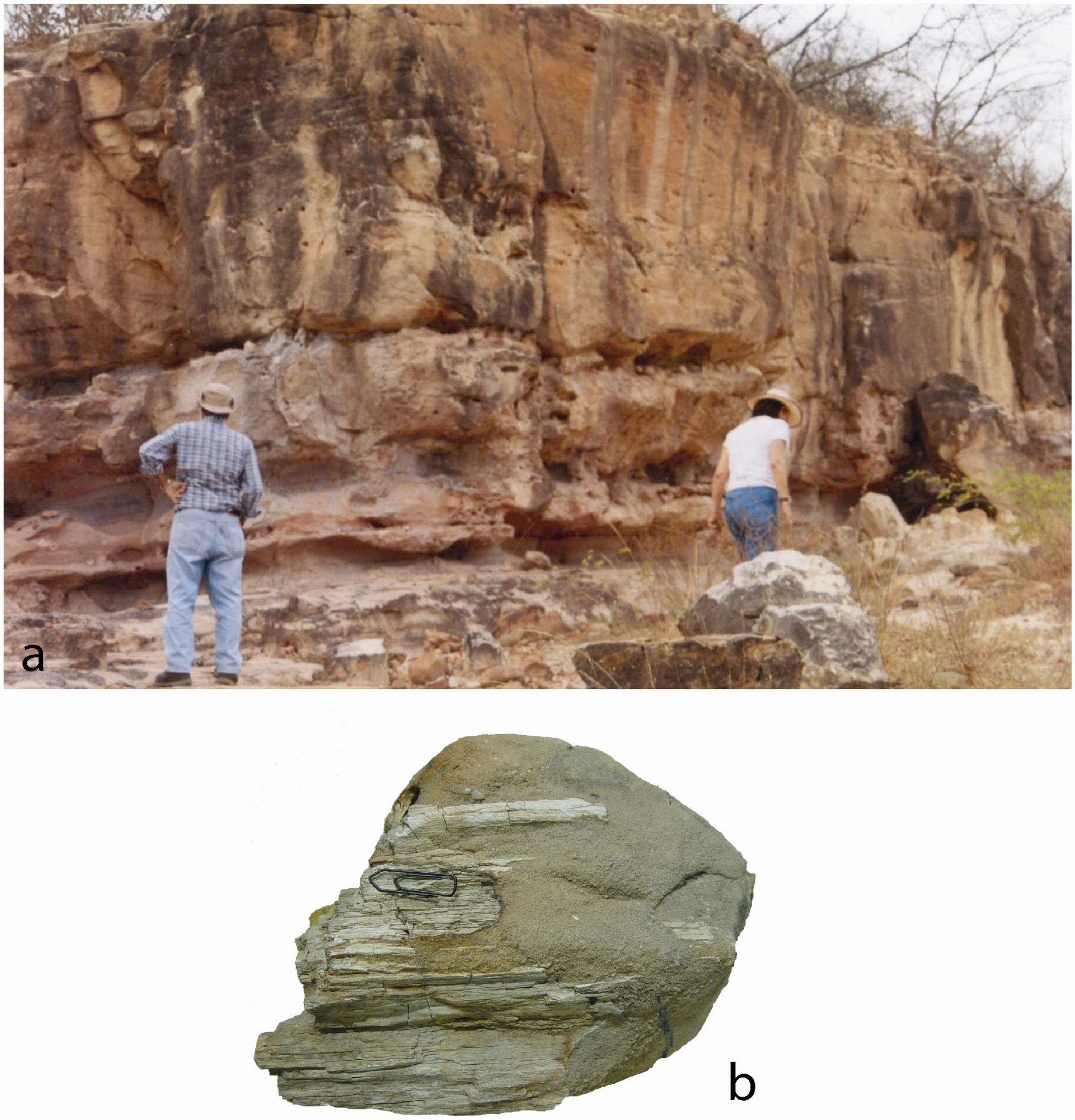


Figura 4: **a.** vista geral do afloramento Grota Funda (Formação Missão Velha, Bacia do Araripe); **b.** fragmento lenhoso com sedimento agregado.

### 1.4.2. Bacia do Paraná

A Bacia intracratônica do Paraná, situada na porção centro - oriental da América do Sul, evoluiu durante o Paleozóico e Mesozóico, e inclui rochas com idades entre o Neo-Ordoviciano e o Neo-Cretáceo, em uma área total de 1.500.000 km$^2$ (Fig. 5). O arcabouço estratigráfico da Bacia (Fig. 6), construído a partir de seus atributos sedimentológicos, estratigráficos, paleontológicos além de datações radiométricas de rochas ígneas associadas, está constituído por seis unidades estratigráficas de segunda ordem ou superseqüências (Vail et al., 1977). O registro de tempo total envolve um intervalo entre 450 e 65 Ma, porém grandes intervalos estão condensados em hiatos que separam as diversas superseqüências. As superseqüências Rio Avaí (Caradociano-Landoveriano), Paraná (Lockoviano-Frasniano) e Gondwana I (Westfaliano-Scythiano) representam grandes ciclos transgressivos-regressivos paleozóicos, enquanto que as superseqüências Gondwana II (Anisiano-Noriano), Gondwana III (Neojurássico-Berriasiano) e Bauru (Aptiano- Masstrichiano) são representadas por pacotes sedimentares continentais e rochas ígneas associadas (Milani e Ramos, 1998; Milani, 2004).

O presente estudo envolve análises de lenhos permineralizados procedentes Formação Botucatu, a qual, em conjunto com as lavas da Formação Serra Geral (Milani, 1997) compõem a Superseqüência Gondwana III.

Esta unidade litoestratigráfica consiste de arenitos eólicos, distribuídos em uma área de mais de 1.700.000 km$^2$. Sua extensão original é incerta, mas a presença de estratos correlacionáveis na África (Stanistreet e Stolhofen, 1999) sugere que a área de deposição da Formação excede seus limites erosivos atuais.

De acordo com Milani et al. (1998) essa formação é definida na base por uma inconformidade regional evidenciada através de toda a bacia. A sedimentação é composta por depósitos eólicos representados por grandes sets de estratos cruzados interpretados como depósitos eólicos de dunas (Bigarella e Salamuni, 1961). A porção inferior contém, ocasionalmente, arenitos grossos a conglomeráticos depositados por rios efêmeros, interpretados por Bigarella e Salamuni (1961) e Scherer (2002) como depósitos de lençóis de areia. A maior espessura do Botucatu (400 metros) ocorre no oeste da bacia; a menor espessura de sedimentos ocorrente na porção meridional sugerindo que o Escudo Sul Riograndense já correspondia a um alto topográfico durante o intervalo da acumulação eólica (Scherer, 2000, 2002). Este pacote eólico estende-se para o sul ocorrendo no Uruguai (Formação Rivera) e na Argentina (Formação São Cristobal). Os arenitos da Formação

Botucatu também são mapeáveis no Paraguai (Formação Missiones). Os limites aflorantes norte e nordeste do Botucatu ocorrem nos Estados de Goiás, Minas Gerais e Mato Grosso. Não existem evidências de continuidade física entre o Botucatu e as bacias rifte do nordeste brasileiro, o que sugere a presença de altos topográficos separando esses arenitos eólicos das bacias rifte (Scherer e Goldberg, 2007; Scherer e Lavina, 2006).

A datação radiométrica Ar/Ar em rochas vulcânicas da Formação Serra Geral, suprajacentes ao Botucatu indicaram uma idade entre 136.6 ± 1.5 Ma e 136.8 ± 0.6 Ma (Onstott, 1993); as datações de Turner et al. (1994) forneceram uma idade 137 ± 0.7 Ma para essas rochas. Considerando o contato concordante entre o Botucatu e a Formação Serra Geral é inferida uma idade Cretáceo Inferior para o final da acumulação eólica do Arenito Botucatu.

Registros de pistas de tetrápodes na Formação Botucatu são comuns nos arenitos eólicos da formação, especialmente no Estado de São Paulo (Von Huene,1931; Leonardi, 1977,1980,1981,1984; Leonardi e Sarjent, 1986; Leonardi e Oliveira, 1990; Leonardi e Carvalho, 2002). Uma idade Jurássico Superior - Cretáceo Inferior tem sido atribuída a essas pegadas (Bonaparte, 1996), sendo essa idade aceita por Milani et al. (1998) em sua proposta estratigráfica para o Mesozóico da Bacia do Paraná. Com base nos dados sedimentológicos e estratigráficos disponíveis, Scherer et al. (2000) propõem uma idade Jurássico Superior para o início da sedimentação da Formação Botucatu na bacia.

Grandes pegadas de dinossauros ornitopode são descritas por Fernandes e Carvalho (2007) para a região de Araraquara, São Paulo. Esse registro confirma a presença de formas gigantes de dinossauros, além das formas anãs, caracterizadas anteriormente como endêmicas por Leonardi e Godoy (1990) e Leonardi (1991). O processo de preservação de tais pegadas indica um caráter paleoambiental peculiar, pois elas seriam produzidas provavelmente em sub-superfície, com características mais úmidas do que os estratos superficiais.

Ao norte do município de Uberlândia, estado de Minas Gerais, no afloramento aqui designado como Fazenda Sobradinho (18º46'56,5''S/ 48º16'0,2E - altitude de 657 m) próximo ao leito da ferrovia entre os municípios de Uberlândia e Araguari, margem esquerda do córrego Sobradinho (Fig. 5), foram registrados lenhos permineralizados, incluídos em arenitos da Formação Botucatu por Suguio e Coimbra (1972), Silva e Santos (1998) e Brito (2001). A associação de lenhos, dispersos num neosolo arenítico ou incluídos nos sedimentos é composta majoritariamente por exemplares de grande porte.

Os fragmentos lenhosos encontram-se comprimidos e segmentados denotando a pressão a que foram submetidos na diagênese. Hasui (1969), que mapeou os litotipos do Botucatu na porção Oeste de Minas Gerais, encontrou-os transgredindo diretamente sobre litologias pré-cambrianas nos municípios de Estrela do Sul e Monte Carmelo, Uberlândia e Tupaciguara, em Minas Gerais. A sua maior expressão em área está no vale do rio Grande, entre os municípios de Sacramento e Desemboque, onde alcançam espessuras de 100m, como na gruta dos Palhares, Barbosa et al. (1970).

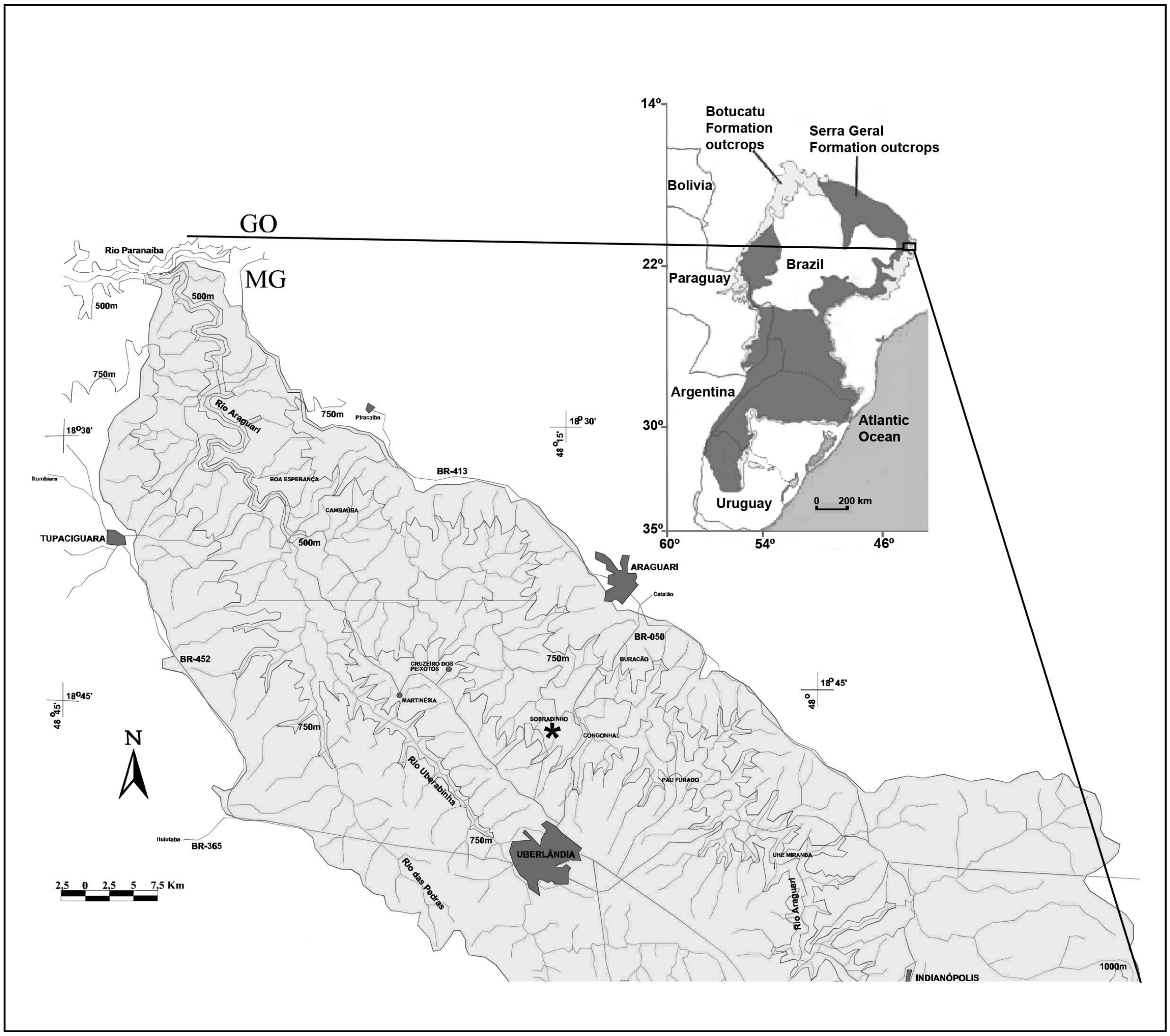


Figura 5: Mapa de localização da Bacia do Paraná, com as áreas onde aflora a Formação Botucatu e localização da área estudada (*) -Afloramento Fazenda Sobradinho – Uberlândia, MG.

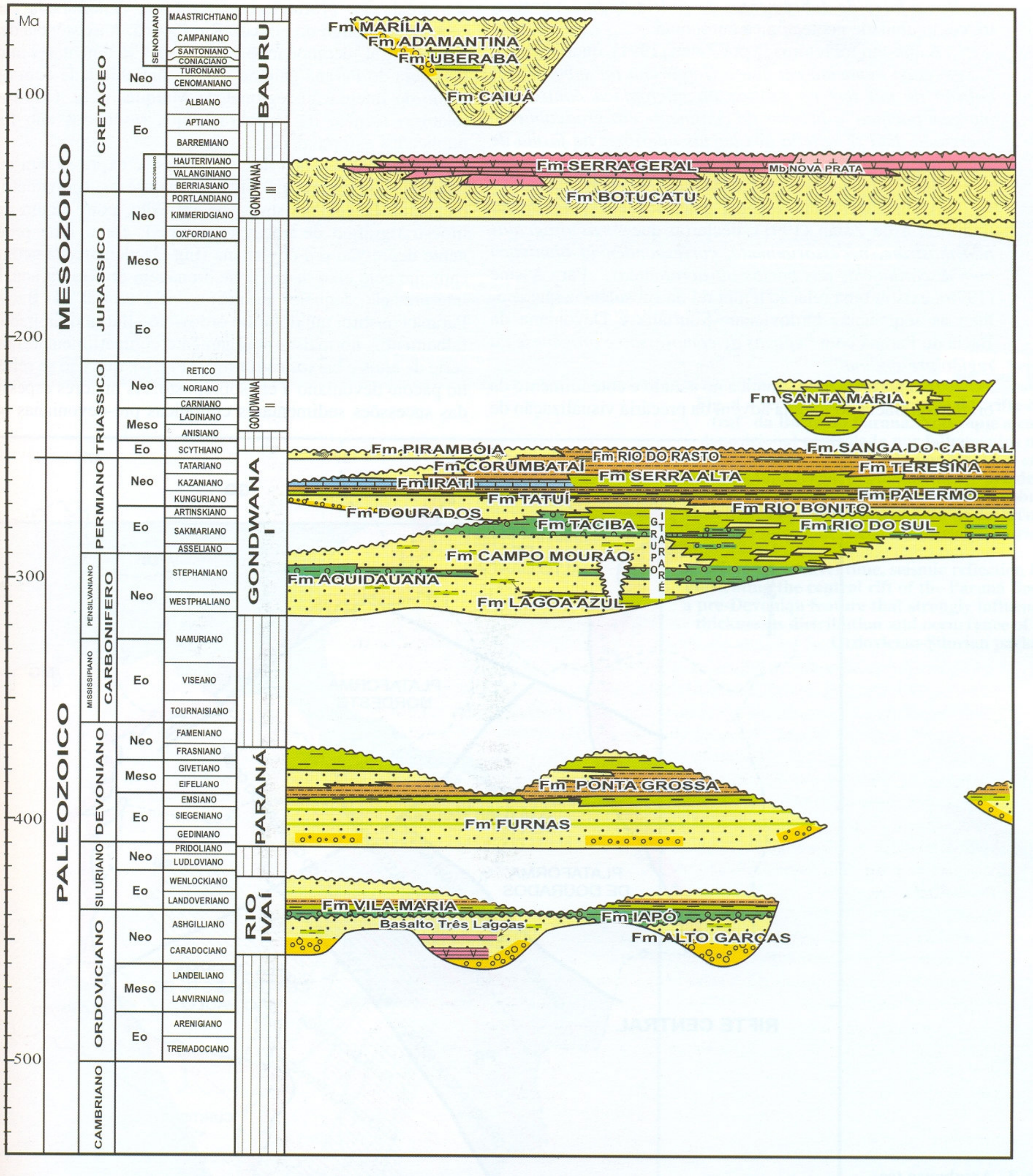


Figura 6: Carta estratigráfica da Bacia do Paraná (modificado de Milani, 2004).

## 1.5. Material e Métodos

### 1.5.1. Material

#### a. *Bacia do Araripe*

O material estudado corresponde a fragmentos de lenhos fósseis provenientes do Afloramento Grota Funda (Fig. 3), procedentes todos do mesmo nível estratigráfico, correspondendo à Formação Missão Velha, Jurássico Superior/Cretáceo Inferior (Berriasiano) (de acordo com Arai *et al*., 2004).

Foram analisados 47 fragmentos lenhosos, dos quais 35 foram coletados pela autora da presente tese (Tabela 1). Dez fragmentos de lenho foram cedidos pelo Instituto de Geociências da Universidade Federal do Rio de Janeiro, registrados na Coleção de Paleobotânica da referida universidade.

Além destes lenhos, foram observados lenhos de maior diâmetro, com mais de 1 m de comprimento, depositados na Coleção de Paleobotânica da Universidade Federal do Rio de Janeiro. Através da análise de seções polidas destes lenhos, verificou-se equivalência entre os padrões anatômicos desses fósseis e os de menor diâmetro, analisado no presente estudo.

A amostragem analisada restringiu-se a 15 exemplares, selecionados a partir da definição do grau de preservação anatômica, uma vez que a impregnação por quartzo impediu a observação dos padrões celulares em muitos espécimes.

O material possui coloração marrom claro, com superfície externa regular e lisa (Fig. 7). Em alguns espécimes há a presença de medula (Fig. 7 c, Fig. 8 a) pequena e centralizada. A disposição dos anéis de crescimento em seção transversal é característica de eixos caulinares, de acordo com critérios de Schweingruber (1996).

Em sua maioria, os fósseis foram encontrados rolados no afloramento. Os fósseis inclusos no sedimento não apresentam orientação definida. Alguns exemplares coletados apresentam sedimento agregado (Fig. 4 b). O processo de fossilização ocorrente é o de permineralização celular (Schopf, 1975), sendo a sílica o componente permineralizante. Os anéis de crescimento, observáveis em faces transversais dos lenhos, são visíveis à vista desarmada (Fig. 7 d, Fig. 8 a,b,c,d). Evidências de ataque de artrópodes são constatadas pela presença de cavidades na superfície externa dos lenhos, além de sistemas de galerias em suas porções internas (Fig. 7 a,b,c,e).

A associação de lenhos silicificados procedentes do Afloramento Grota Funda, considerada alóctone por Da Rosa e Garcia (2000), tem, todavia, características de hipoautoctonia, pois alguns espécimes preservam o córtex, não se evidenciando sinais de transporte extensivo, tais como o arredondamento superficial das amostras.. Por outro lado, a presença de exemplares de lenho com diâmetro expressivo (mais de 1m), não comprimidos, e altura considerável (2 m), leva a ratificar as evidências de hipoautoctonia para a associação. O aspecto fragmentário da maioria dos espécimes deve-se provavelmente, à desagregação local dos troncos e ramos de maior porte, provocada por erosão e exposição prolongada.

Tabela 1: Listagem do material estudado proveniente de afloramento da Formação Missão Velha (Bacia do Araripe) registrados na Coleção de Paleobotânica da UFRGS e na Coleção de Paleobotânica da UFRJ. As amostras grifadas foram utilizadas nas análises dendrológicas; as utilizadas na caracterização de padrões de ataque de artrópodes estão demarcadas por asteriscos (*).

| | **Amostra Tombo** | **Depósito** | **Diâmetro maior (cm)** | **Diâmetro menor (cm)** | **Seção plana -** sp **Lâminas delgadas –** radial (R), transversal (X) e tangencial (T) | **Observações** |
|---|---|---|---|---|---|---|
| 1 | PB 3824 (*) | UFRGS | 10 | 7 | sp | Má preservação dos anéis de crescimento - |
| 2 | **PB 3826** (*) | UFRGS | 7 | 7 | sp ,R, X,T | - |
| 3 | PB 3827 (*) | UFRGS | 8 | 3,4 | sp | Má preservação dos anéis de crescimento |
| 4 | **PB 3828** | UFRGS | 8 | 9,8 | sp , R, X,T | - |
| 5 | PB 3829 | UFRGS | 5 | 4 | - | - |
| 6 | PB 3830 (*) | UFRGS | 3,7 | 3,5 | - | - |
| 7 | PB 3831 | UFRGS | 6 | 3,7 | sp | Preservação deficiente |

| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | PB 3832 | UFRGS | 14,5 | 8 | sp | Má preservação dos anéis de crescimento |
| 9 | PB 3833 | UFRGS | 4 | 3 | sp | Má preservação dos anéis de crescimento |
| 10 | PB 3834 | UFRGS | 13,5 | 5,8 | sp | Má preservação dos anéis de crescimento |
| 11 | PB 3835 | UFRGS | 4,5 | 4 | - | - |
| 12 | **PB 3836** | UFRGS | 6,7 | 6,3 | sp , R, X,T | - |
| 13 | PB 3837 | UFRGS | 4,5 | 3,5 | - | - |
| 14 | PB 3838 | UFRGS | 8 | 5,5 | - | - |
| 15 | PB 3839 | UFRGS | 3,3 | 2,5 | - | - |
| 16 | **PB 3840** | UFRGS | 4 | 3,7 | sp , R, X,T | - |
| 17 | PB 3841 | UFRGS | 4,2 | 2,3 | - | - |
| 18 | PB 3842 | UFRGS | 3,1 | 2 | - | - |
| 19 | PB 3843 | UFRGS | 3,2 | 1,5 | sp | Má preservação dos anéis de crescimento |
| 20 | PB 3844 | UFRGS | 3,5 | 2 | sp | Má preservação dos anéis de crescimento |
| 21 | PB 3845 | UFRGS | 4,5 | 4 | - | - |
| 22 | PB 3846 (*) | UFRGS | 4,5 | 3 | sp | Má preservação dos anéis de crescimento |
| 23 | PB 3847 | UFRGS | 4 | 1,5 | - | - |
| 24 | PB 3848 | UFRGS | 2,2 | 2,2 | - | - |
| 25 | PB 3849 | UFRGS | 4 | 2,6 | - | - |
| 26 | PB 3850 | UFRGS | 3,7 | 1,3 | sp | Má preservação dos anéis de crescimento |
| 27 | PB 3851 | UFRGS | 5,4 | 3,8 | - | - |
| 28 | PB 3852 | UFRGS | 4,5 | 3,1 | - | - |
| 29 | PB 3853 | UFRGS | 18 | 9 | - | - |
| 30 | **PB 3854 (*)** | UFRGS | 6,7 | 5,7 | sp , R, X,T | - |
| 31 | PB 3855 | UFRGS | 4,5 | 3,7 | - | - |
| 32 | PB 3856 | UFRGS | 15 | 11,5 | - | - |
| 33 | PB 3857 | UFRGS | 19 | 15 | - | - |
| 34 | PB 3858 | UFRGS | 8 | 8 | - | - |
| 35 | PB 3859 | UFRGS | 20 | 14,5 | - | - |
| 36 | **PB 3860** | UFRGS | 19 | 19 | sp , R, X,T | - |
| 37 | **PB 93** | UFRJ | 9,5 | 7,9 | sp , R, X,T | - |
| 38 | **PB 366** | UFRJ | 10 | 5,6 | sp , R, X,T | - |
| 39 | **PB 367 (*)** | UFRJ | 6,7 | 6,7 | sp , R, X,T | - |
| 40 | **PB 371** | UFRJ | 17,2 | 12,8 | sp , R, X,T | - |
| 41 | **PB 675** | UFRJ | 14,5 | 11,5 | sp , R, X,T | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **(*)** | | | | | |
| 42 | PB 677<br>**(*)** | UFRJ | 10 | 9,5 | sp , X | |
| 43 | **PB 758** | UFRJ | 14,4 | 13,8 | sp , R, X,T | - |
| 44 | PB 785<br>**(*)** | UFRJ | 8,5 | 5,5 | sp | - |
| 45 | **PB 791** | UFRJ | 11 | 9,9 | sp , R, X,T | - |
| 46 | **PB 849**<br>**(*)** | UFRJ | 14,9 | 10 | sp , R, X,T | - |
| 47 | **PB 900** | UFRJ | 22,7 | 12,7 | sp , R, X,T | - |

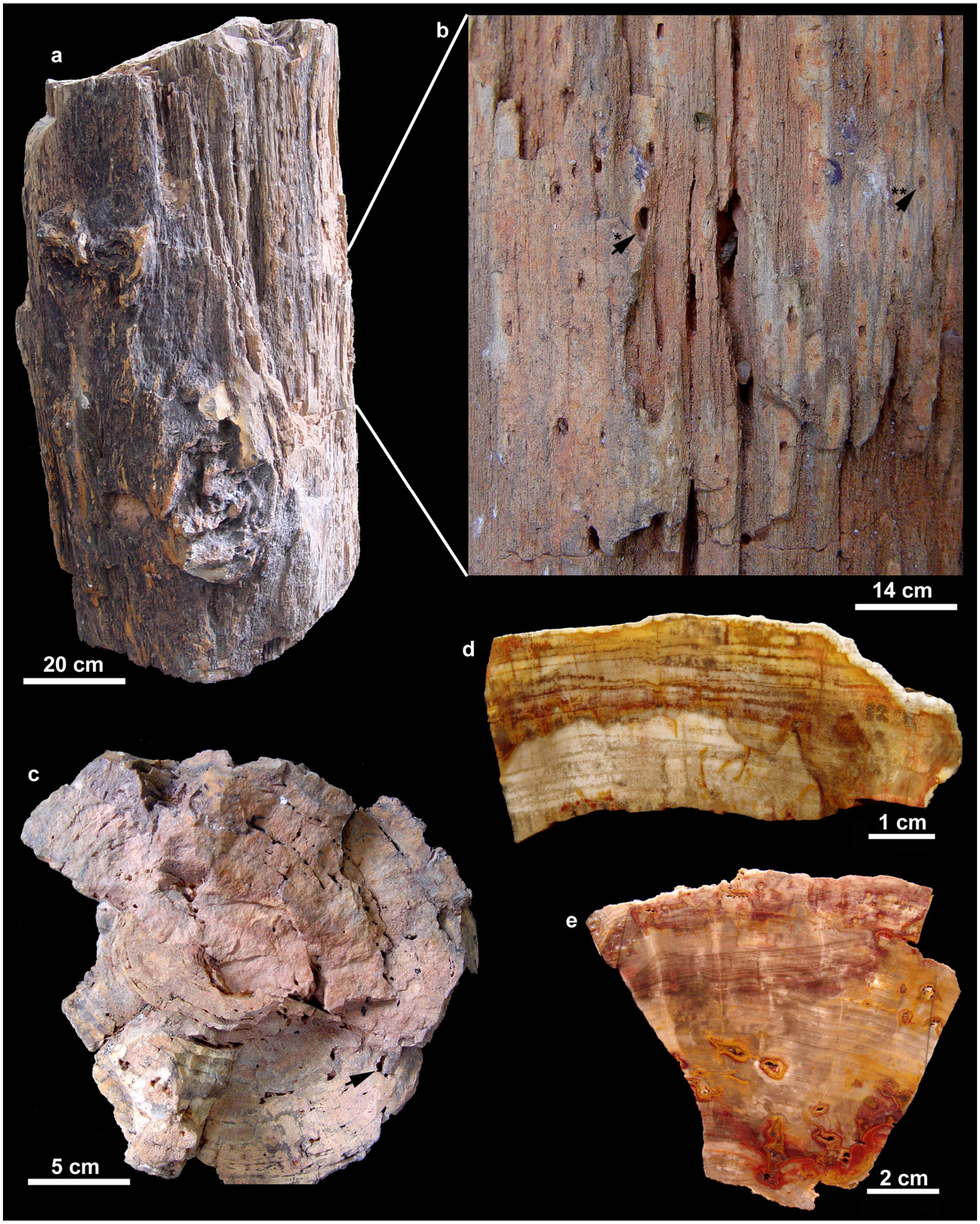


Figura 7: Material proveniente do Afloramento Grota Funda, Bacia do Araripe, a. lenho fóssil de grande porte; b. detalhe da superfície externa demonstrando pequenas aberturas elípticas (*) que correspondem a danos causados por invertebrados, e cavidades maiores

(**), que correspondem a regiões de paredes celulares colapsadas no interior dos túneis construídos por invertebrados; c: seção transversal de um lenho fóssil demonstrando o limite dos anéis de crescimento e o diâmetro circular a irregular dos túneis axiais, seguindo a curvatura dos anéis de crescimento; d, e: seções polidas de diferentes amostras de lenhos fósseis evidenciando o padrão dos anéis de crescimento.

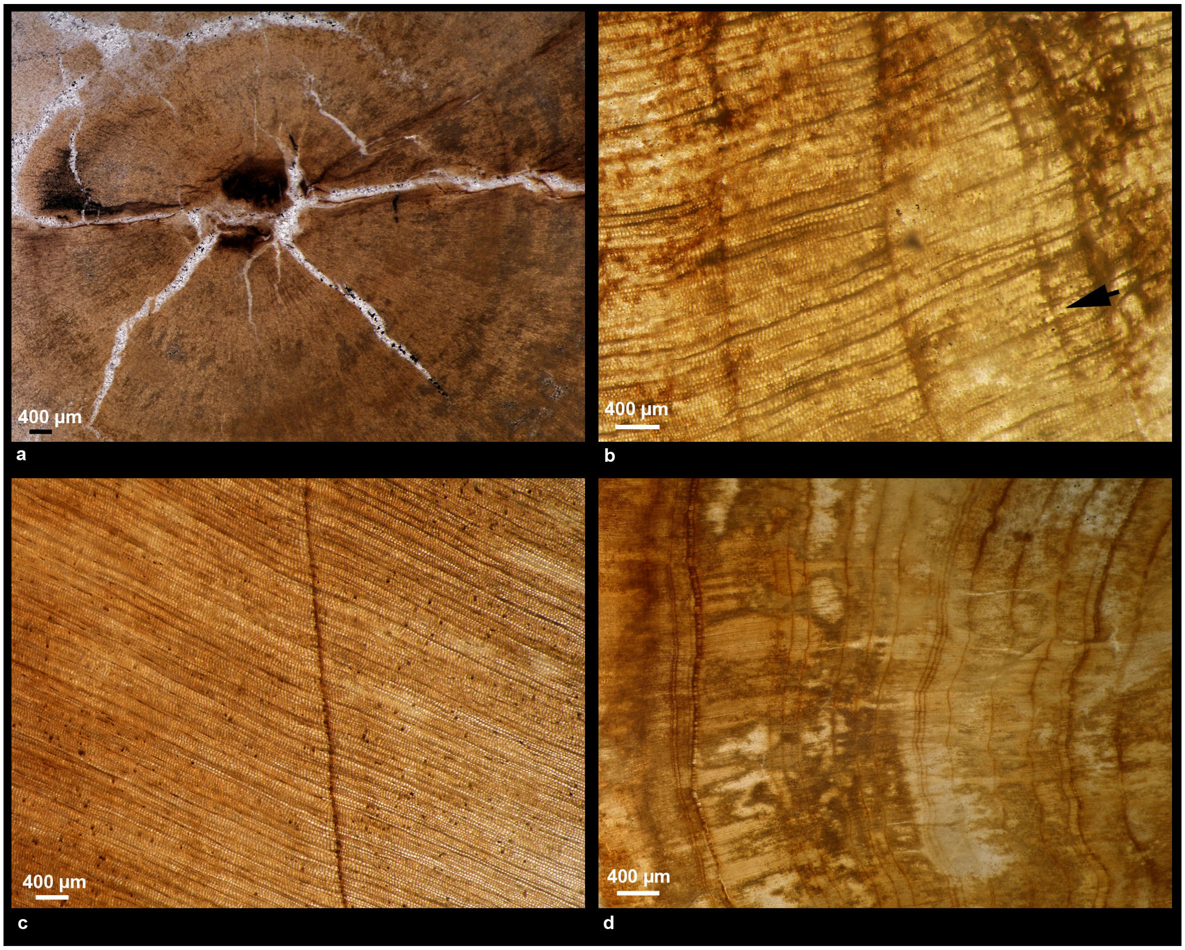


Figura 8: Lâminas delgadas (seções transversais)de diferentes amostras de lenhos fósseis evidenciando o padrão dos anéis de crescimento, material proveniente do Afloramento Grota Funda, Bacia do Araripe, **a**. lenho fóssil com medula preservada; **b**. anéis de crescimento, seta demonstra falso anel de crescimento; **c**: limite de anel de crescimento; **d.** grande variação da espessura dos anéis de crescimento.

Nos estudos de interação planta - artrópode utilizou-se a amostragem selecionada para as análises dendrológicas. A definição dos padrões de galerias e dos padrões morfológicos dos coprólitos foi estabelecida através da análise de lâminas delgadas dos espécimes PB 367-c, PB 675-a, PB 675c, PB 677-b, PB 785-a, PB 785-b, PB 785-c, PB 849-b, PB 849-c, PB 3826-b, PB 3826-c, PB 3827-a, PB 3824-b, PB 3824-c, PB 3828-a, PB 3830-a , PB 3846-a, PB 3854-a. Blocos para análise em microscopia eletrônica foram elaborados a partir das amostras Pb 785 e PB 3827.

### b. Bacia do Paraná

O material procede de um afloramento da Formação Botucatu, aqui denominado Fazenda Sobradinho, em um horizonte intercalado com basalto e solos alterados vinculados à Formação Serra Geral, localizado nas proximidades da sede do município de Uberlândia, Minas Gerais (Fig. 5). O material encontra-se em sua grande maioria incluso no sedimento, ou encoberto por uma camada de solo (Fig. 9 a, b, Fig. 10, a, c, e).

As amostras compreendem porções de lenho estabilizado de grandes espécimes (diâmetro: 20- 80 cm x comprimento: 1m a 5 m), muito silicificados, de cor amarelo - avermelhados, prostrados, apresentando evidente compressão lateral (Figs. 9, 10). Os anéis de crescimento são observados a vista desarmada, mas a região central do lenho, correspondente à medula, raramente está preservada; o floema e córtex, embora presentes em muitas amostras, não apresentam estruturação celular observável. A morfologia externa de alguns espécimes, os padrões anatômicos e a orientação no sedimento permitem inferências quanto à sua afinidade com raízes *in situ* (Fig. 10 c, e). Esta evidência levaria a inferir o nível original do desenvolvimento da associação de coníferas, todavia estudos tafonômicos futuros se fazem necessários para comprovar esse inédito e importante dado, considerando-se as condições de deposição da Formação Botucatu na Bacia do Paraná.

A presença de bases abauladas de troncos, com também de fragmentos, que por sua morfologia externa e disposição no sedimento, parecem corresponder a raízes (Fig. 10 c, e), indicam uma deposição autóctone/hipoautoctone para a associação. Mussa (1974) descreve a espécie *Paleopynoxylon josuei,* procedente do afloramento Fazenda Sobradinho, atribuindo-lhe, porém, uma idade Neojurássica, e incluindo a ocorrência, equivocadamente, na Formação Pirambóia.

A amostragem desse afloramento consiste de 17 espécimes; todavia, dada a grande alteração no padrão dendrológico e de estruturação anatômica, apenas 10 lenhos maduros foram selecionados para análise estatística.

### 1.5.2. Técnicas de preparação laboratorial

Os cortes dos planos anatômicos e a elaboração de laminas delgadas foram efetuados no Laboratório de Lâminas Delgadas do Departamento de Sedimentologia e Petrologia, Instituto de Geociências da Universidade Federal do Rio Grande do Sul, e no Laboratório de Lâminas Delgadas do Departamento de Geologia, da Universidade Federal do Rio de Janeiro

#### *a. Seções planas*

Visando observar e registrar os padrões de desenvolvimento dos anéis de crescimento, foram executadas seções planas dos eixos transversais através do seguinte protocolo:

a) cortar as amostras em seção transversal
b) lixar as amostras em máquina politriz com abrasivo Carbeto de silício (Csi) em pó diluído em água, seguindo a bateria de granulometria a seguir: 120; 220; 320; 500; 800; 1200; 2000.
c) lavar as amostras com água corrente

Tabela 2: Listagem do material estudado, proveniente de afloramento da Formação Botucatu (Bacia do Paraná) registrados na Coleção de Paleobotânica da UFRGS e na Coleção de Paleobotânica do DNPM do Rio de Janeiro. As amostras grifadas foram utilizadas nas análises dendrológicas.

| | **Amostra Tombo** | **Depósito** | **Diâmetro maior (cm)** | **Diâmetro menor (cm)** | **Seção plana -** sp **Lâminas delgadas –** radial (R), transversal (X) e tangencial (T) | **Observações** |
|---|---|---|---|---|---|---|
| 1 | PB 4309 | UFRGS | 8,5 | 6,7 | sp, R,X,T | |
| 2 | PB 4310 | UFRGS | 19,7 | 10 | sp | |
| 3 | **PB 4311** | UFRGS | 8,1 | 5,4 | sp | |
| 4 | **PB 4312** | UFRGS | 4,5 | 5,7 | sp | |
| 5 | **PB 4313** | UFRGS | 14,2 | 4,5 | sp | |
| 6 | **PB 4314** | UFRGS | 6,7 | 6,7 | sp, R,X,T | Má preservação dos anéis de crescimento |
| 7 | PB 4315 | UFRGS | 6,8 | 5,7 | sp, R,X,T | Má preservação dos anéis de crescimento |
| 8 | PB 4316 | UFRGS | 7 | 5 | sp, R,X,T | Má preservação dos anéis de crescimento |
| 9 | **PB 4317** | UFRGS | 12,6 | 10,6 | sp | |
| 10 | **1302-09** | DNPM - RJ | 15,6 | 10 | sp | |
| 11 | **1306-02** | DNPM - RJ | 12 | 9.5 | sp | |
| 12 | 1306-11 | DNPM - RJ | 13,7 | 11,5 | sp | Má preservação dos anéis de crescimento |
| 13 | **1306-12** | DNPM - RJ | 20,5 | 10 | sp | |
| 14 | 1306-19 | DNPM - RJ | 8,5 | 7,5 | sp, R,X,T | Má preservação dos anéis de crescimento |
| 15 | **1306-20** | DNPM - RJ | 17,3 | 15,2 | sp, R,X,T | |
| 16 | **1306-25** | DNPM - RJ | 16,4 | 10,3 | sp, R,X,T | |
| 17 | 1306-29 | DNPM - RJ | 25 | 22,5 | sp | Má preservação dos anéis de crescimento |

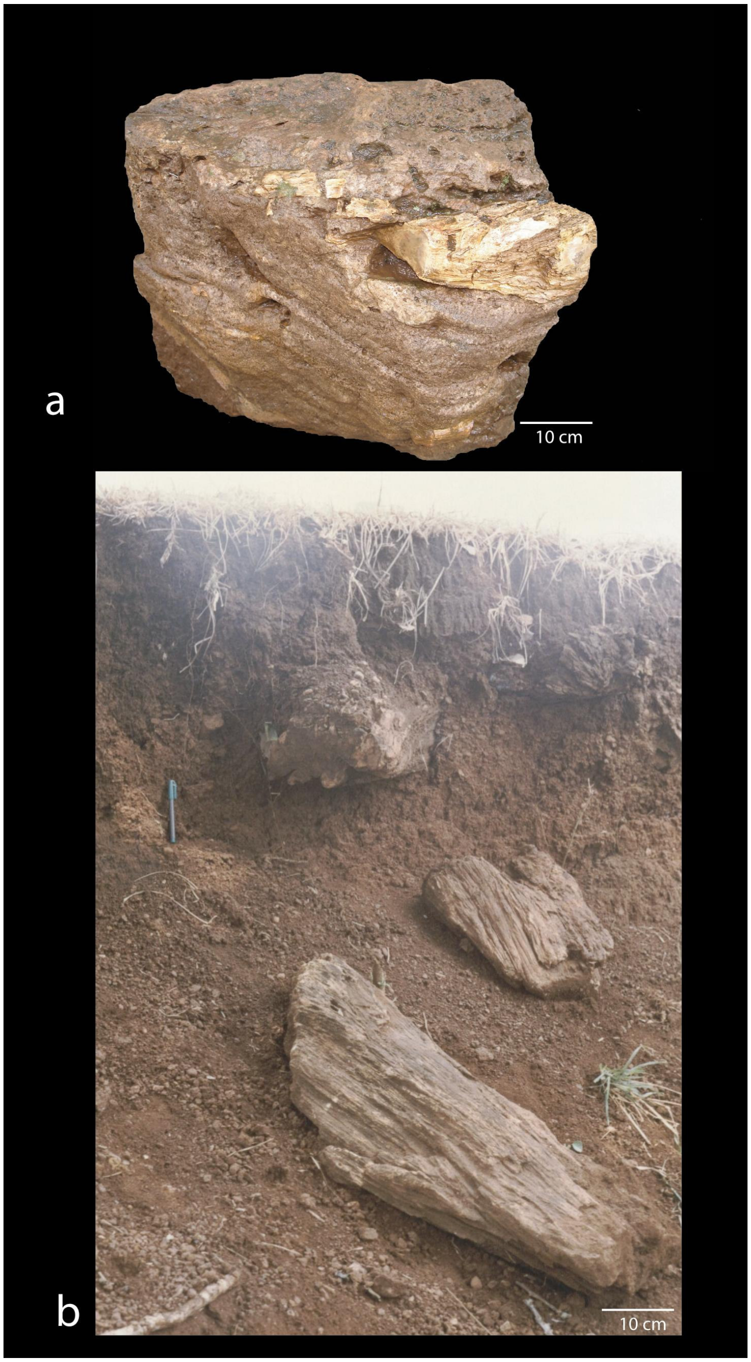


Figura 9: Material proveniente do Afloramento Fazenda Sobradinho, Bacia do Paraná, **a:** fragmento de lenho fóssil incluso em um bloco de sedimento; **b:** ocorrência dos lenhos no afloramento, com lenho incluso no sedimento e rolado.

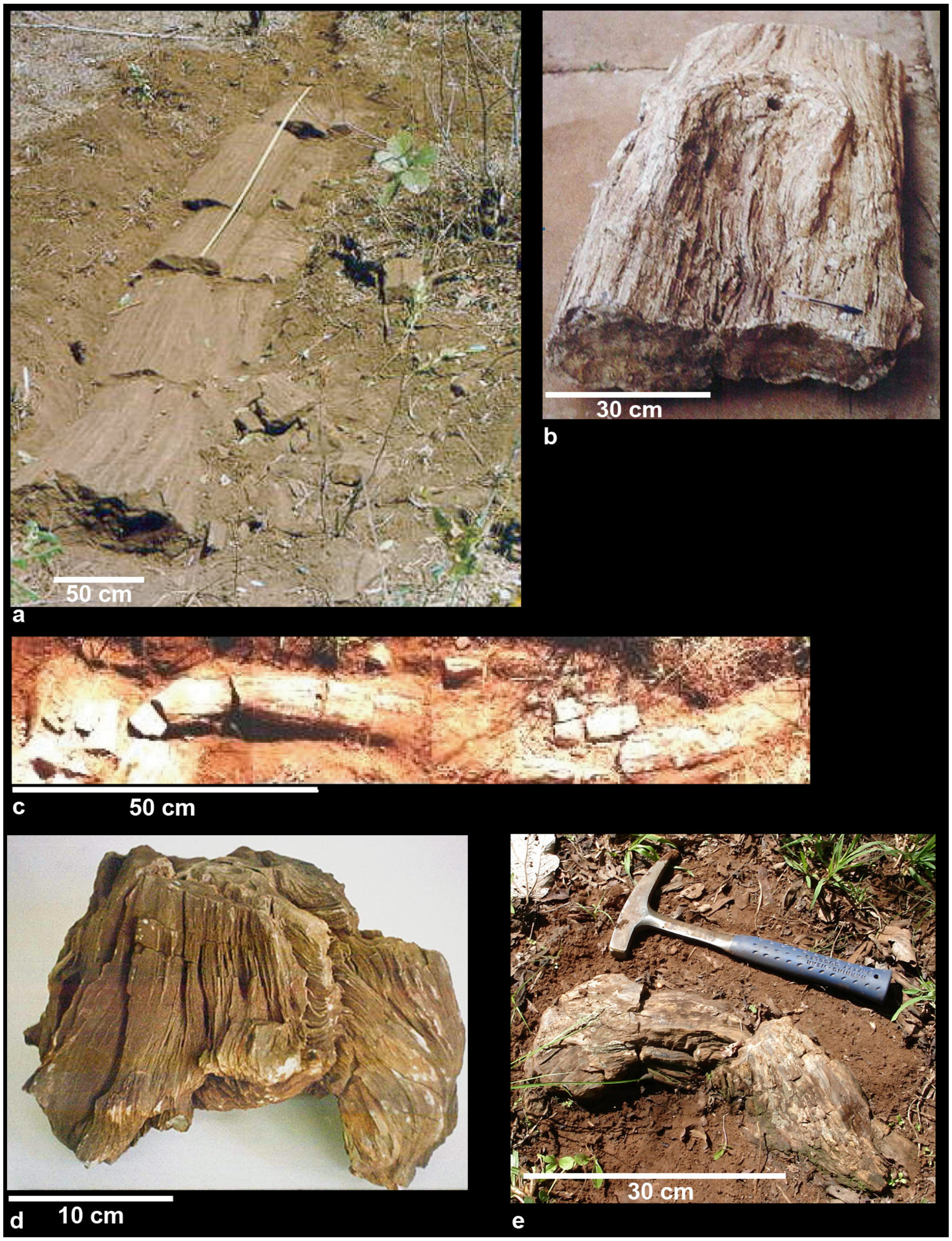


Figura 10: Material proveniente do Afloramento Fazenda Sobradinho, Bacia do Paraná, **a**: lenho fóssil incluso no sedimento; **b:** lenho demonstrando compressão lateral; **c:** raiz fóssil *in situ* inclusa no arenito; **d:** lenho basal achatado; **e**: raiz fóssil *in situ* inclusa em solo arenítico alterado.

### *b. Lâminas Delgadas*

A confecção das lâminas delgadas em planos transversais, radiais e tangenciais segue os princípios padrões de análise de madeiras, visando caracterizar anatomicamente os lenhos. A técnica utilizada para a confecção de lâminas delgadas dos lenhos fósseis utiliza o seguinte protocolo:

a) cortar os lenhos na seção desejada - transversais, radiais e tangenciais - com máquina com serra diamantada lubrificada com óleo
b) retirar amostras menores dos fragmentos utilizando máquina com serra lubrificada com água
c) lixar amostras com abrasivo carbeto de silício (320 - 500) e óxido de alumínio (1500 – 3000)
d) lixar novamente as amostras com carbeto de silício em uma placa de vidro
e) lavar as amostras com sabão e água
f) secar as amostras em estufa ($50^{o}$ por 24 horas)
g) colar as amostras em lâminas de vidro com araldite CY 248 e endurecedor HY 95 (6:1).
h) secar as amostras em estufa ($50^{o}$ por 24 horas)
i) serrar o excedente de rocha das amostras em máquina lubrificada com água, deixando mais ou menos 1 mm.
j) lixar as amostras em máquina politriz até a obtenção da espessura desejada, primeiramente com Carbeto de silício 320 em placa de viro e posteriormente utilizar o óxido de alumínio 1.500.
l) limpar as lâminas com xilol e etiquetar.

O grau de abrasão foi controlado através da observação em microscópio ótico, visto que a espessura da lâmina é diferenciada em relação à lâminas petrográficas de rocha.

### *c. Blocos para microscopia eletrônica*

Foram obtidos a partir de seções determinadas dos lenhos, metalizados com ouro, não aderidos a stubs, uma vez que as características do equipamento eletrônico não exigem tal montagem.

### *d. Registro fotográfico*

As fotografias do afloramento foram feitas com máquina Yashica FX3 e filme Kodak ASA 100. As fotografias macroscópicas das lâminas delgadas, das seções planas e dos lenhos fósseis foram realizadas no Laboratório Fotográfico do Instituto de Geociências, Departamento de Paleontologia da Universidade Federal do Rio Grande do Sul, com máquina fotográfica Yashica FX3 Super com lente Wetzlar 60 mm com tubos de extensão.

O registro fotomicrográfico em secões polidas e lâminas delgadas dos lenhos fósseis foi realizado com sistema automático de fotografia acoplado a microscópio ótico de luz transmitida Carl Zeiss –modelo MC80 e filme preto e branco Kodak T-Max 100, ASA 100.

## 1.5.3. Métodos de Estudo

As análises dendrológicas e anatômicas dos lenhos foram efetuadas a partir de lâminas delgadas observadas em microscópico Carl Zeiss-modelo MC80 utilizando-se ocular graduada e tabela de conversão, com aumentos de 3,5 – 10 e 40 X, sendo a observação efetuada nesse último aumento, com óleo de imersão.

Os índices de sensibilidade média e sensibilidade anual (*sensu* Douglas, 1928), foram ratificados através da mensuração da espessura dos anéis dos anéis de crescimento diretamente na seção polida com o auxílio de um paquímetro. Em algumas amostras, as espessuras dos anéis de crescimento foram medidas com o auxílio de microscópio ótico com escala graduada. O cálculo dos índices foi realizado com a utilização de planilha do Microsoft Excel.

A sensibilidade média é um método estatístico que verifica a variabilidade média na altura dos anéis de crescimento em uma série temporal de anéis pela medida das diferenças relativas na altura de um anel em relação ao próximo. Douglass (1928) estabeleceu o índice de sensibilidade média a partir da seguinte equação:

$$\text{Sensibilidade Média} = \frac{1}{n-1} \cdot \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right|$$

Onde,
x = altura do anel
t = ano do anel
n = número de anéis da seqüência

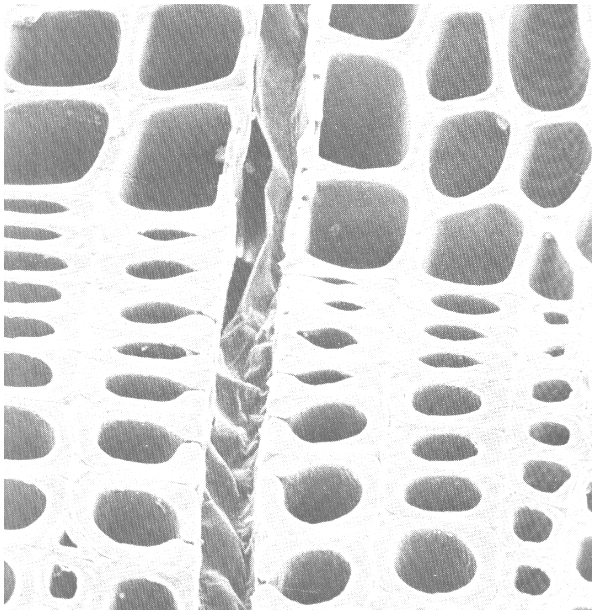
As alturas dos anéis de crescimento em seqüência são tratadas como pares consecutivos e a diferença entre cada par é dividida pela média de altura do par de alturas analisado. Os valores obtidos podem variar de 0 (não há variação) a no máximo 2 (maior variação). Um valor arbitrário foi estipulado para classificar as árvores em complacentes, que crescem em climas favoráveis e uniformes (SM menor que 0,3) e sensíveis, que crescem em climas oscilantes (SM maior que 0,3).

A sensibilidade anual é calculada em cada exemplar e apresentada através de histogramas onde se demonstra a variação de espessura dos diferentes anéis de crescimento do lenho permitindo identificar a variabilidade climática ao longo de uma seqüência de anéis.

Os lenhos fósseis aqui analisados também foram enquadrados no esquema proposto por Creber e Chaloner (1984 a). Visando fornecer subsídios à interpretação de anéis de crescimento em lenhos fósseis, os autores realizaram um estudo sobre a influência de fatores ambientais na estrutura lenhosa. Assim, é apresentada uma classificação dos anéis de crescimento baseada em relações de lenho inicial/lenho tardio. Esta técnica é centrada nas curvas das somas cumulativas dos desvios com relação à média do diâmetro radial em cada anel. Foram identificados seis tipos de padrões de desenvolvimento de anéis (tipos A, B, C, D, E e O), todos eles relacionados a determinadas condições ambientais bem estabelecidas. Os resultados também foram plotados segundo metodologia utilizada por Denne (1989) baseado em Mork (1928), que considera como parâmetro climático além do diâmetro do lúmen, a espessura das paredes dos traqueídeos.

As análises mesoscópicas da interação planta - artrópode foram realizadas em seções naturais e em seções polidas dos lenhos. A definição do padrão de ataque foi estabelecida a partir da observação de lâminas delgadas em microscópico Carl Zeiss-modelo MC80; a definição morfológica dos coprólitos foi efetuada a partir de observação de blocos em microscópio eletrônico de varredura do Centro de Microscopia Eletrônica da UFRGS.

# 2- Artigos



# 2- ARTIGOS

## 2.1. "Palaeoclimatic inferences in the Early Cretaceous – Missão Velha Formation of Araripe Basin (Brazil) – based on dendrological data" – *Cretaceous Research*

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### ABSTRACT

Growth ring analysis on silicified coniferous woods from the Missão Velha Formation (Araripe Basin - Brazil) has yielded important information about periodicity of wood production during the early Early Cretaceous in the equatorial belt. Despite warm temperatures, dendrological data indicate that the climate was characterized by cyclical alternation of dry and rainy periods influenced by cyclical precipitations, typical of savanna conditions. The abundance of false growth rings can be attributed to both occasional droughts and to arthropod wood-boring damage. The present climate data agrees with palaeoclimatic models that inferred summer-wet biomas for the Late Jurassic/Early Cretaceous boundary in the southern equatorial belt.

**KEY WORDS**: Silicified woods; Dendroclimatology; Pre-rift phase; Araripe Basin – Brazil

### 1- INTRODUCTION

The term equable (warm, low seasonality) is often used to describe Jurassic and Cretaceous climate, when there was only sluggish equator to pole atmosphere and ocean circulation (Barron and Washington, 1982). The need for a better definition of the term was indicated by Axelrod (1984), because recent modeling results show it may be a simplistic view of that climate. The distribution and thermal tolerances of land plants during the evolution of a greenhouse phase, provides one of the main sources of climatic evidence through the Late Jurassic and Early Cetaceous. A climate uniformly warm was inferred by the presence of fossil flora in low and high latitudes since of their composition (ferns, cycadophytes and conifers) and latitudinal spread (Jefferson, 1982; Douglas and Williams). However palaeoclimatic reinterpretations (Drinnan and Chambers, 1986) concluded that southern and northern floras may represent warm summer climates rather than year-round warmth. Frakes et al. (1992), based in the development of evaporites, concluded that the latest Jurassic appears to have been arid, at least in low and middle latitudes. However the Early Cretaceous was much more humid and coal deposits become prominent in the equatorial region (Peru and Mexico) (Ziegler et al., 2003).

Palaeoclimate zones based on the global distribution of lithological climate indicators such as coals, evaporites and aeolian sands as well as the distribution of plants and animals sensitive to climate were defined by different authors. Ziegler (1990) applied the biome squeme developed by Walter (1985) that reduced the macroclimate of present day surface to nine major biomes, for palaeoclimatic global reconstruction.

The most recent palaeoclimatic maps for the Phanerozoic are presented by Scotese (2003), plotting on palaeogeographic maps the distributions of sensitive climate rocks, plants and animals that form specific climatic belts. On the other hand, the maps time intervals are too extensive for studies on specific stages.

Based on a compilation of geological and palaeontological data, Chumakov (1995) proposed world climatic maps for the Cretaceous identifying eight climatic belts pole to pole. In the Early Cretaceous (Berriasian), the equatorial region of the South America-Africa landmass, included in the Tropical – Equatorial hot arid belt is considered to have been largely arid without evidence of sufficient moisture to have supported forests.

Creber and Chaloner (1984) ratified previous global palaeoclimatic reconstruction indicating a very broad equatorial zone (32°N to 32° S) at the Cretaceous, as evidenced by the absence of growth rings in woods or very weakly defined ones. Consequently, at Cretaceous times, the lower latitudes generally would experienced a season less climate, which permitted more or less continuous tree growth as a result of photoperiodic mechanism coupled to an annual leaf-flushing period.

In the northeastern brazilian interior basins (Araripe, Rio do Peixe, Recôncavo/Tucano/Jatobá, and Iguatu), the sedimentary records of the pre-rift sequence occur in scattered exposures (Fig. 1). They represent the remains of what was once a great shallow basin, the Afro-Brazilian Depression - ABD (Ponte, l972).

Climatic differences invoked by Da Rosa and Garcia (2000) to have divided the ABD into two regions, was supported by palaeocurrent, provenance, diagenetic, and palaeontological data. The abundance of silicified woods in Missão Velha Formation of Araripe Basin suggested the development of a Berriasian conifer forest on the humid northern highland margins, separated from the arid to semi-arid conditions prevailing in the southern part of the basin, evidenced by the presence of extensive aeolian facies. The presence of growth rings in the fossil woods reflects, undoubtedly, seasonality. This data contrast climate patterns established by Creber and Chaloner (1984) using fossil woods.

The present study outlines analyses of a silicified wood assemblage from an outcrop of Missão Velha Formation of Araripe Basin about more or less 8ºS. The main focus of this paper is: 1) to document dendroclimatic analysis of growth rings, using statistical procedures; 2) to offer palaeoclimatic inferences based in growth ring analyses; 3) to refine global palaeoclimatic models inferred for the Late Jurassic/Early Cretaceous, an also the regional climates inferred by the Afro-Brazilian Depression at that time interval.

## 2 - GEOLOGICAL SETTING

The Araripe Basin is the most extensive of the Brazilian northeastern interior basins, with an area of approximately 12.200 km$^2$, located on the boundary of Ceará, Pernambuco and Piaui states (7º02'-7º49' S and 38º30'-40º55'W) (Fig. 1).

The stratigraphic chart proposed by Assine (1992) characterized the Araripe Basin as a relictual composite of four genetically distinct basins, partially superimposed in space, and represented by four stratigraphic sequences bounded by unconformities. The unfossiliferous Paleozoic Sequence, corresponding to Cariri

Formation, was dated as Siluro-Devonian, based on supposed lithological affinity with rocks of the Tucano-Jatobá and Parnaíba basins; the Juro – Neocomian Sequence is composed, in that chart, by the basal siltstone and shale-rich Brejo Santo Formation, which is overlain by the Missão Velha Formation, redefined in relation to prior studies (Beurlen, 1962; Braun, 1966; Ghignone et al., 1986) to contain medium to coarse-grained sandstones with silicified woods superposed by the gray shales of the Indaiara Formation. The Aptian – Albian Sequence included the Barbalha and Santana Formations, and the Albian-Cenomanian Sequence is formed by the unfossiliferous Exu Formation.

The Missão Velha alluvial system encompasses also the Antenor Navarro Formation in the Rio do Peixe Basin, the Sergi Formation in the Reconcavo - Tucano-Jatobá Basin and has been correlated to N´Dombo Formation (Gabon Basin), Lucula Formation (Congo-Cabinda Basin) and Offshore Congo, all African basins (Da Rosa, 1994). The age of the Missão Velha Formation was estimated as Late Jurassic based upon ostracods assemblages (Pinto and Sanguinetti, l958 a, b) and no older than Early Cretaceous (Berriasian) by Horne (1995), corresponding to the São João chronostratigraphic stage of the Araripe Basin (Coimbra et al., 2002).

The stratigraphic chart of Araripe Basin (Arai et al., 2004) and also the stratigraphic revision of the Lower Cretaceous Brazilian northeastern interior basins defined by Arai (2006), indicates that Dom João Stage is mostly within the Jurassic, although its uppermost part can range into the basal Cretaceous (Berriasian). On the other hand, it was concludes that the term “Missão Velha Formation” was inadequately related to two distinct stratigraphic units, that corresponds to the Dom João Stage (Missão Velha Formation *sensu stricto*), with a Berriasian maximum age interval, and an other one corresponding to the Alagoas Stage (current Rio da Batateira Formation). In the present study the designation “Missão Velha Formation” is used to identify a lithostratigraphic pre-rift unit of the Araripe Basin, according the framework of Arai et al. (2004) defined in figure 2.

The wood-bearing Grota Funda (UTM: 24M 0489727/9196725) lies 6 km east of Missão Velha city, bordering route 293 in Ceará state. The exposed sedimentary sequence is 4 m high and 30 m wide. This site exposes a prominent fluvial and aeolian facies, composed of a succession of medium-coarse sandstones with trough cross-bedding, interbedded with beds of trough cross-bedded conglomerates. Silicified woods are the exclusive fossils, and occur included in the coarse-grained sandstone or rolled, rarely as components of the conglomerates. The fossil woods show no preferential orientation.

## 3- DENDROCLIMATOLOGIC ANALYSIS

### *3.1. Wood Description*

The fossil woods fragments at Grota Funda have a diameter from 0.1 to 1 m. The fragments are not rounded or abraded and bark is also present in rare specimens, suggesting that they have not been transported far from their source. Forty-five samples were collected from the site and fifteen mature woods were selected for detailed palaeoclimatological growth ring analysis.

Large dispersed fossil woods with uncompressed diameters of 0.50 - 1 m and lengths weathered out up to 3 m are also common in the sandstones, or at the ground surface (Fig. 3, a). This character is indicative of hipo-autochthonous depositional conditions. The smaller wood fragments were probably produced by desegregation of bigger trunks. Thin-sections from pieces of the external secondary xylem of these specimens were also studied. The results showed that the large and small woods were anatomically equivalent.

The wood is mostly silicified and light brow. Growth rings are prominent in transverse section; earlywood and latewood are clearly distinguishable (Fig. 3, d, e). Boring activities are evident in the outer surface of several samples (Fig. 3, b, c, and e). Detailed analysis of the boring system, reported by Pires and Guerra Sommer (unpublished data) provides the first relevant data for addressing evidences of phytophagy in these coniferous silicified woods. The damage pattern was linked to attack of oribatid termites (Isoptera). The order Isoptera is known from the Early Cretaceous, by wing impressions of the species *Valditermes brenanae* (family Mastotermitidae) found in Weald Clay by Jarzembowsky (1990). Consequently the evidences of termite-plant interaction in the wood assemblage of Missão Velha Formation constrained the depositional interval to the Early Cretaceous.

Formal taxonomic analyses were not developed in the studied wood assemblage. Nevertheless, two gymnosperm xylotypes (Wheler e Lehman, 2005) were recognized, based on parameters such as the size of earlywood tracheids in transverse section, patterns of radial pitting on tracheids and cross field pitting in radial section. The woods possess resiniferous tracheids scattered within growth rings (Fig. 4 a). The anatomical differences allowed for identifying: 1. *Cupressoid/Podocarpoid* wood type 1; 2. *Araucarioid* wood type 2. Main features of these wood types are detailed in figure 4 .

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### 3.2. Analysis of growth rings

#### *3.2.1. Methodology*

Growth rings were measured from transversely polished sectioned blocks of the silicified wood utilizing binocular stereoscopic microscopy or were measured with sliding caliper directly on the polished wood surface. Details of growth ring structure were obtained by the observation of thin slides on transmitted light optical microscopy of thin-sections.

Statistical procedures used in the analyses of growth rings from the fifteen fragments of fossil wood followed those of Fritts (1976: based on Douglass, 1928; Creber, 1977; Creber and Chaloner, 1984; and Parrish and Spicer, 1988). These include the variance of ring width, Mean Sensitivity (MS), Annual Sensitivity (SA) and growth ring classification scheme**.**

Inter annual variation in growth rate is determined by Mean Sensitivity indicators, which represents a measurement of the sensibility of trees to variation in their environment. The indices are obtained by the equation:

$$MS = 1/n - 1 * \sum_{t=1}^{T=n-1} \left| 2\,(X_{t+1} - X_t) / (X_{t+1} + X_t) \right|$$

Where:

n: is the number of rings measured in a sequence;

t: is the number in the ring count;

X: is the ring width.

The values of mean sensitivity range from 0 to a maximum of 2. An arbitrary value of 0.3 is taken to separate “complacent” trees that grow under a favorable and uniform climate ($MS \leq 0.3$) from those that are “sensitive” to fluctuating climate parameters ($MS \geq 0.3$; Douglas, 1928). Different authors (Creber and Chaloner, 1984; Francis, 1984; Brea, 1998; Francis and Poole, 2002; Pires et al., 2005) have used mean sensitivity as a tool for palaeoclimatic analysis. According to Keller and Hendrix (1997) Mean Sensitivity values are not necessary a reliable measure of environmental factors. Kay (1978) also considered that a tree of a single species growing within the interior of a forest naturally has lower sensitivity values than those growing along the forest borders, regardless of climatic variability.

The degree of year to year variability is demonstrated by annual sensitivity is derived from the equation of Mean Sensitivity and corresponds to the difference in width between a pair of consecutive rings divided by their average width. The indicator may be a more valid measure of the environmental variability to which the tree has been exposed (Keller and Hendrix, 1997).

Analysis of the general growth ring characterization in the early and latewood were based on the cell amount and diameter, cellular walls thickness, as well the nature of earlywood/latewood transition, according to IAWA Committee (1989).

The nature of seasonality can be also inferred by the proportion of earlywood/latewood (Parrish and Spicer, 1988). Thus, distinct patterns of latewood in temperate modern woods which reflect growing conditions can be applied in fossil assemblages providing information about seasonality (Spicer and Parrish, 1990).

Mean ring width is used to indicate the growth rate and length of growing season, according to Fritts (1976) the wider the ring, the faster the growth or the longer the growing season.

The classification scheme of growth rings proposed by Creber and Chaloner (1984) carried out a study on the influence of environmental factors on woody structure based on relationships of earlywood/latewood. Six types of growth patterns were identified, all of them related to distinct environmental conditions: A, B, C, D, E and O. In the present study, two samples were selected, one of each recognized wood type to test the classification proposed by Creber and Chaloner (1984).

Specimens are housed in the Laboratory of Paleobotany, Departamento de Estratigrafia e Paleontologia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil, and in the Collection of Paleovertebrates Paleoinvertebrates and Paleobotany, Departamento de Geologia of

Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

### 3.3. Results

Statistical data where obtained from 277 rings in 15 samples. The Mean Sensitivity is 0.191 - 0.902; the average of Mean Sensitivity is 0.427; the minimum annual sensitivity is 0 and the maximum annual sensitivity is 1.147 (Table 1).

The maximum annual sensitivity exceeds 0.7, in almost all samples, except in PB 3854. The annual sensitivity of the specimens increases year after year, except for 2 specimens (PB 371, PB 3854) that have low mean sensitivity (Figs. 5,6,7).

All the specimens have wider growth rings according to IAWA Committee (1989). The measured growth rings range from 0.54 - 7.38 mm wide (mean: 2.19 mm). Within individual growth rings the transition from earlywood to latewood is abrupt (Fig. 8 a,b,d). Latewood is very narrow, consisting of 1-2 narrow cells with a thick walls and narrow lumen (Fig. 8, d) indicating that the cell conducting space is small. The earlywood is characterized by thin walled cells with a wide lumen. A large proportion of earlywood (60 - 100 cells) and small quantities of latewood (2 cells) is common to all samples but the ring boundaries are well defined.

The growth ring types of the studied assemblage are similar to type D (Fig. 9) in the ring classification scheme of Creber and Chaloner (1984).

False growth rings are abundant in most samples (Fig. 8 b,c,d). Their occurrence (more than 1 per growth ring), is linked to the final portion of the earlywood, at the end of the growing season. They may be distinguished from seasonal growth rings because they are commonly discontinuous and have a gradual transition to thick-walled narrow cells then a gradual reversal to large thin-walled cells (Spicer, 2003).

Resiniferous tracheids are scattered (Fig. 8 e, Fig. 4 a) in the xylem tissue. Wood damage is evidenced by the presence of galleries, bordered by a zone of reaction tissue, often consisting of a narrow dark outer band and a wide inner area, which is thought to be necrotic tissue (Fig. 10 a,b).

## 4- PALEOCLIMATIC INTERPRETATIONS

Statistical analyses of the wood assemblage from Grota Funda locality, of the Araripe Basin are important for inferring palaeoclimatic patterns. The Mean Sensitivity analysis indicates that individual samples corresponds mainly to sensitive types (87%), with MS more than 0.3. These data point to an irregular growth environment. On the other hand, the annual sensitivity above 0.7 is indicated for almost all samples indicating the occurrence of extreme climatic events. High variations in the growth ring width associated to a high annual sensitivity values indicate good conditions for tree growth, but with variable pluviometer conditions year by year (Gérards et al., 2007).

The general characterization of the wider growth rings indicates that growth was fast in a relatively short growing period, or that the growing period was large, or both. According to Spicer (2003), the small amount of latewood suggests the transition from full growth to full dormancy was rapid and there was not a long period of growth slowdown.

Growth rings with a gradual transition from earlywood to latewood are encountered mainly in the middle latitudes of both hemispheres, where climatic models predict the occurrence of temperate climates. This “progressive” type of wood”, (types B, C, and E of Creber and Chaloner, 1984) is typical from Early Cretaceous woods in middle latitudes for both hemispheres. Trees growing under a more or less season-less climate, as in the tropics, generally show more or less uniform secondary wood (Valdes and Sellwood, 1993) and are included in the type O of Creber and Chaloner (1984).

The similarity of the studied material to the type D, proposed by Creber and Chaloner (1984) indicates that the growing season was relatively uniform, with a terminal event representing a cessation or retardation of cambial cell division.

The presence of false growth rings reflects that external factors affected the different cycles of growth. These structures can be produced by: water supply restrictions, occurrence of fire or freezing, or invertebrate attack (Spicer, 2003). Otherwise, more than a single false growth ring was observed within a single growth ring (Fig. 8 b,c). Consequently, the origin of these anomalous growth rings could be related to plant stress represented by the occasional droughts at the end of growing season and insect infestation.

Dendroclimatological studies demonstrate that the growth pattern of woods represent palaeoclimatic signatures of seasonal cycles. Any cyclical variation in growing conditions can bring about the growth ring origin, but most often the controlling factors of growth can be: 1) photoperiod, 2) temperature and, 3) water supply and precipitation. In the Tropical – Equatorial Hot arid belt (Chumakov, l995), where photoperiod and temperature do not significantly vary, cyclical periods of water restriction could be the limiting growth factor and not the photoperiod or temperature.

The unusual conditions which allows the generation of growth rings in plants close to the paleopoles and those from the tropics in Early Cretaceous, are generally interpreted in terms of a high carbon-dioxide greenhouse world (Chaloner and McElwain, 1997).

Brison et al. (2001) based on growth rings analyses from woods of different Mesozoic localities scattered on five continents, looked at the geographical and taxonomical distribution of the tree growth ring types defined by Creber and Chaloner (1984). The authors concluded that growth rings in Mesozoic woods were not determinate by environmental factors alone, and are influenced by endogenous factors; consequently, a palaeoclimatological analysis of the growth ring types would to be based on taxonomically diverse assemblages and can envisage applications at a more local scale, either geographic or temporal. Falcon-Lang (2005) also consider that quantitative analysis of fossil growth ring data in light of the modern results indicates that even the detailed studies are inadequate in distinguishing a palaeoclimatic signal from the background noise of variability.

Nevertheless, Gerards et al. (2007), based on dendroclimatologic data confirm that during the Early Cretaceous (Berriasian), the Mons Basin (Belgium), located at 30-35°N in palaeogeographic models (Scotese, 2003), presumably in a tropical climate, was characterized by a succession of marked dry and wet seasons, under unstable palaeoenvironmental conditions. Otherwise, evidence of seasonal climate in the southern middle latitude was obtained in growth ring analyses by Jefferson (1982) in the Lower Cretaceous (Alexander Island - Antarctic) that indicate moderate to high seasonality. Falcon-Lang and Cantrill (2000) also registered for the

Alexander Island (Albian) similar wood patterns, from *Araucarioxylon* (invalid genera), *Podocarpoxylon* and *Taxodioxylon* morphotypes.

Different geological data indicates that the conifer assemblage of Missão Velha Formation was derived from low-lying areas, in adjacent floodplain (Da Rosa and Garcia, 2000), at low latitudes (8° S), during the climax of a greenhouse phase (Fischer, 1984; Frakes et al., 1992), with increasing atmospheric $CO_2$ (Tajika, 1999).

The similarities among the statistical data obtained from two different wood types could suggest alternatively that:1. the features of the growth rings were environmentally induced and not a consequence of the growth characteristics of a particular species that could have been genetically coded; 2. increased stress conditions could act as an artifact in mean sensitivity data; 3. taxonomic affinities among xylotypes would produce similar growth ring pattern.

The growing conditions experienced by the tree during the plant development in the ABD, at the Early Cretaceous, have left prominent growth rings, where the transition from earlywood to latewood is abrupt, indicating a climate characterized by the alternation of dry and wet periods. The periodic rainfall corresponded to the tree growing phase and, consequently, to the strongest factor controlling tree growth. The onset of soil-water shortage, in the dry season, would correlate with the earlywood/latewood transition. On the other hand, the presence of growth rings in woods for Earliest Cretaceous time-interval in Paraná Basin (Brazil), but in distinct latitudinal position and biome (tropical desert) revealed different dendrological pattern (Pires and Guerra Sommer, unpublished data). This evidence demonstrates that growth rings patterns have, even in greenhouse stages, peculiar signatures in different latitudes; this character confirms their importance as “paleophytobarometers”. That study demonstrated also that physiologic and taxonomic plant patterns, associated to particular environmental parameters, can influence plant growth.

In present days, two well demarcated seasons are defined in boreal and tropical climates (Köeppen, 1936). As it is indicated by palaeoclimatic models (Chumakov, 1995; Scotese, 2003), a boreal climate must be discarded for the Missão Velha Formation. In the broader tropical climate, three different climate types are included: 1. humid climate season less; 2. savanna; and 3. monsoon. As it is demonstrated by the presence of growth rings in woods, a season less climate must be discarded for the deposition of the Missão Velha Formation. The growth patterns characterized by two well demarcated seasons, as demonstrated by the growth ring structure, are defined in monsoon and savanna climates (Wrigth, 1990).

Global palaeogeography, dominated by the large, middle latitude, equator-parallel Brazilian-African landmass, would have been particularly conductive for monsoon circulation .The monsoon system is a dynamic component of the modern climate system. The inherent seasonality of monsoon circulation result in cool, dry winters and warm, wet summers over the continents. Monsoon circulations are driven by the different rates of response of the land and the oceans to solar heating in summer and radioactive heat loss in winter. The large seasonal wings in land temperature and small seasonal changes in ocean temperature reflect these contrasting responses of land and ocean (Rudddiman, 2001; Ritter, 2006).

Models of simulation of Pangean climates during the pre-rift phase (Kutzbach, 1994) indicated a strong reversal between summer and winter monsoon circulations. According to Scherer and Goldberg (2007), the Gondwana monsoons became milder from the Early Jurassic onwards, terminating at the latest Jurassic or earliest Cretaceous. Nevertheless, because of its huge size, climate model simulates widespread dry continental climate in the Pangean interior, in the absence of the moderating influence of oceanic moisture (Rudddiman, 2001).

Taking into account the palaeogeographic data and models of climate simulation for the Pangea during the Early Cretaceous, a savanna type of climate could be better inferred for the time of deposition of the Missão Velha Formation. This year-round warm tropical climate is defined by pluviometer and temperature regimes, with a very long dry season (winter) and a wetter, rainy season (summer). Like the monsoon climate, savanna climate has a distinct seasonality to its precipitation. Still, its wet season is much shorter and receives far less precipitation than the monsoon climate (Ritter, 2006).

The presence of fossils of turtles, crocodiles, lizards and amphibians described from sandstone sequences of the Missão Velha Formation (Brito et al., 1994) indicated that the region was not an extreme desert, and fresh water may have been being present in at least ephemeral streams and lakes. The streams are likely to have been sourced of the mountainous flanks of the rift valley that was subsequently to become the southern Atlantic Ocean (Spicer, 2003).

The combined evidence from fossil floral composition, leaf physiognomy, and sedimentological indicators suggests that this region was characterized by a hot, sub-humid to semi-arid climate typical of present-day savanna region (Willis and McElwain, 2002).

The palaeoclimatic parameters evidenced in growth rings of the wood assemblage of Grota Funda outcrop allowed to infer a low latitude summer-wet biome well characterized in the paleoclimatic map from the Jurassic-Cretaceous transitions presented by Rees et al. (2000) (Fig. 11). These dendrological data associated to results obtained in arthropod-plant interaction (Pires e Guerra-Sommer - unpublished data) constrains the stratigraphic level of fossil wood occurrence in Missão Velha Formation to the interval early Early Berriasian, confirming the stratigraphic framework proposed by Arai et al. (2004) and Arai (2006).

## 6- CONCLUSIONS

1) The presence of growth rings as a common character in fossil woods from the Grota Funda outcrop, Missão Velha Formation (Araripe Basin) indicates cyclical variation in tree growing conditions;

2) Growth rings characteristics seams to be induced environmentally and not a consequence of the growth characteristics of single taxon that could have been genetically coded;

3) Subtly developed growth rings in fossil woods are interpreted to have formed in response to a seasonal climate, probably due to restrictions on precipitation, which led to a soil-water shortage; cambial dormancy must occurred cyclically;

4) The Mean Sensitivity coefficient from growth rings in fossil woods is high and indicates unstable palaeoenvironmental conditions. This implies that the climatic seasonality did not have homogeneous rhythm, originated probably by year to year variability characterized by frequent disturbances in rainfall;

5) In such climate, droughts during the growing season produced false growth rings; arthropod damage during the life-cycle of trees could also have contribute to the production of false growth rings;

6) Dendrological data suggest that during the deposition of Missão Velha Formation, in the northern part of Afro-Brazilian Depression landmasses experienced a seasonal climate characterized by cyclical alternation of dry and wet periods. The patterns of growth rings are consistent with a savanna climate;

7) Integration between the present dendrological data and results from arthropod-plant interaction in the studied plant assemblage, indicate a southern summer wet biome developed during the early Early Cretaceous throughout a greenhouse climate phase.

## 7 - ACKNOWLEDGEMENTS

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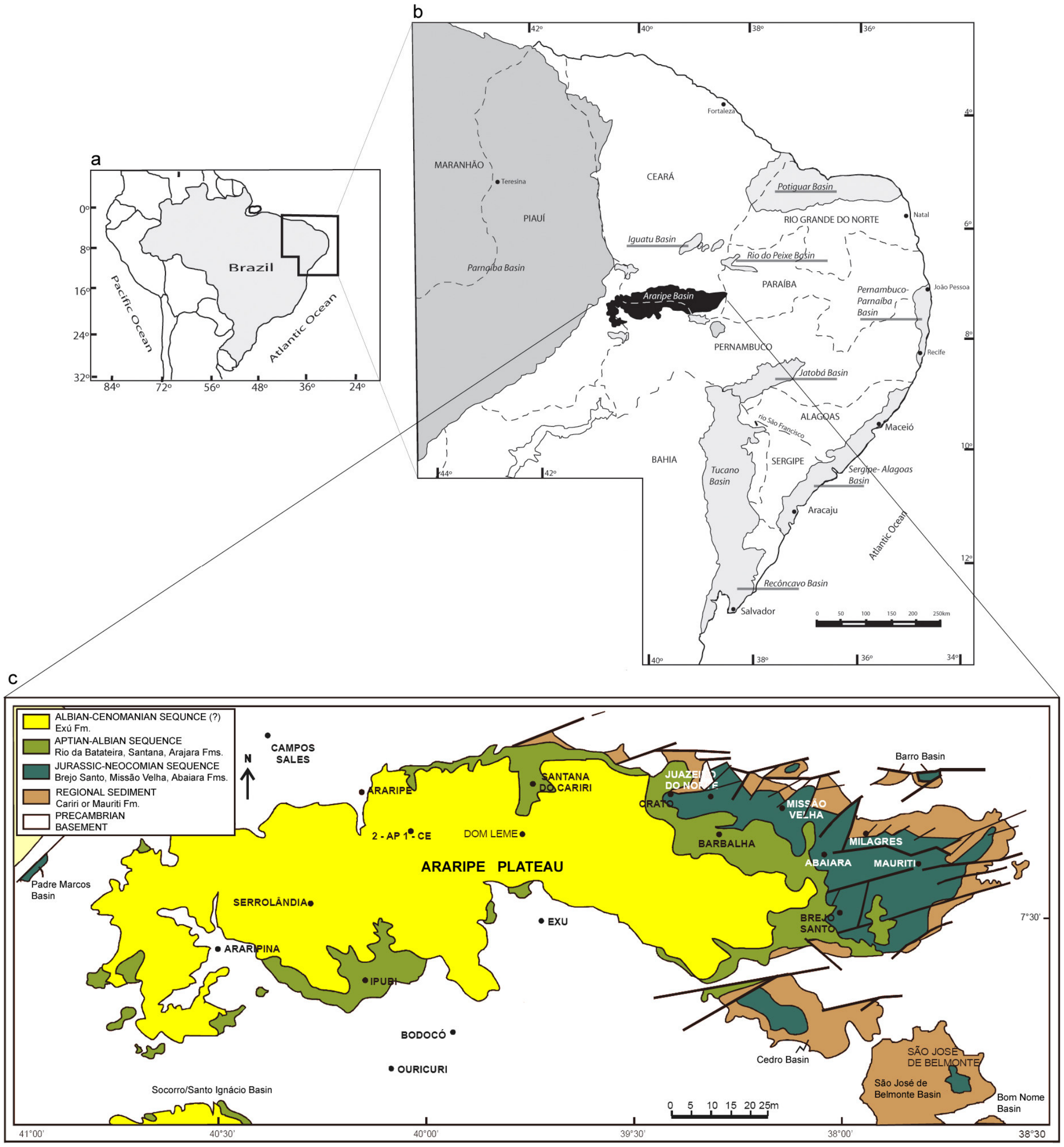

**Figure 1:** Location of the studied area; a: map of Brazil; b: map of northeastern Brazil showing the location of Araripe Basin (in black) and the interior basins of the northeast of Brazil; c: geographic delimitation of Araripe Basin.

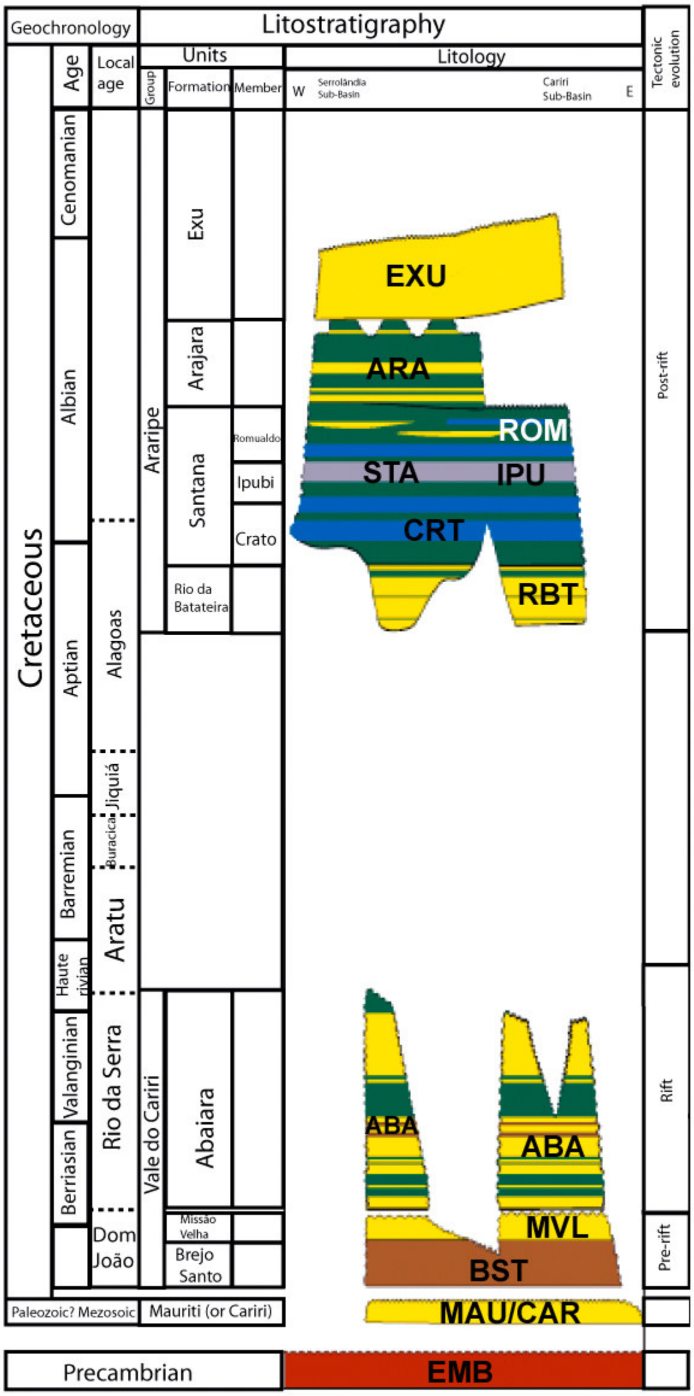

**Figure 2**: Stratigraphic column of the Araripe Basin (modified of Arai et al., 2004).

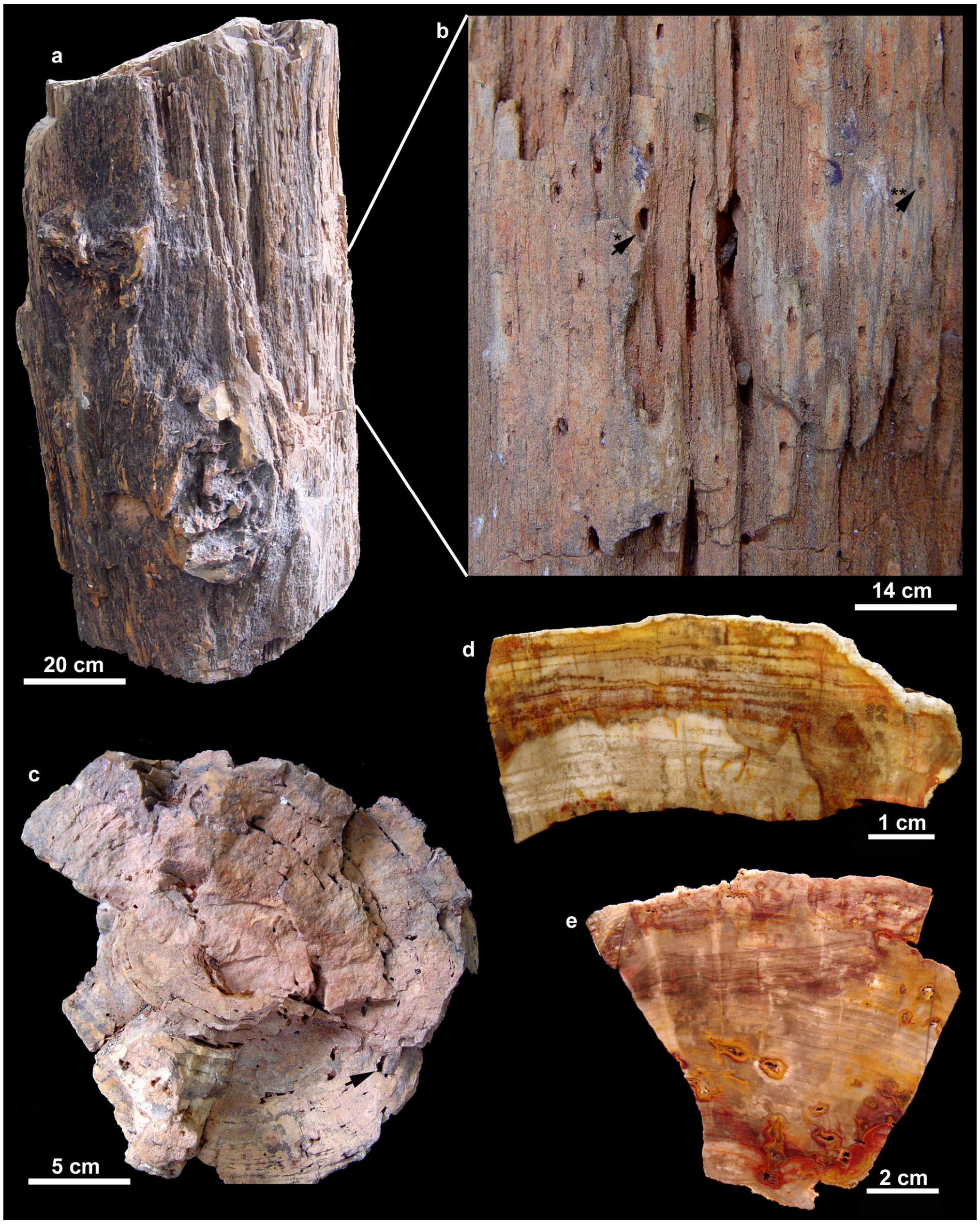

**Figure 3:** a. large fossil wood from the Gota Funda oucrop; b. detail of the outer surface showing the smallest eliptical features (*) correspond to invertebrate bores and large holes (**), irregular in shape, corresponding to regions of collapsed walls of internal borings; c: cross section of large permineralized wood, showing growth ring boundaries and circular to irregular diameter of axial tunnels, following the curvature of growth rings; d, e: polished cross section of secondary wood of different samples showing growth ring pattern.

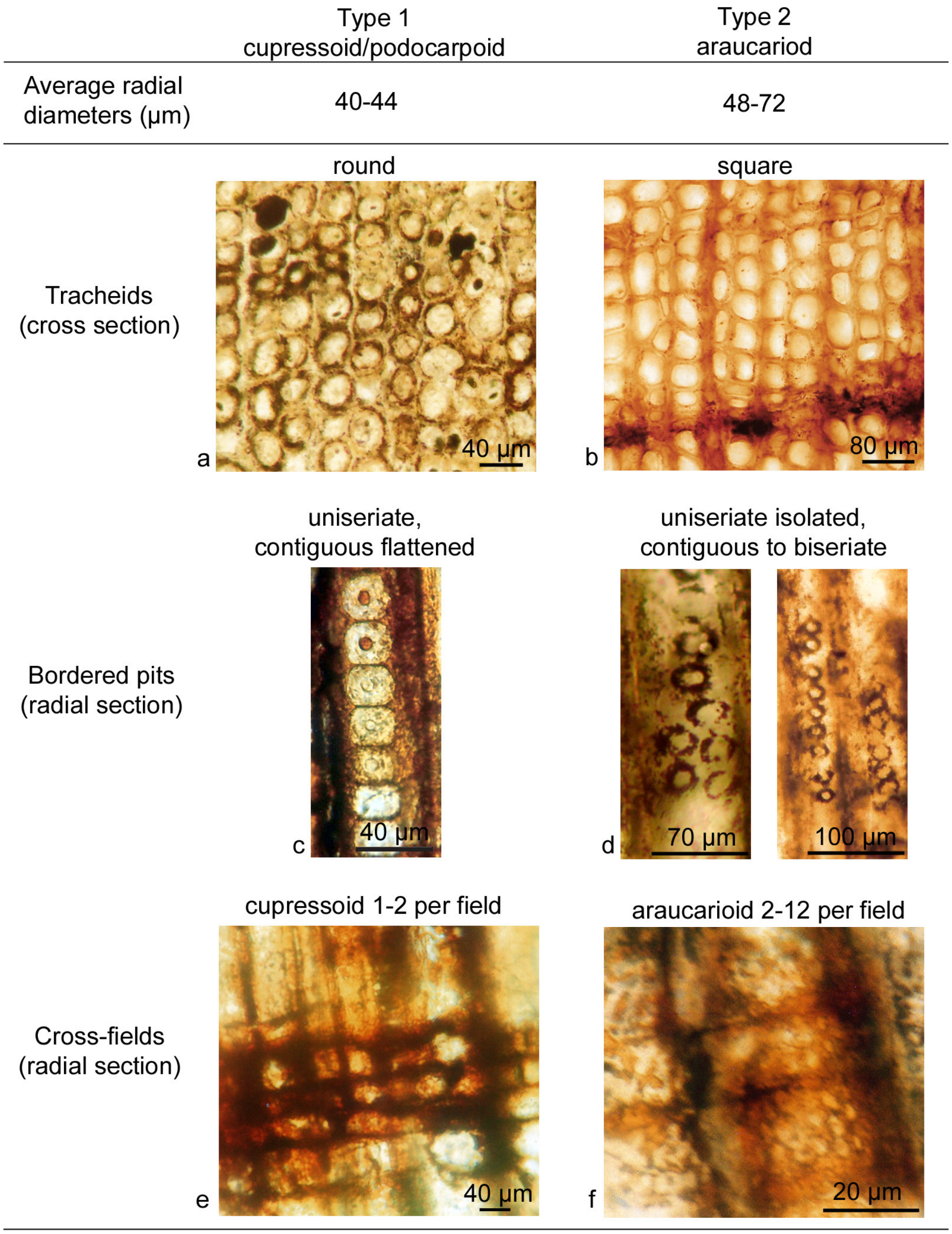

**Figure 4:** Diagnostic anatomical patterns found in xylotypes 1 and 2 from Grota Funda Outcrop.

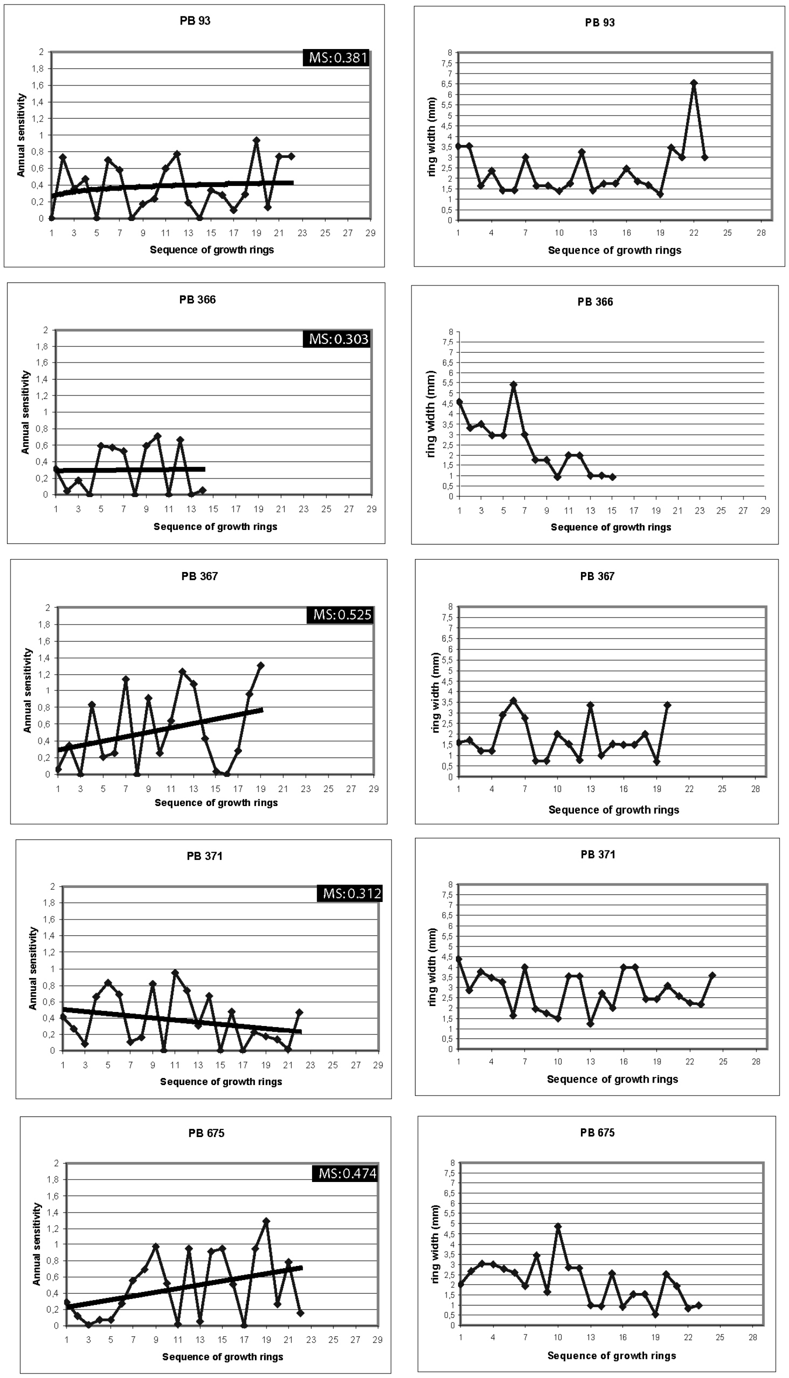

**Figure 5:** Annual sensitivity and ring width graphics of 5 samples of fossil woods (PB 93-PB 675).

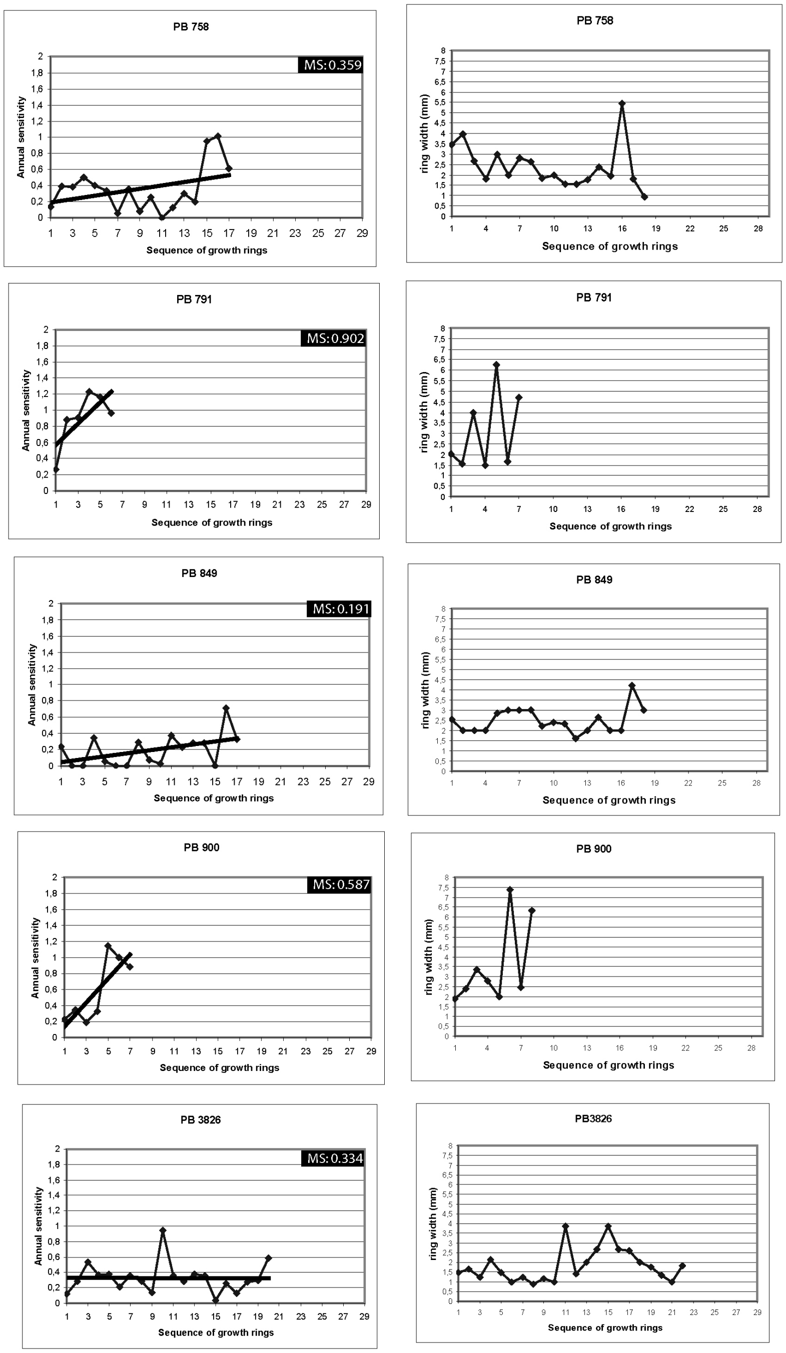

**Figure 6:** Annual sensitivity and ring widths graphics of 5 samples of fossil woods (PB 758-PB 3826).

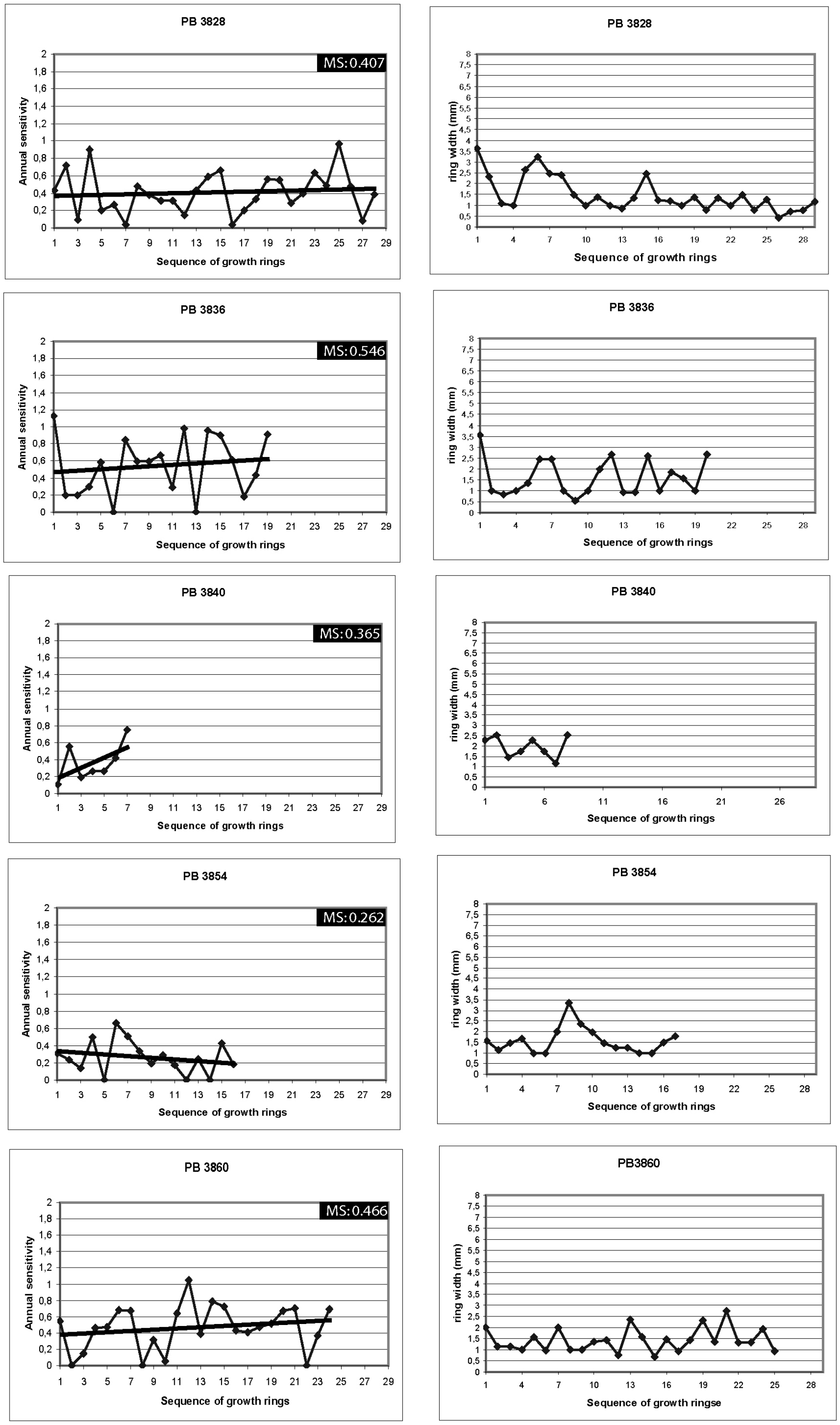

**Figure 7:** Annual sensitivity and ring widths graphics of 5 samples of fossil woods (PB 3828-PB 3860).

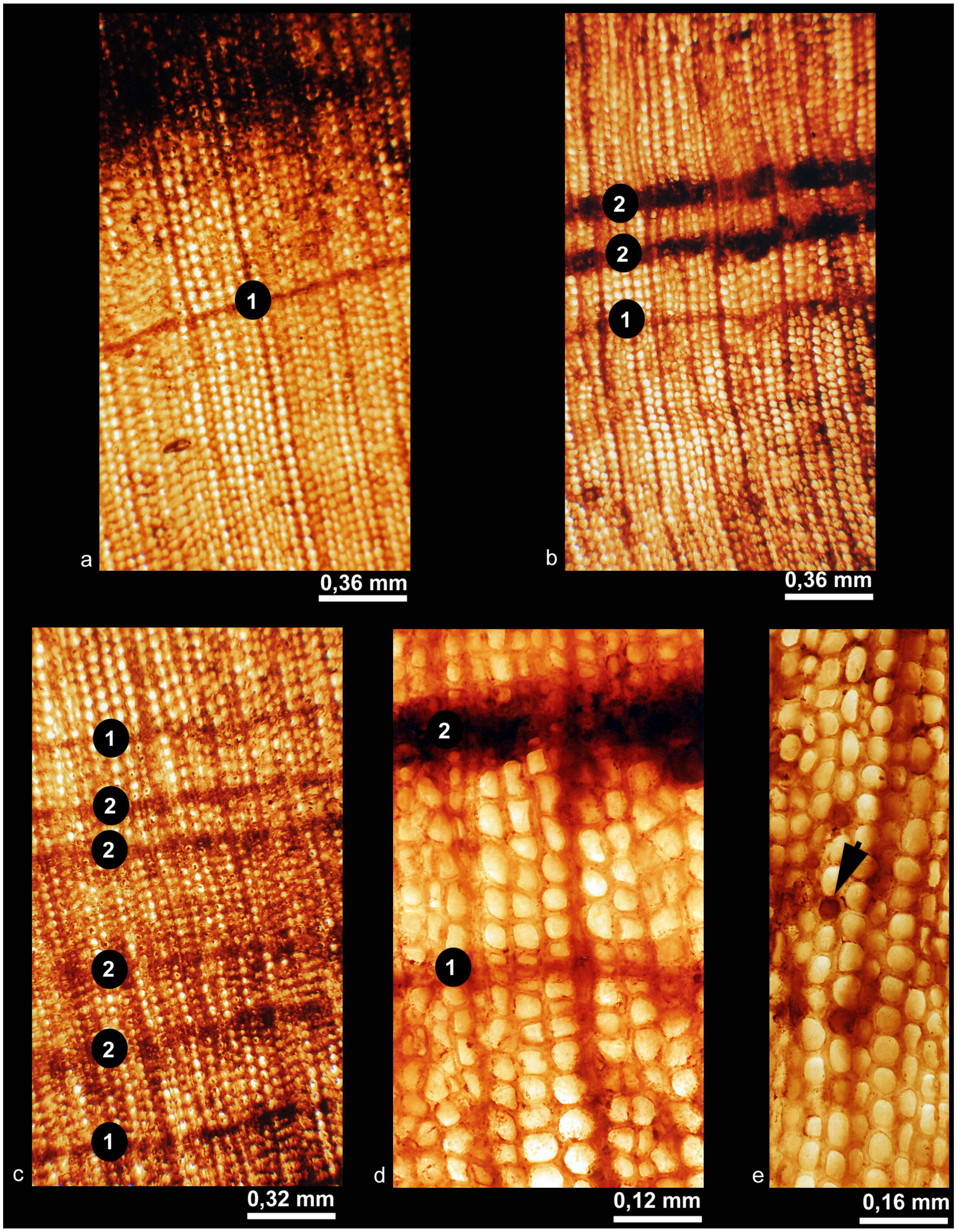

**Figure 8:** Transverse thin sections of fossil woods (optical microscope), **a**. limit of a growth ring, characterized by a abrupt transition to earlywood to latewood, the arrow indicates the limit; **b.** limit of growth ring (arrow 1), and two false growth rings (arrow 2); **c.** limit of a true growth ring (arrow 1) and a lot false growth rings (arrow 2); **d.** detail of **b**, detailing two cells of latewood (arrow 1) and a false growth ring (arrow 2). **e.** detailing a resiniferous tracheid.

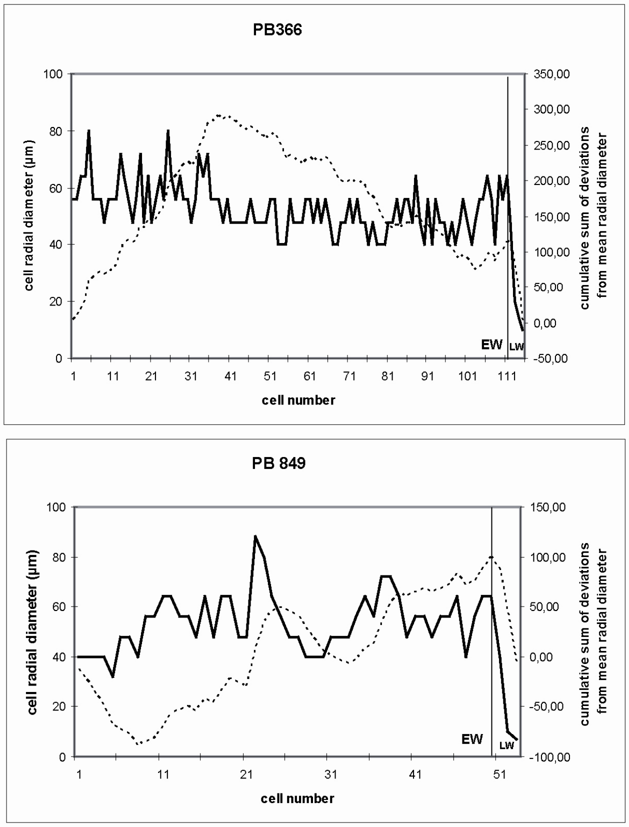

**Figure 9:** Variation in cell radial diameter along selected growth rings (solid line) and cumulative sum of deviations from mean radial diameter (dashed line) in 2 samples – PB 366 and PB 849. Vertical line separates earlywood (EW) from latewood (LW).

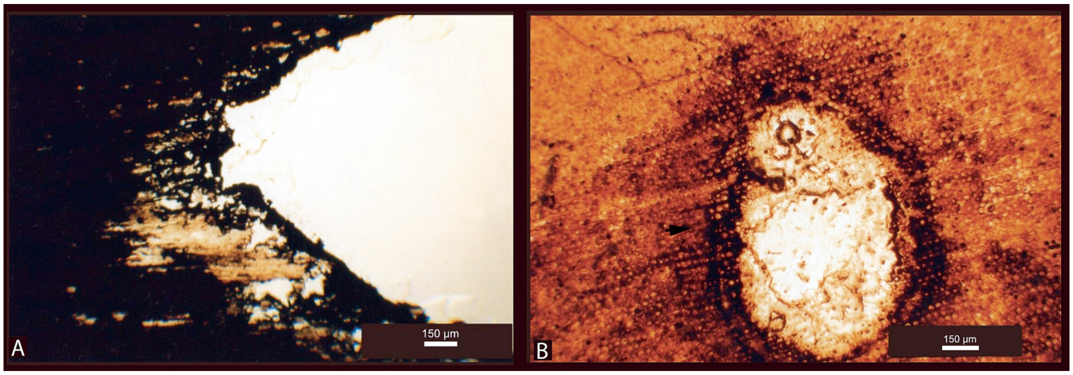

**Figure 10: a.**: Radial section, **b.** Transverse section, showing the necrotic tissue.

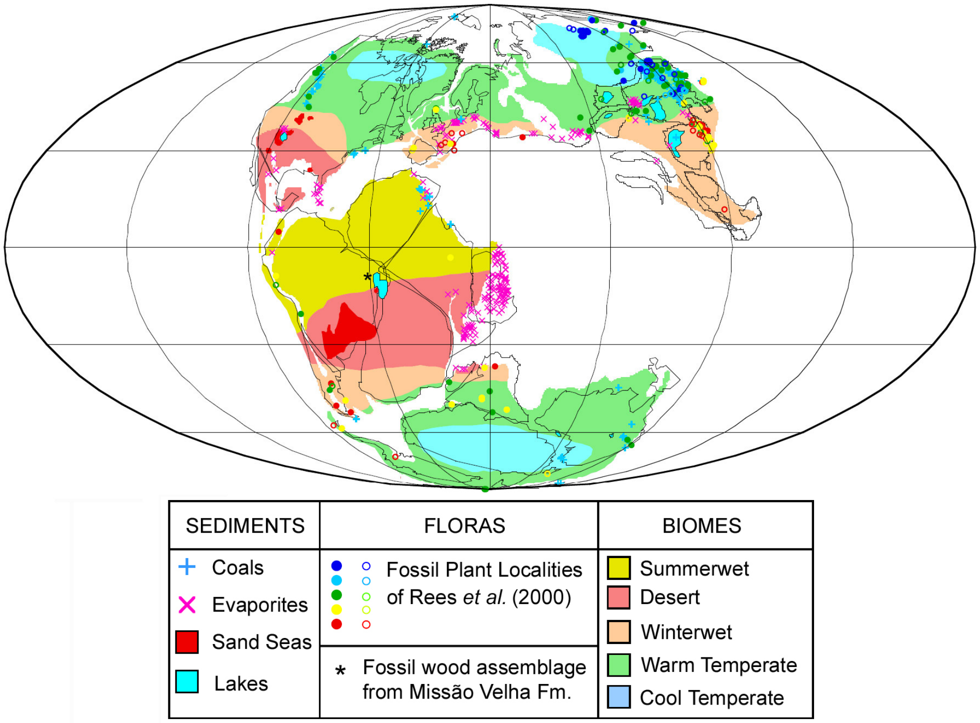

**Figure 11:** Palaeoclimatic map from the Jurassic-Cretaceous transition with the localization of fossil wood assemblage of Missão Velha Formation (modified by Rees et al., 2000).

| | Samples | Number of growth rings | Minimum ring width (mm) | Maximum ring width (mm) | Mean ring width (mm) | Mean sensitivity MS | Minimum annual sensitivity | Maximum annual sensitivity |
|---|---|---|---|---|---|---|---|---|
| 1 | PB 93 | 23 | 1.25 | 6.55 | 2.38 | 0.381 | 0 | 0.936 |
| 2 | PB 366 | 15 | 0.95 | 3.33 | 2.47 | 0.303 | 0 | 0.712 |
| 3 | PB 367 | 20 | 0.70 | 3.57 | 1.78 | 0.525 | 0 | 1.307 |
| 4 | PB 371 | 24 | 1.64 | 4.00 | 2.68 | 0.312 | 0 | 0.946 |
| 5 | PB 675 | 23 | 0.55 | 4.86 | 2.13 | 0.474 | 0 | 1.286 |
| 6 | PB 758 | 18 | 0.95 | 5.45 | 2.41 | 0.359 | 0 | 1.011 |
| 7 | PB 791 | 7 | 1.55 | 6.25 | 3.09 | 0.902 | 0.268 | 1.226 |
| 8 | PB 849 | 18 | 2.00 | 4.20 | 2.49 | *0.191* | 0 | 0.709 |
| 9 | PB 900 | 8 | 1.89 | 7.38 | 3.57 | 0.587 | 0.189 | 1.147 |
| 10 | PB 3826 | 22 | 0.86 | 3.86 | 1.82 | 0.334 | 0.038 | 0.943 |
| 11 | PB 3828 | 29 | 0.76 | 3.62 | 1.47 | 0.407 | 0.033 | 0.971 |
| 12 | PB 3836 | 20 | 0.54 | 3.57 | 1.61 | 0.546 | 0 | 1.125 |
| 13 | PB 3840 | 8 | 1.15 | 2.53 | 1.96 | 0.365 | 0.111 | 0.750 |
| 14 | PB 3854 | 17 | 0.97 | 3.35 | 1.55 | *0.262* | 0 | 0.660 |
| 15 | PB 3860 | 25 | 0.69 | 2.78 | 1.43 | 0.466 | 0 | 1.045 |
| Total/mean | | **277** | | | **2.19** | **0.427** | | |

**Table 1**: Results of growth rings analysis; complacent values in italic.

## 2.2. "Arthropod-plant interaction in Early Cretaceous (Berriasian) of the Araripe Basin – Brazil" – *Journal of South American Earth Sciences*

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## Abstract

Arthropod-plant interactions described in this report provide the first relevant data for addressing evidences of phytophagy in an assemblage of coniferous silicified woods from the pre-rift phase in Araripe Basin (Brazil). A complex boring system, filled sometimes with small, oval to hexagonal coprolites, allowed to infer activities of oribatid mites (Isoptera). Previous dendrological data defined the typical savanna climate during the Early Cretaceous on landmasses of northern Afro-Brazilian Depression, where termite boring activities are common.

Peculiarities of wood preservation show that the damage was probably caused by herbivores, not detritivores.

***Keywords***: Wood Boring, Oribatid, Equatorial Belt, Early Cretaceous, Araripe Basin - Brazil

## 1. INTRODUCTION

In the northeastern Brazilian interior basins, the sedimentary records of the pre-rift sequence occur in scattered exposures about 8° south of latitude (Fig. 1 (a, b and c)). They represent the remains of what once was a great shallow basin, the Afro-Brazilian Depression - ABD (Ponte, l972). The equatorial region of the South America-Africa landmass was included in the tropical-equatorial hot arid belt (Chumakov, 1995), largely arid, without evidence of sufficient moisture to have supported forests. Nevertheless, growth ring analyses (Fig. 2 (a, c, d and e)) in silicified coniferous woods from the Missão Velha Formation (Berriasian), Araripe Basin, conducted by Pires and Guerra-Sommer (unpublished data) have yielded important information about periodicity of wood production in the southern equatorial belt. Despite warm temperatures, dendrological data indicate that the climate was characterized by cyclical alternation of dry and rainy periods influenced by cyclical precipitation. These growth rings patterns are consistent with a tropical savanna climate condition during a greenhouse climate phase.

Evidences of arthropod attack can be seen by the naked eye all around the external surface of the vascular cylinder and also in cross sections of the coniferous silicified woods from Missão Velha Formation (Fig. 2 (b and c). Despite the large number of compression insect fauna preserved in the Santana Formation, which overlies the Missão Velha Formation and represents an important Fossil-Lagerstätten for the Aptian (Labandeira and Eble, 2006), an absence of arthropod-plant interaction has surprisingly been reported up to the present, making this occurrence a matter of great significance.

Wood bores are known in various groups among living arthropods. Beetles and termites are the most common, but ants, bees, wasps, moths, butterflies and mayflies may also take part in wood boring (Eaton and Hale, 1993; Grimaldi and Engel, 2004; Francis and Harland, 2006). Bores are common evidence of damage in fossil woods because highly lignified tissues of stems and branches tend to be very well preserved in the fossil record. Different bore patterns have been reported in woods from the Late Carboniferous to Tertiary age. Boucot (1990), Scott et al. (1992) and Labandeira et al. (1997) reviewed the literature and summarized the fossil record of wood borings.

In this study, evidence of a previously unknown arthropod-plant relations in Brazilian pre-rift phase is described with the main focus of: 1) to record the patterns of plant damage on fossil woods, 2) to obtain palaeocological information about wood-boring.

## 2. GEOLOGICAL SETTING

The Araripe Basin is the most extensive of the Brazilian northeastern interior basins, with an area of approximately 9,000 km$^2$, located on the boundary of Ceará, Pernambuco and Piauí states (7º02'-7º49' S and 38º30'-40º55' W). Together with the Recôncavo/Tucano-Jatobá and Rio do Peixe basins it constitutes the remnants of the Afro-Brazilian Depression.

The stratigraphic chart of Araripe Basin (Arai et al., 2004, and also the stratigraphic revision of the Lower Cretaceous of the interior basins of Northeast Brazil defined by Arai, 2006), indicates that the Missão Velha Formation ranges within the Upper Jurassic (Thitonian) - Lower Cretaceous (Berriasian). In the present study the designation “Missão Velha Formation” is used in accordance with the framework of Arai et al. (2004) represented in Fig. 3.

The wood bearing Grota Funda outcrop (UTM: 24M 0489727/9196725) lies 6 km east of Missão Velha city, bordering route 293 in Ceará state. The exposed sedimentary sequence is 4 m high and 30 m wide. This site exposes a prominent fluvial and aeolian facies, composed by a succession of medium-coarse sandstones with trough cross-bedding, interbedded with beds of trough cross-bedded conglomerates. Silicified woods are the exclusive fossils, and occur included in the coarse-grained sandstone or rolled, rarely as components of the conglomerates. The hipoautochtonous wood fragments at Grota Funda have a diameter from 5 cm to 1 m. Large dispersed fossil woods with uncompressed diameters of 0.50-1 m and lengths weathered out up to 3 m (Fig. 2 (a)) are also common in the sandstones or at the ground surface. The pieces of wood show no preferential orientation, and are not abraded, suggesting that they have not been transported far from their source.

## 3. WOOD DESCRIPTION

The wood is mostly silicified and light brown. Cell structure is well preserved in many of the samples. Growth rings are prominent in transverse section (Fig. 2 (c, d and e)); earlywood and latewood are clearly distinguishable (Fig. 4 (b)).

Formal taxonomic analyses were not developed in woods. Nevertheless, two gymnosperm wood xylotypes were recognized by Pires and Guerra-Sommer (unpublished data) based on parameters such as the size of earlywood tracheids in transverse section, patterns of radial pitting on tracheids and cross field pitting in radial section (xylotype 1- cupressoid/podocarpoid and xylotype 2- araucarioid). Main diagnostic features of these wood types are represented in Fig. 4.

## 4. MATERIAL AND METHODS

Mesoscopic analyses were developed in polished sections of hand specimens of wood; thin slides were made for optical observations in reflected, transmitted and differential interference contrast light. To study the frequency and the morphologic characteristics of borings, 15 specimens were observed; the structure and organization of the coprolites in selected specimens include slide numbers Pb 367-c Pb 675-a; Pb 675-c; Pb 677-b; Pb 785-a; Pb 785-b; Pb 785-c; Pb 849-b; Pb 849-c; Pb 3824-b; Pb 3824-c; Pb 3826-b; Pb 3826-c; Pb 3827-a; Pb 3828-a; Pb 3830-a; Pb 3846-a; Pb 3854-a. Small fragments have been directly mounted on the stubs for scanning electron microscope studies.

Al material is housed in the Paleobotany Sector, Departamento de Paleontologia e Estratigrafia of the Univesidade Federal do Grande do Sul, Porto Alegre and in the Paleontological sector of the Departamento de Geologia Instituto de Geociências, Universidade Federal do Rio de Janeiro, Brazil.

## 5. EVIDENCE OF ARTHROPOD-PLANT INTERACTIONS

### *5.1. Borings*

The bores are easily recognizable in the woods as empty, scattered features, randomly distributed in the outer surface of the specimens, of various sizes and shapes from 2 to 5 mm diameter (Fig. 5 (a)). Anatomical analyses evidenced that the smallest elliptical features correspond to original invertebrate bores (Fig. 5 (b)) whereas the larger holes, irregular in shape (Fig.5a (d1,c1)) correspond to regions of collapsed walls of internal axial borings.

The small surface holes (1-2 mm long) are regularly oval shaped and represent the opening of tunnels that bend upwards in the xylem (Figs. 2 (b) and 5 (d2)). In cross section (Fig. 5 (a) and Fig. 6 (a)) this axial tunnels have nearly circular diameter (1 to 2 mm) but lateral coalescence between adjacent tunnels is also observed (Fig. 5 (c)). The dispersion pattern of the borings follow the curvature of growth rings and seem to be controlled by the evolution of the secondary xylem (Figs. 2 (c) and 5 (a)). In radial sections most tunnels are slightly less than 1 mm in diameter. All are straight and appear to be unbranched; usually they are isolated with some distance apart from each other (Fig. 5a (b1) and 5b). In tangential section, the lateral coalescence of axial tunnels is also evidenced. Consequently, their diameter is highly variable, with some of only 1 mm width and others of over 5 mm (Fig. 5a (e1) and 5e). The vertical extent of this axial borings is unknown but they have been observed in a limited section of 5 cm of the xylem. Irregular clusters of interconnected tunnels, with different orientation are also observed (Fig. 5 (c and d). Integration between different wood sections evidenced that tunnels follow mainly the grain and run through the wood more or less along tangential orientation, although transversal tunnels were also observed. By the naked eye, their lumens are sometimes filled with structureless matter, stuck together but still silicified, clearly distinguished from the structured xylem tissue (Fig. 5 (d and e, arrows).

Under optic microscopic magnification, in cross section, the walls of the tracheid that boarded the borings have been gnawed, (Fig. 6 (b and c), sometimes leaving behind remnants of the cell wall into the borings. In some places, tunnels are bordered by a narrow dark outer band and a wide inner area, which is thought to be necrotic tissue cavities (Fig. 6 (a)). This evidence and the presence of resiniferous tracheids in some xylem areas (Fig. 4 (a)) can be correlated with processes occurring in extant plants with secretors systems which act as strong barriers against external attack (Farrel et al., 1991).

Even though several tunnels are empty, some of them contain dark, fairly hexagonal bodies (Figs. 6 (c, d) and 7 (c, d), which are herein identified as arthropod coprolites by their similarities with fecal pellets produced by living phytophageous arthropods (Scott and Taylor, 1983) and with similar fossil accepted as such (Zhou Zhiyan and Zhang Bole, 1989; Rogers, 1938; Rhor et al., 1986; Goth and Wilde, 1992; Ash, 2000; Kellogg and Taylor, 2004).

### *5.2. Coprolites*

Typically the coprolites occur within the tunnels in both rather compact masses, highly silicified (Figs. 5 (d, e) and 7 (a, b)) and as individual pellets, mainly at the margins of the borings (Fig. 8); the original shape of coprolites is shown sometimes as external hexagonal molds produced by cementation (*sensu* Schopf, 1975) as represented in Fig. 6 (b, arrows). Individual fecal pellets are evidenced along of borings (Figs. 7 and 8 (c, d)). They are irregularly circular to oval in longitudinal view, with a fairly regular outline and range from 70 to 320 µm in length (Figs. 6 (c, d) and 7 (c, d, arrows)). In transverse section they are hexagonal and most are 160 to 230 µm in diameter (Fig. 7 (c, d, arrows)). In addition to inside the tunnels, fecal pellets are also seen scattered in different sections of the xylem (Fig. 6 (d)). They are typically dark in color and have no recognizable plant tissues, but in a few places they are unusually thin and some bits of unidentifiable matter can be observed (Fig. 6 (c)).

## 6. DISCUSSION

### *6.1. Timing of the boring*

The abundance of borings all around the external surface of bigger uncompressed stems (about 1m diameter – Fig. 2 (a)), suggests that the entire external surface was accessible to the insects, and not lying on the ground or partially buried. This evidence indicates that damage was produced during the life cycle of the plant**.** On the other hand, the presence of necrotic tissue in the tunnel boundaries could evidence that the stem was living when attacked. Taking into account the severe climatic conditions prevailing during the life cycle of the wood assemblage, it could be considered the hypothesis of characterizing the wood boring arthropods as secondary invaders, during severe droughts. They attack only after a plant has been weakened by another stressing condition, and are symptom of other problems with the health of the tree, but may contribute to its decline (Drees et al., 2006).

### *6.2. Identification of the borer*

The three-dimensional preservation of complex wood boring-system formed by cavities of various shapes and sizes shows evidence of organic infestation. The process of damage is characterized mainly by an axial orientation of the burrowing behavior associated to both irregular patterns of lateral coalescence and clustering of tunnels with different orientation. The preferential locus of damage, parallel to ring development (Figs. 2(c) and 5(a)), indicates the feeding preference of the boring organisms, being the secondary vascular tissue the principal food source.

Wood bores are known in various Orders among living insects, particularly in Coleoptera, such as in Buprestidae, Lyctidae, Anoiidae, Bostrychidae, Scolytidade, Ipidae and Ceramycoidea (Grimaldi and Egel, 2004). Beetles are more diverse, but oribatid mites also bore and eat wood, and are the most ecologically significant group that excavates wood (Grimaldi and Engel, 2004). In the fossil record, boring galleries are described from the Late Carboniferous (Scott and Taylor, 1983, Cichan and Taylor, 1982). Most of them are believed to be produced by beetles such as Anobiidae (Link, 1949; Ash and Savidge, 2004), Scolytidae (Chamberlain, 1958; Wood, 1973, 1982 and 1986; Labandeira et al., 2001) Cerambycidae (Tidwell and Ash, 1990) and Bubrestidae (Genise and Hazeldine, 1995).

Damage on wood by beetles tends to be carried out in the larval stage, forming tunnels and galleries with a wide range of sizes. The boring systems are organized according peculiar feeding strategies and present almost regular morphologies corresponding to exit holes and individual tunnels. In this case study, the absence of any evidence of that organization excludes the possibility that wood bores were beetles.

The morphological features (size, shape and surface texture) of the coprolites found in the tunnels, according the criteria of Labandeira et al. (2007), are within the size range produced by oribatid mites. The presence of extant organisms with similar wood boring strategy reinforces comparative analyses. The shape of the present material is very similar to those coprolites described by Ash and Savidge (2004) for the Triassic of Arizona and with fecal pellets described by Francis and Harland (2006) for Isle of Wight, UK.

The different size classes of coprolites found in wood samples were attributed by Zhou Zhiyan and Zhang Bole (1989) to distinct maturity stages of a coleopteran insect boring activity in *Protocupressinoxylon*, a conifer from the Middle Jurassic of China. Nevertheless, Kellogg and Taylor (2004), utilizing criteria of Labandeira et al. (1997) and Bal (1970) inferred that both of the size classes described by Zhou Zhiyan and Zhang Bole (1989)were probably produced by oribatid mites.

The order Isoptera is known from the Early Cretaceous by wing impressions of the species *Valditermes brenanae* (family Mastotermitidae) found in Weald Clay by Jarzermbowsky (1990). There is evidence that extinct martotermes were highly phytophagous, like the living species (Grimaldi and Eggel, 2004). The primitive venation pattern of *Valditermes brenanae* wings led Thorne et al. (2000) to conclude that termites evolved during the Late Jurassic/Early Cretaceous. The oldest termite genus *Meiatermes*, (Hodotermitidae) is also recorded in Santana Formation (Aptian-Albian) from Araripe Basin (Brazil) by the genus *Meiatermes araripina*. According to Grimaldi and Eggel (2004) the Cretaceous hodotermitids must have foraged on herbaceous and probably even woody vascular plants. Fossil remains of nests of putative "dry wood termites" (Kalodermitidae) are registered in a wood section from the Late Cretaceous of Western Texas (Rhor et al., 1986). The primitive features of the genus *Archeorhinotermes rossi* (Rhinotermitidae) from the Early Cretaceous of Burmese ambar, which generally feed on rooting wood in extant floras, led Krishna and Grimaldi (2003) to consider unlikely the hypothesis of Emerson (1971) that modern rhinotermitid originated in Late Cretaceous. The "higher termites" (Termitidae) are a very young group, with the oldest fossils occurring in the Eocene. These termites have wood as a minor part of their diet, and where it is consumed it is decayed by fungal mycelia (Grimaldi and Engel, 2004).

Nevertheless, putative termite nests are described for the Triassic Chinle Formation (Hasiotis, 2003; Hasiotis and Dubiel, 1995; Ash, 2000) and by Kellogg and Taylor (2004) from three localities in the Central Transantartic Mountains, ranging from Permian to Triassic. Nevertheless, Genise (2004) and Grimaldi and Engel (2004) are skeptical of all records of Pre-Cretaceous termites.

Features of the borings and fecal pellets from wood described from the Early Cretaceous Wessex Formation (Barremian) Isle of Wight, described by Francis and Harland (2006) are considered as the oldest evidence of termites. Examples of boring activities within wood in Cretaceous and Neogene attributed to termites mainly by the hexagonal fecal pellets are given by different authors in Table 2. Nevertheless the size of the pellets is considerably larger than the material studied here.

The distinct hexagonal shape of the fecal pellets and their clustering in boring systems comparable with previous described material, summarized in Table 1, indicate affinities of the material here analyzed with termite infestation in woods. Nevertheless, the tunnel system and the coprolites described herein are not sufficient diagnostic to hypothesize taxonomic affinities for the boring termites.

Taking into account the patterns of damage shown by the fossil woods, the arthropod infestation could be assigned to the ichnogenus *Paleosclolytus* of Jarzembowsky (1990) described from borings in fossil woods from the Early Cretaceous in England. According to the standardized description of Genise (1995) for arthropod traces in plants, the present attack evidences should be included in the ichnogenus *Xylonichnus*, a stem boring trace occurring in conifer branches.

## 7. PALAEOENVIRONMENTAL, PALAEOCLIMATIC AND STRATIGRAPHIC IMPLICATIONS

Climatic inferences of Pires and Guerra-Sommer (unpublished data) suggest for the northern part of the equatorial Afro-Brazilian Depression at the Jurassic-Cretaceous boundary extreme climatic events, identifiable as a wood savanna type of climate. In that summer wet climatic belt, at low latitude (approximately 8° south, Fig. 9), coniferous trees are characterized as plants probably growing in low-diversity stands (Rees et al., 2000). Such palaeoclimatic variables associated to the climax of greenhouse conditions and increasing atmospheric $CO_2$ were particularly suitable for termites. Peculiarities of wood preservation seem to show that the damage documented here was probably caused by herbivores, not detritivores.

As the order Isoptera is known no earlier than Early Cretaceous (Grimaldi and Engel, 2004; Francis and Harland, 2006), evidence for termite activities during the Missão Velha Formation deposition ratifies an Early Cretaceous deposition, in agreement with previous data of Arai et al. (2004) and Arai (2006), at least for the studied stratigraphic interval.

## 8. ACKNOWLEDGEMENTS

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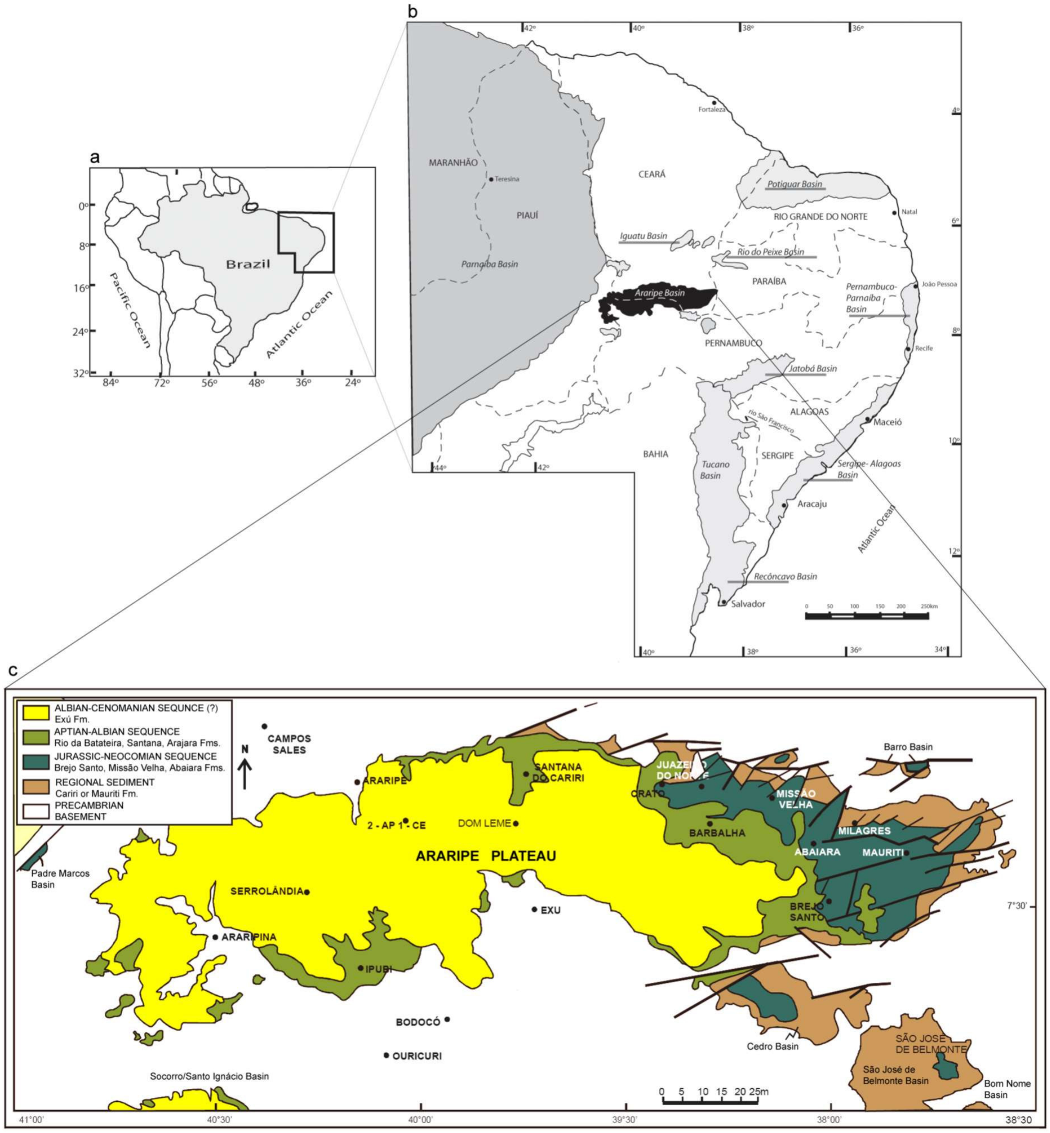

**Figure 1:** Location of the studied area; (a) map of Brazil; (b) map of northeastern Brazil showing the location of Araripe Basin and the interior basins of the northeast of Brazil; (c) geographic delimitation of Araripe Basin different units.

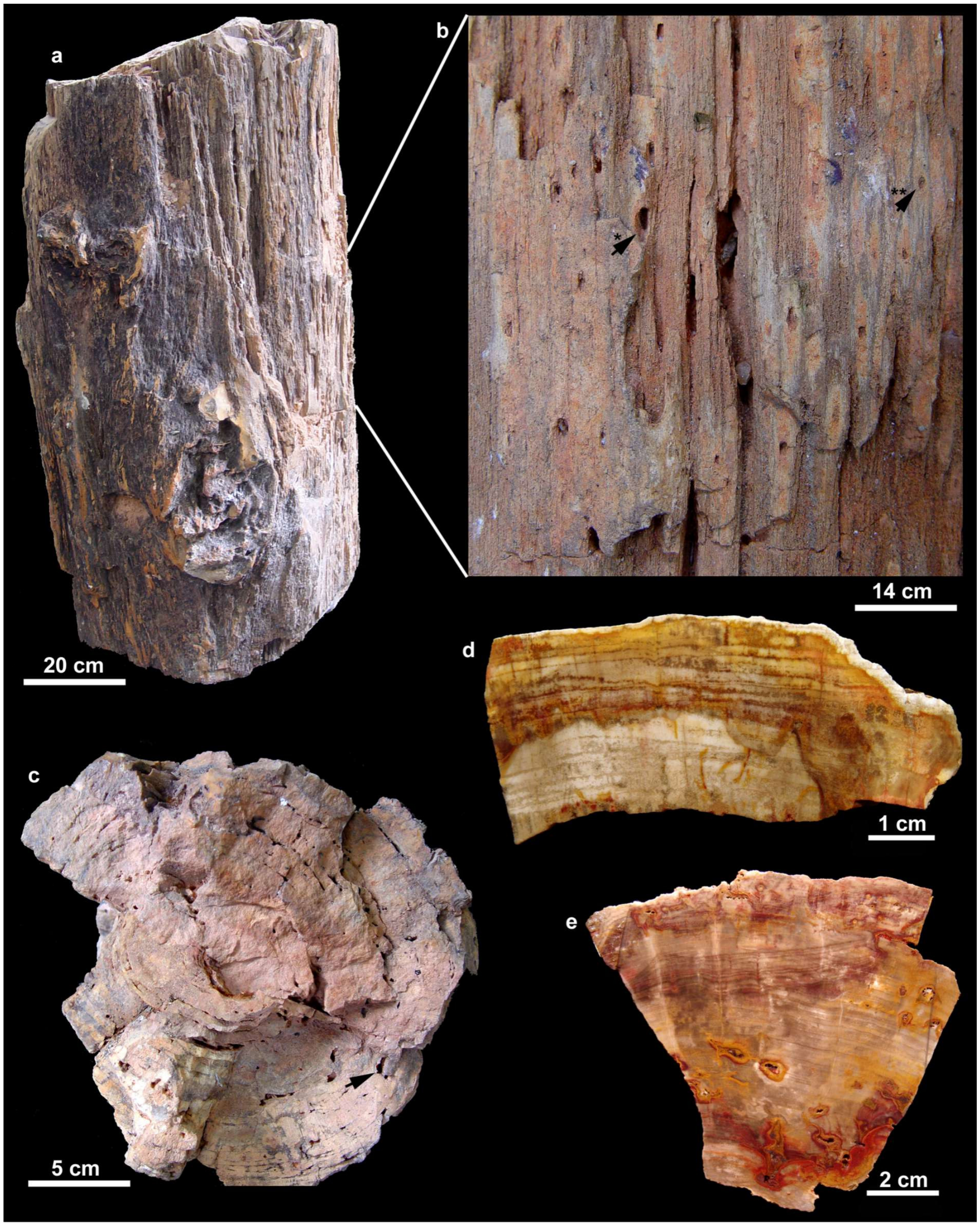

**Figure 2:** (a) Large permineralized trunk from the Grota Funda outcrop; (b) detail of the outer surface showing the smallest elliptical features (*) corresponding to invertebrate bores and large holes (**), irregular in shape, corresponding to regions of collapsed walls of internal borings; (c) cross section of large permineralized wood, showing tree ring boundaries and circular to irregular diameter of axial tunnels, following the curvature of growth rings; (d) and (e) polished cross sections of secondary wood of different samples showing growth ring pattern.

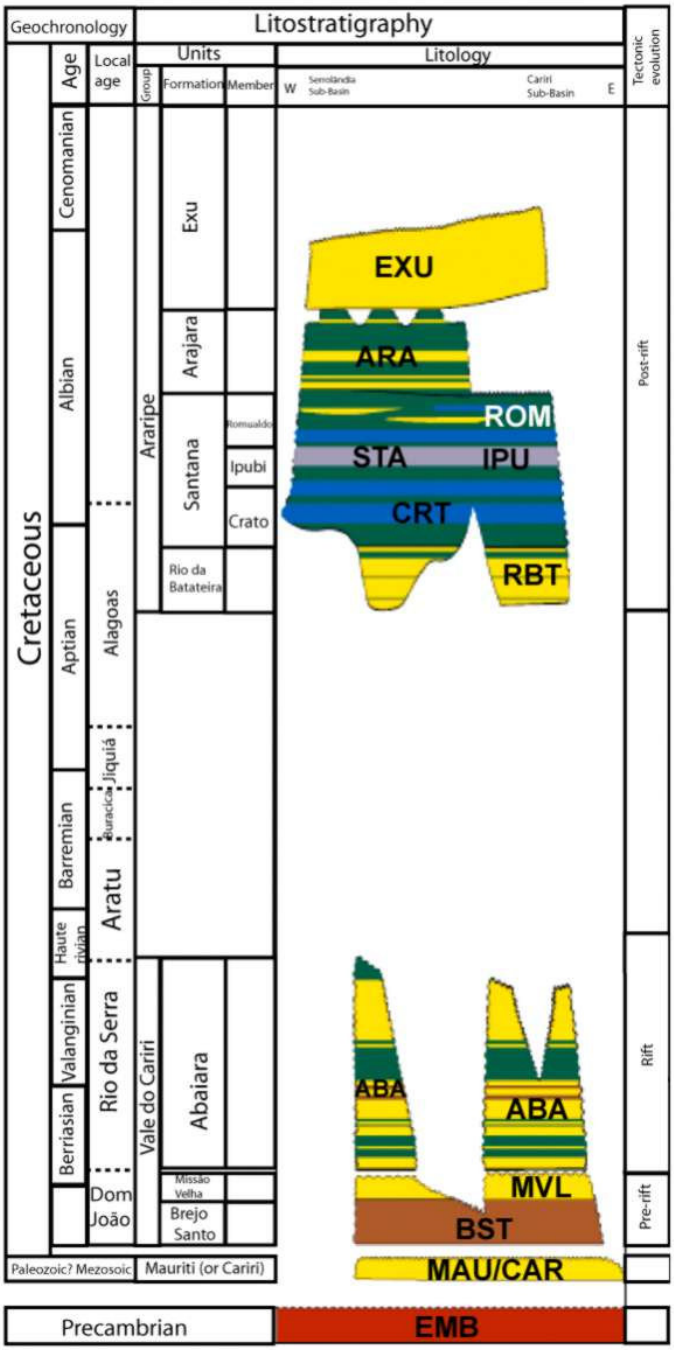

**Figure 3**: Stratigraphic column of the Araripe Basin (modified from Arai et al., 2004).

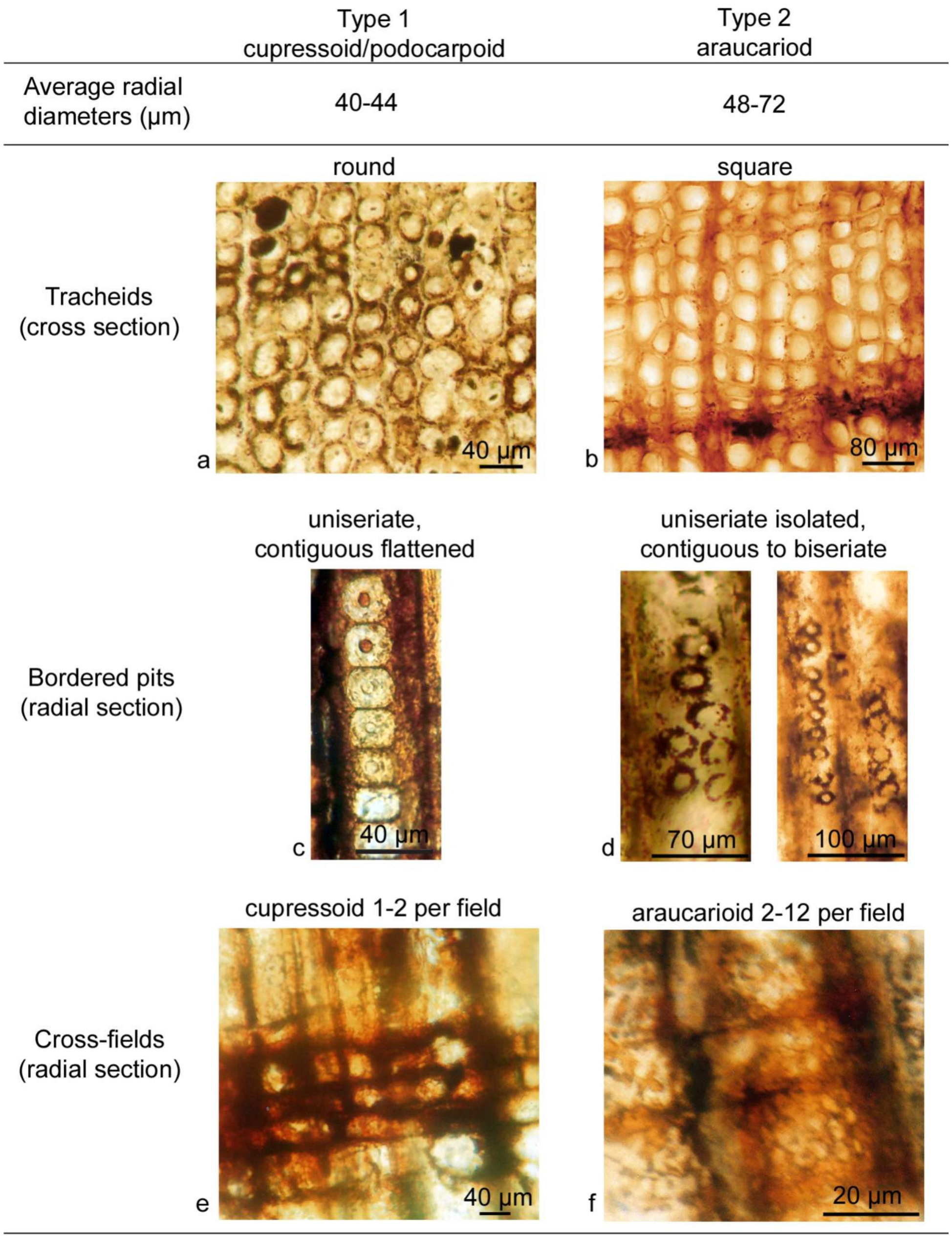

**Figure 4**: Diagnostic anatomical patterns found in xylotypes 1 and 2 from Grota Funda outcrop.

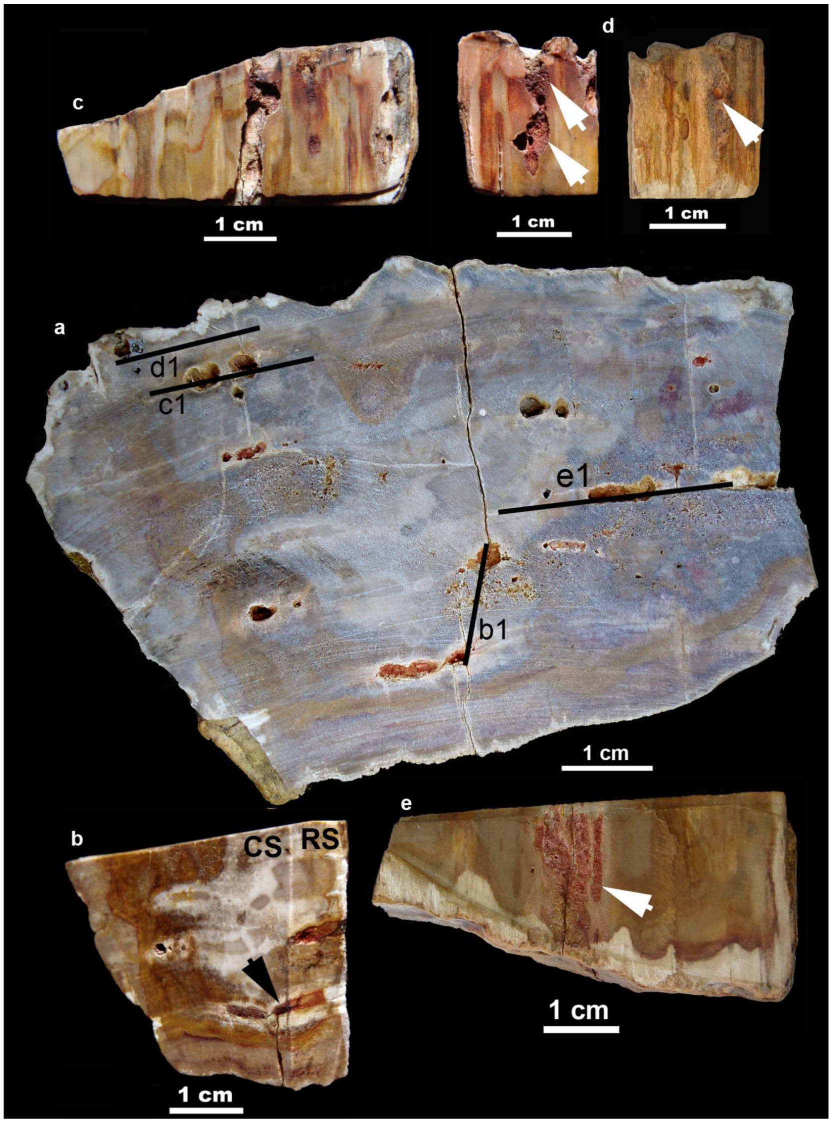

**Figure 5**: Three-dimensional preservation of wood boring-system; (a) cross section of secondary wood evidencing circular to elongate diameter of axial tunnels; (b) and (b1) radial section evidencing the axial, unbranched morphology of tunnels (cs= cross section; rs= radial section); (c), (c1), (d) and (d1): tangential sections showing irregular clusters of interconnected tunnels, with different orientation and lumens partially filled with structureless matter distinguished from the structured xylem tissue; (d) outer surface with small elliptical borings; (e) tangential section showing the lateral coalescence of axial tunnels.

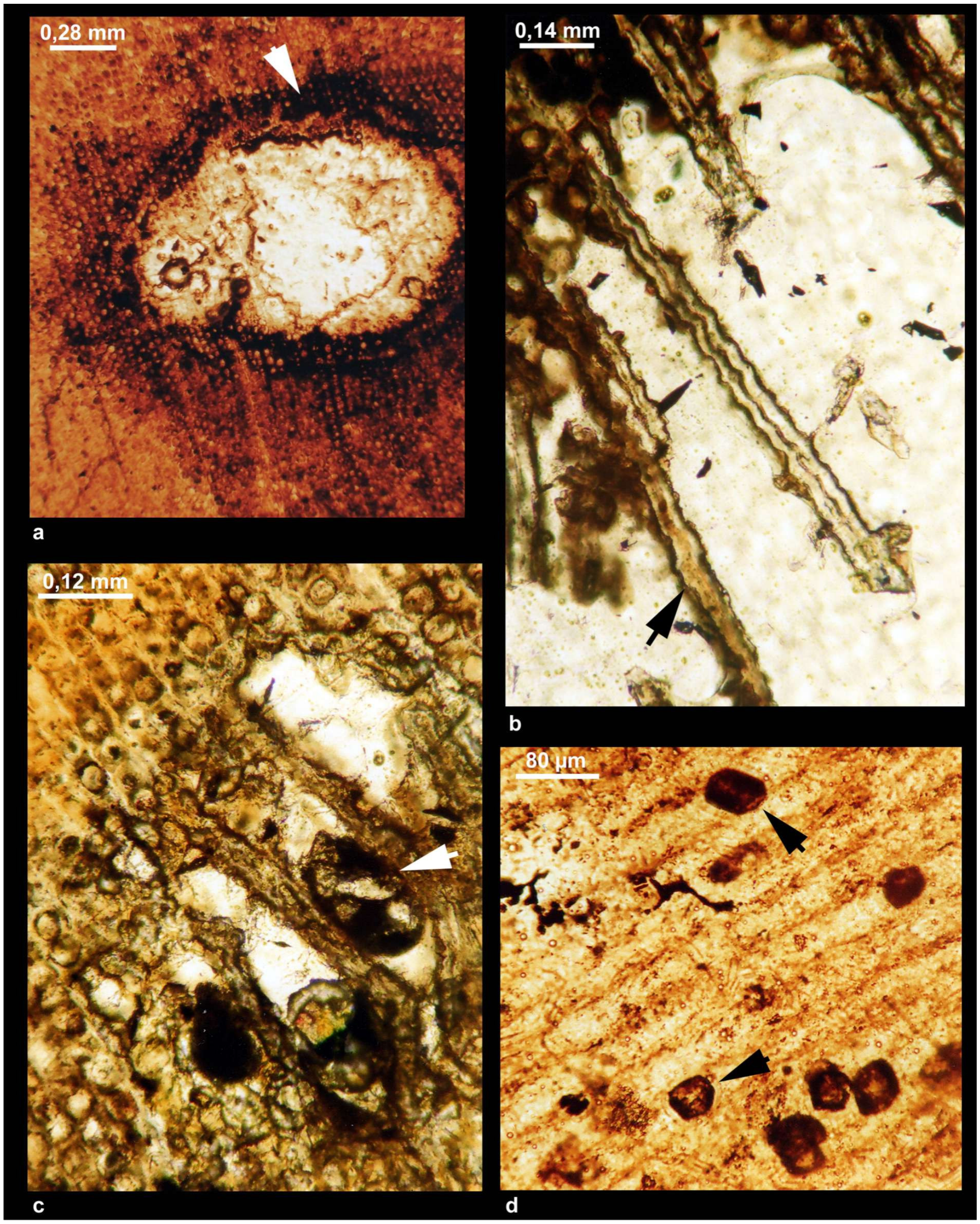

**Figure 6**: (a) cross section of a tunnel bordered by necrotic tissue (arrow), observed under optical microscope; (b) damaged xylem tissue bordering the boring; (c) fecal pellet (?) inside a gallery showing macerate organic matter (d) fecal pellets scattered in the xylem.

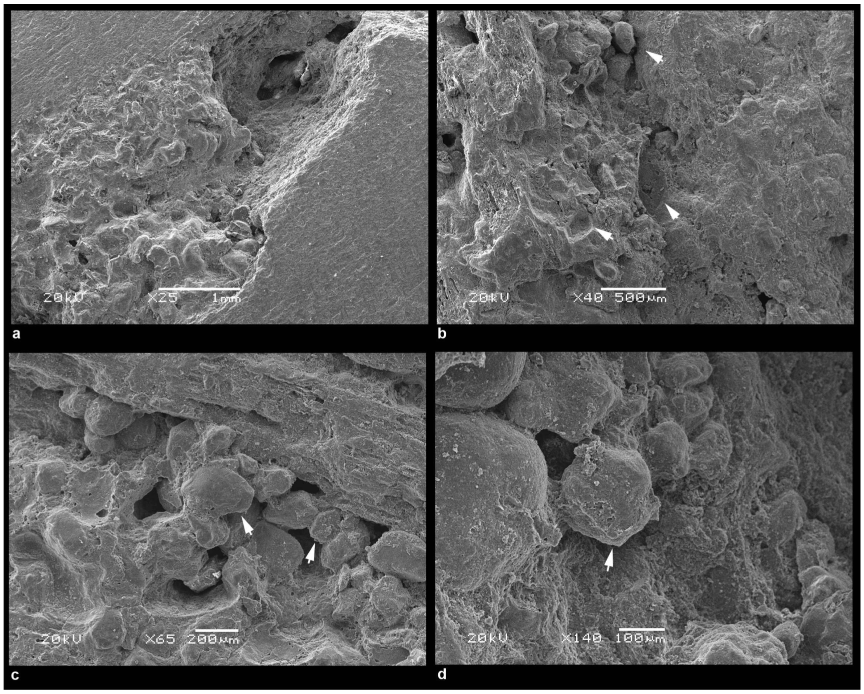

**Figure 7**: scanning electron micrographs of tunnels; (a) coprolites within the tunnels in rather compact, highly silicified masses; (b) original shape of coprolites shown as external hexagonal molds, produced by cementation (*sensu* Schopf, 1975); (c) and (d) individual fecal pellets: circular (*), irregularly ovoid (**), with hexagonal cross section (arrows) evidenced along the side of borings.

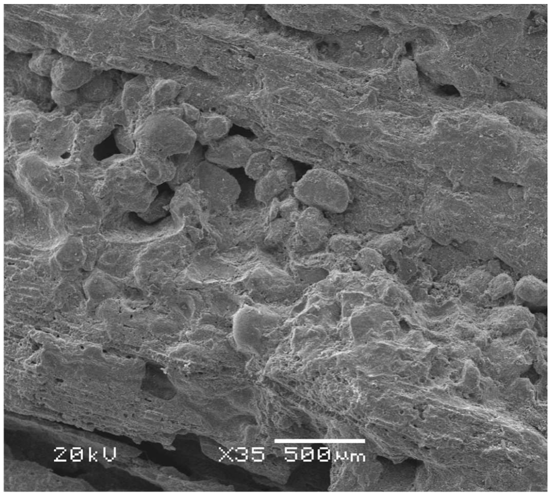

**Figure 8**: scanning electron micrograph of a tunnel's lumen showing compact, highly silicified masses in the center and well preserved fecal pellets at the border.

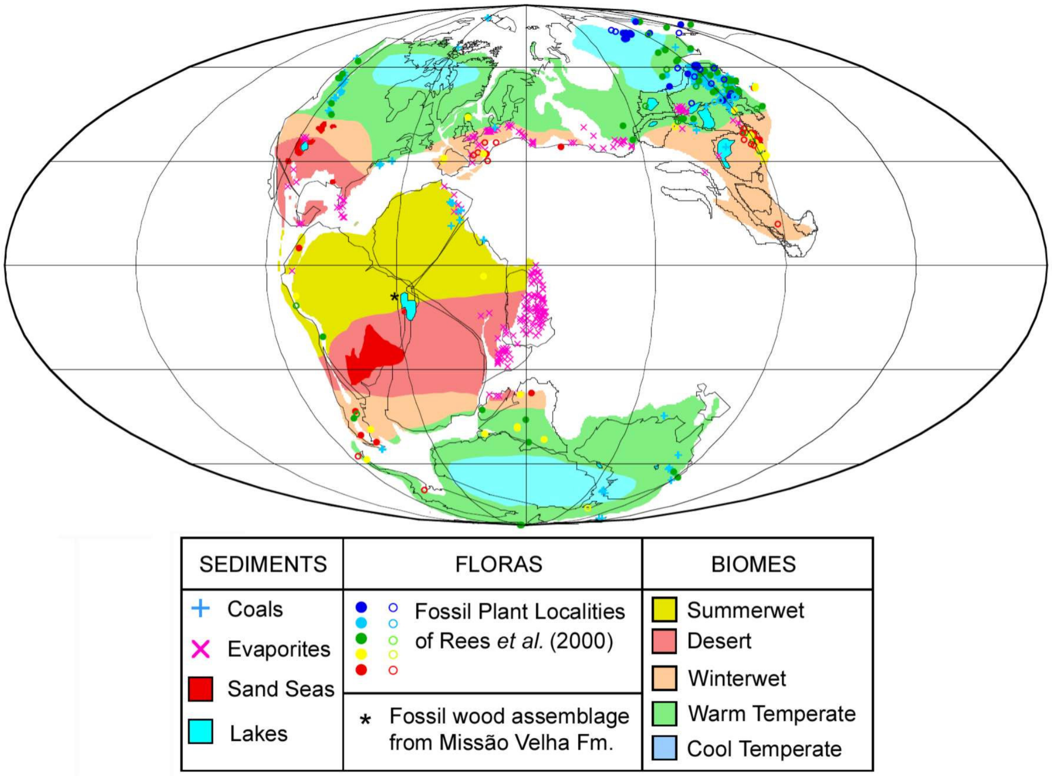

**Figure 9:** Late Jurassic/Early Cretaceous palaeogeographic map by Rees et al. (2000) showing different global climatic zones or biomes. * indicates fossil wood assemblage of Missão Velha Formation.

| | Possible coprolite producers | | | | | |
|---|---|---|---|---|---|---|
| Defining criteria | Oribatid mites | Insects (adults) | Insects (larvae) | Collembolans | Diplopods | Enchytraeid worms |
| Size: 50-260 µm | * | | * | * | | * |
| Shape: Spherical to avoid | * | | | | | |
| Surface texture: Smooth | * | * | * | | | |
| Contents:Fairly densely compacted; few recognizable elements | * | * | * | | | |
| Known wood borer | * | * | * | | * | |

**Table 1**: Characteristics of mites and their coprolites, compared to those produced by other arthropods (modified by Kellogg and Taylor, 2004)

| Author | Age | Procedence | Cross Section | Long X Wide (µ) |
|---|---|---|---|---|
| Francis and Harland, 2006 | Early Cretaceous | UK | Hexagonal | 400-600 x 400-500 |
| Rohr *et al.*, 1986 | Late Cretaceous | Texas | Subhexagonal | 750 x 500 |
| Rogers, 1938 | Pliocene | EEUU | Hexagonal | 700-900 x 300-500 |
| Rozefeld and DeBaar, 1991 | Tertiary | Australia | Hexagonal | 2000-2600 x 800-1000 |
| This paper | Early Cretaceous | Brazil | Hexagonal | 70-320 x 160-230 |

**Table 2**: Different sizes of putative termite fecal pellets from the Mesozoic and Cenozoic.

## 2.3. "Early Cretaceous coniferous wood assemblage from an arid desert biome (Botucatu Formation, Paraná Basin, Brazil): Dendrological parameters and their relation to paleoclimatic data" – *Gondwana Research*

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[b] Guerra-Sommer, Margot

[c] Scherer, Claiton Marlon dos Santos

[d] Santos, Adriano Rodrigues dos

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## Abstract

An Early Cretaceous coniferous wood association, showing affinities with extant Pinaceae, from northern portion of the Botucatu Formation (Paraná Basin, Brazil) is an evidence of some humidity under arid conditions prevailing in a desert biome. Dendrological analysis for the monotypic wood assemblage indicated that growing conditions were seasonal, but most stressed during the life cycle. Quantitative parameters controlling growth ring development might be highly related with environmental characters and not only a single consequence of climate. Taxonomic and physiologic parameters were decisive as a response to environmental constrains. The conifer assemblage was developed during the climax of a greenhouse phase with increasing atmospheric $CO_2$ and has no modern analogs in present “icehouse” world.

**Keywords:** Dendrology, Early Cretaceous, Equatorial Belt, Aeolian Sandstones.

## 1 - INTRODUCTION

During the Cretaceous, the configuration of the continents changed from the prevailing Mesozoic pattern of two supercontinents (Laurasia and Gondwana) straddling an equatorial ocean (Thetys), to one with several continents separated by oceans, which extends into high latitudes. Different geological clues evidence that this period can be characterized as an extreme greenhouse interval, with diverse biota scattered across a variegated mosaic of land, shallow sea and ocean.

In the Early Cretaceous the South America-Africa landmass were included in the Tropical – Equatorial Hot arid belt (Chumakov, 1995), or in the Arid climatic belt according the paleoclimatic map of Scotese (2003) without evidence of sufficient moisture to have supported rainforests.

Nevertheless, as it was shown by Doyle et al. (1982), Frakes et al. (1992) and Vakhramev (1991), conditions were not monotonously equable, and the Cretaceous climate was marked by distinct latitudinal provinces. Generalized temperature curve of Martin (1995) estimates for this interval a climatic cool-warm interval during the evolution of a greenhouse phase. The Southern Hemisphere was hotter and more arid than the Northern Hemisphere that was characterized by a climate seasonally dry and monsoonal. From combined floral and lithological data, Rees et al. (2000) established a palaeoclimate modeling from the Jurassic, recognizing five main biomes, from the basal Jurassic to the Jurassic-Cretaceous boundary; in frameworks from different age-intervals, low latitudes are seasonally dry.

Otherwise, dendroclimatic studies of Pires and Guerra Sommer (unpublished data) have yielded important qualitative and quantitative information about periodicity of wood production during the early Early Cretaceous (Berriasian) in the equatorial belt. The wood association was developed during the deposition of a great shallow basin, the Afro-Brasilian Depression (Missão Velha Formation, Araripe Basin). Despite warm temperatures, at this low latitude (more or less 8°S) dendrological data indicates that the climate was characterized by cyclical alternation of dry and rainy periods influenced by cyclical precipitations. Otherwise, the climatic seasonality did not have homogeneous rhythm, originated probably by year to year variability characterized by frequent disturbances in rainfall. The patterns of growth rings were considered as consistent with a tropical savanna climate, included a summer-wet biome of Rees et al. (2000) during a greenhouse climate phase.

During the Tithonian-Berriasian, the fragmentation of Gondwana was intensified. While rift basins formed in the southern and northeastern portions of South America, a wide topographic area of a cratonic basin (Paraná Basin) accumulated a thick packaged of aeolian dune deposits (Scherer and Goldberg, 2007). The Botucatu Formation accumulation at the southern part of the basin represents, according to Scherer and Lavina (2006) a period of climate stability associated with hyper arid conditions.

Vertebrate and invertebrates ichnofossils are common in the northeastern and northwestern parts of the basin. The terapod tracks comprise an endemic fauna of bipedal dinossauroids of larger and smaller types, theropodian and ornithopodian, along with theromorphoid and mammalian forms (Leonardi et al., 2007). Given that these animals would require water, this does at least indicate that the region was not an extreme desert and that fresh water may have been present as streams and lakes, thought possibly ephemeral.

Radiometric dating (Ar/Ar) obtained in the basalts of superjacent Serra Geral Formation obtained an age of 136.6 ± 1.5 m.y. to 130.8 ± 0.60 m.y. (Onstott et al., 1993). Additionally Turner et al. (1994) obtained an age of 137 ± 0.7 m.y. for the oldest volcanic rocks. Taking into account the stratigraphic chart of Gradstein and Ogg (2004), these data suggest an Early Cretaceous age for the termination of accumulation in the subjacent Botucatu Formation.

The present investigation documents the record of an assemblage of large prostate silicified logs that occur at high densities in an outcrop of the Botucatu Formation, interbedded in basaltic levels at the northeastern part of the Paraná Basin (Minas Gerais State). Well preserved growth rings in permineralized conifer trunks indicate water availability and seasonality in growing conditions.

Taking into account the available data and its effect on the model for climatic evolution of the Botucatu Formation of Paraná basin at the Early Cretaceous, the aim of the present contribution is to: 1. record the presence of a hipoauthoctonous-authoctonous wood assemblage; 2. document dendrological analysis of growth rings, 3. offer paleoclimatic inferences based in growth ring analyses; 4. accurate previous palaeoclimatic interpretations for the studied interval.

## 2 – PALAEOGEOGRAPHIC AND GEOLOGICAL SETTING

The Jurassic was characterized by the fragmentation of Pangea. In the Late Jurassic to Early Cretaceous, the separation between Gondwana and Laurasia was well in progress, and a wide ocean had already developed between those continents (Scotese, 2003). Moreover, the eustatic sea level was high during this time interval, flooding large areas of Laurasia and allowing the development of extensive epicontinental seas. In Gondwana, however, marine deposits apparently formed only at the west margin along a narrow strip of the retro arch region of the Andes, while the continental interior displayed exclusively continental sedimentation. The absence of epicontinental seas on inland Gondwana is a result of the continental palaeotopography. A wide plateau with an elevation in excess of 100 m developed due to the high thermal flux, and consequently high continental freeboard, analogous to that observed in Africa today (Worsley et al., 1984).

The period between the end of the Jurassic and the beginning of the Cretaceous was characterized by the fragmentation of the Gondwana, with the development of continental rift systems, leading to the formation of the South Atlantic. Rift basins were formed in the southern and northeastern portions of South America, and a wide intracratonic area, known as Paraná Basin, accumulated a thick package of aeolian dune deposits.

The Paraná Basin (1.700.000 km$^2$) (Fig. 1), located in southeast South America, has six depositional supersequences (Milani, 2004) originated by second order eustatic and tectonic events. These supersequences, detailed in figure 2, from base to top are: 1) Rio Ivaí (Ordovician - Silurian), 2) Paraná (Devonian), 3) Gondwana I (Carboniferous - Early Triassic), 4) Gondwana II (Late Triassic), 5) Gondwana III (Jurassic - Early Cretaceous), 6) Bauru (Late Cretaceous). The Gondwana III (Jurassic - Early Cretaceous) supersequence comprises the basal Botucatu Formation, object of the present study, and the overlain 300 to 800 m thick succession of volcanic rocks of the Serra Geral Formation.

The Botucatu Formation consists of aeolian sandstones that crop out along the borders of Paraná Basin. The Botucatu paleoerg stretched out to the southwest. In Uruguay, the aeolian package is called the Riveira Formation (Ferrando and Montana, 1988) whereas in Argentina (Chaco – Paraná Basin) it is known as the San Cristobal Formation (Padula and Migramm, 1969; Pezzi, and Mozetic, 1989; Garrazino, 1995). At western portion of the basin, the sandstones of Botucatu Formation are map able into the Paraguay, where they are called the Missiones Formation (Cleriei et al., 1986). The northern and northeastern limits of the Botucatu outcrop area are located in Mato Grosso, Goiás and Minas Gerais states in Brazil. The issue whether these limits are erosive or depositional remains unclear (Bigarella, 1979). A transgression of the aeolian sediments of the Botucatu Formation directly over Pre-

Cambrian lithologies in the region of Estrela do Sul e Monte Carmelo, Uberlândia e Tupaciguara (Minas Gerais State), was observe by Hasui (1969). There is no evidence of a physical continuity between the “Botucatu Basin” and the rift basins in northeastern Brazil, which suggests that topographic highs physically separated the aeolian sandstones of the Botucatu Formation from the rift basins.

The Botucatu Formation is defined at the base by a regional unconformity that can be traced across the entire basin (Milani et al., 1998). It is composed of dominantly aeolian deposits, represented by large scale sets of cross-strata (1-30 m) interpreted as aeolian dune deposits (Almeida, 1954, Bigarella and Salamuni, 1961). The lowermost deposits immediately above de basal contact locally contain conglomerates and gravelly sandstones deposited by ephemeral streams, as well as coarse-grained sandstones interpreted as aeolian sand sheets deposits (Bigarella and Salamuni, 1961; Soares, 1975; Almeida and Melo, 1981; Scherer, 2002). The thickness of Botucatu Formation varies from 0 to 800 m, the greatest thickness occurring in the northwestern portion of Paraná Basin (Milani, 1997). Lava flows covered the previously active aeolian dunes in the erg, thereby entirely preserving their morphologies (Scherer, 2002).

The onset of sedimentation in the Botucatu Formation is mainly inferred by vertebrate ichnofossils (Bonaparte, 1996; Leonardi et al., 2007) suggesting an age of Late Jurassic–Early Cretaceous. Otherwise, Scherer (2000), based in the intimate relation between the aeolian sandstones and lava flow deposits and the lack of regional unconformities indicates a shorter time interval, latest Jurassic, for the onset of the aeolian sedimentation.

Radiometric dating (Ar/Ar) has previously been carried out in volcanic rock samples of the Serra Geral Formation, which overlays Botucatu Formation, in the Alto Piquiri well (Onstott et al., 1993). The resulting ages span a range from 136.6 ± 1.5 m.y. to 130.8 my. Additionally, Turner et al. (1994) obtained an age of 137 ± 0.7 my for the oldest volcanic rocks, which suggests an earliest Cretaceous age for the termination of aeolian accumulation in the Botucatu Formation. Roisenberg (2000) and Scherer and Lavina (2006), based on several radiometric dating (Turner et al., 1994; Steward et al., 1996; Renee et al., 1996) yielding an age range from 138 to 128 m.y. for the deposition of Serra Geral volcanic rocks in the Rio Grande do Sul and Paraná States. Holz et al.

(2007) asserts that a mean value of 132 m.y. supplies a reliable chronological reference for the end of the Botucatu sedimentation. The 10 m.y. spread of numerical ages may reflect, according Holz et al. (2007) the difference from the earliest to the latest flows in a thick basalt pile in the central part of the basin. This indicates that in different parts of the basin the onset of the lava flows may have happened in different times.

Scherer and Goldberg (2007) interpreted the direction of the sediment transport in the aeolian sandstones of the Botucatu Formation on the basis of cross strata dip directions which allowed the reconstruction of regional wind patterns in middle - western Gondwana. Regionally, cross strata dip directions indicate variations of paleowind directions across the outcrop area of the Botucatu paleoerg. The northern portion of the paleoerg (palaeolatitute < $20^{o}$) was characterized by paleowind blowing from the north, whereas the southern portion was under influence of paleowing coming from the SW.

The wood-bearing Fazenda Sobradinho (18°46’56,5’’ S/48°16’0,2 E – altitude 657 m), previously registered by Suguio and Coimbra (1972) and Brito (1979), lies between Uberlândia e Araguari cities, Minas Gerais State, bordering the railroad (Fig. 1). The exposed sedimentary sequence of 10 m is interbedded within two basalt levels. This site exposes a prominent aeolian facies, composed of a succession of medium-coarse sandstones with trough cross-bedding. Silicified logs are the exclusive fossils, and occur included in the coarse-grained sandstone (Fig. 3 a) or within altered sandy soils (Fig. 3 b). The woods show no preferential orientation. Prostate logs are highly compressed, sometimes segmented (Fig. 4 a, b). Otherwise, the presence of both, basal flared stems (Fig. 4 d) and putative “*in situ*” roots (Fig. 4 c, e) points to an autochtonous/hipoautoctonous deposition for this wood assemblage.

## 3 - DENDROCLIMATOLOGICAL ANALYSES

### *3.1. Wood Description*

The wood samples are portions of large prostate silicified logs that occur in high density, included in sandy sediments of the Botucatu Formation, interbedded with Serra Geral Formation. Almost all the samples at the site have laterally compressed diameters from 21 to 84 cm, and lengths weathered out up to 5 m (Figs. 3, 4). Few samples contain preserved pith (Fig 5 a); none of the specimens have preserved phloem or cortex. Some of the samples, by its external morphology and orientation, seems to represent *in situ* preserved roots (Fig. 4 c), which would indicate the original forest level, but the obliteration of anatomical detail by quartz deposits impede such determination. Basal flared stems are also common fossils (Fig. 4 b). Difficulty of colleting at the site combined with the weight of the trunks, only fragments of mature woods of each specimen were could be retrieved.

Seventeen samples were collected from the site but, given the lack of any cell structure in most of the fossils, only 10 mature woods were selected for detailed palaeoclimatological tree ring analysis (Table 1). Anatomic details were observed from thin slides on transmitted light optical microscopy of thin-sections.

The wood is mostly silicified and light brown (Figs. 3, 4, 5). Cell structure is not well preserved in many of the samples, and because of this difficulty, formal taxonomic analyses were not developed. Nevertheless, one single wood type was documented in almost all the specimens, characterizing a monotypic plant association. The pinoid xylotype (*sensu* Wheler e Lehman, 2005), represented in figures 6 and 7 was recognized by parameters such as: round tracheids in transverse section (Fig. 6 a, b, c); latewood characterized by reduction of radial size, wall thickenings not observed (Fig. 6 c); vertical secretor canals with walls not thickened, concentrated in the boundary of growth rings (Fig. 6 a, b, e); horizontal (Fig. 6, d, f) and vertical secretory ducts perceivable (Fig. 7 e); radial pitting of tracheids of mixed type of arrangement (Fig. 6 d, e and Fig. 7 d); high rays (Fig. 7 a) composed by up to 12 cells, heterogeneous, composed by radial parenchyma and transversal tracheids (Fig. 7 b, c); cross-field pitting mainly indistinct; when observable they are of pinoid type (Fig. 7 e). The main xylotype characteristics are present in *Paleopinuxylon josuei* Mussa 1974, described for this outcrop, a Protopinaceae with affinity with extant *Pinus*.

### *3.2. Analysis of growth rings*

#### *Methodology*

Growth rings were measured from transversely polished sectioned blocks of the silicified wood utilizing binocular stereoscopic microscopy or were measured with sliding caliper directly on the polished wood surface. Details of growth ring structure were obtained by the observation of thin slides on transmitted light optical microscopy of thin-sections.

Statistical procedures used in the analyses of growth rings from the 10 fragments of fossil wood followed those of Fritts (1976: based on Douglass, 1928), Creber (1977), Creber and Chaloner (1984), Parrish and Spicer, (1988) and Denne (1989). These include the variance of ring width, Mean Sensitivity (MS), Annual Sensitivity (SA) and growth ring classification scheme.

Mean ring width is used to indicate the growth rate and length of growing period, according to Fritts (1976) the wider the ring, the faster the growth or the longer the growing period.

Inter annual variation in growth rate is determined by mean sensitivity indicators, which represents a measurement of the sensibility of trees to variation in their environment. The indices are obtained by the equation:

$$MS = 1/n-1 * \sum_{t=1}^{T=n-1} \left| 2\,(X_{t+1}-X_t) / (X_{t+1}+X_t) \right|$$

Where:

n: is the number of rings measured in a sequence;

t: is the number in the ring count;

X: is the ring width.

The values of mean sensitivity range from 0 to a maximum of 2. An arbitrary value of 0.3 is taken to separate “complacent” trees that grow under a favorable and uniform climate ($MS \leq 0.3$) from those that are “sensitive” to fluctuating climate parameters ($MS \geq 0.3$; Douglas, 1928). According to Keller and Hendrix (1997) mean sensitivity values are not necessary a reliable measure of environmental factors. Kay (1978) also considered that a tree of a single species growing within the interior of a forest naturally has lower sensitivity values than those growing along the forest borders, regardless of climatic variability.

The degree of year to year variability is demonstrated by annual sensitivity is derived from the equation of mean sensitivity and corresponds to the difference in width between a pair of consecutive rings divided by their average width.

The indicator may be a more valid measure of the environmental variability to which the tree has been exposed (Keller and Hendrix, l997).

The nature of seasonality can be also inferred by the proportion of earlywood/latewood. Distinct patterns of latewood in temperate modern woods which reflect growing conditions have been applied in fossil assemblages providing information about seasonality (Spicer and Parrish, 1990). Determination of earlywood/latewood boundary has been determinate by different methods. Creber and Chaloner (1984) determined the boundary by the cumulative sum deviation from the mean (CSDM) radial cell across a single growth ring. Research in extant plants use to establish growth ring boundary by the ratio of cell wall thickness to lumen diameter (Mork, 1928; Denne, 1989). These two techniques were applied and produced different results for percent latewood.

### *3.3. Results*

Statistical data where obtained from 119 growth rings in 10 samples. The Mean Sensitivity range from 0.288 to 0.862; the average of Mean Sensitivity is 0.569; the minimum annual sensitivity is 0 and the maximum annual sensitivity is 1.729 (Table 1).

The maximum annual sensitivity exceeds 0.7, in almost all samples. The annual sensitivity of the specimens increases year after year in samples 1302-09, 1306-02, 1306-20, PB 4312, and PB 4317, decrease in samples 1306-19, PB 4311, PB 4313, and PB 4314, and stay stable in PB 1306-25 (Figs. 8, 9).

All the specimens have wider growth rings (Fig. 5 b) according to IAWA Committee (1989). The measured growth rings range from 0.09 – 1.22 cm wide (mean: 0.37 cm). Secretors canals are common at the boundary of the growth rings (Fig. 5 c). The widths of the growth rings vary year to year (Fig. 5 d) as it can be observed in the figure 8 this characteristic is common in all specimens.

The transition early-latewood is gradual (Fig. 6 c). The earlywood is characterized by thin walled cells; according the criteria of Creber and Chaloner (1984); 2-4 narrow cells are evidenced in latewood. Using the statistic patterns of Denne (1989) based in Mork (1928) it becomes clear that the growth ring was characterized only by the abrupt decrease of the cell lumen, without thickening of the cell walls (Fig. 10).

False growth rings are abundant in almost all samples (Fig. 5 d). They may be distinguished from seasonal growth rings because they are commonly and have a gradual transition to thick-walled narrow cells then a gradual reversal to large thin-walled cells (Spicer, 2003).

## 4 – PALAEOCLIMATIC INTERPRETATIONS

The simulations of the Early Cretaceous climate indicate that arid desert biomes associated with hyper arid conditions may indeed have prevailed at the southern lower latitudes during the pre-rift phase of Pangea. In this climate, characterized by high stability, the equatorial zone is markedly dryer than today, with large continental interiors. Much of this land mass would be remote from moisture sources.

Paleofloras composed by ferns, conifers, and cycads are registered both at low and high latitudes in both hemispheres. These plant assemblages were interpreted as representing warm temperate climates in the past because their latitudinal spread (Smiley, 1967; Douglas and Williams, 1982; Jefferson, 1982; Frakes et al., 1992; Chumakow, 1995; Scotese, 2003). Palaeontologic data for the Botucatu Formation, until now, were constrained to dinossauroid tracks (Bonaparte, 1996; Leonardi et al., 2007). According to Willis and McElwain (2002) the absence of fossil floras together with an abundance of wind-blown (aeolian) sediments, supports the presence and the extension of this sub- tropical desert bioma.

The presence of a dense association of hipoautochtonous large conifer logs within a sedimentary sequence characterized by large scale cross strata, identified as a dry aeolian system developed in Paraná Basin, Brazil (Botucatu Formation), contrasts with the climatic prediction of stratigraphic data (Scherer, 2000; Scherer and Lavina, 2006) and palaeowind patterns (Scherer and Goldberg, 2007), which indicate there is no evidence of moisture enough to have supported forests.

The particular nature of the outcrop, that occur in a restricted stratigraphic distribution (more or less 2m thickness) representing a microenvironment interbeded in two basalt layers, and the monotypic pattern of fossil woods, showing evidences of autochthony, eliminates the possibility of some taphonomic bias as: i. occurrence of different contemporaneous taxa, that growing in the same palaeoenvironment or ii. accumulations of diverse specimens from the same taxon, transported from different localities.

The use of quantitative growth ring parameters as palaeoecological indicators at this exceptional wood fossil site allowed for infer not only about seasonality, but also the inter-annual variability of growth; growing conditions were seasonal, but most stressed during the life cycle; individual wood displays comparatively rings of variable width, and the common presence of false rings could be related to plant stress represented by occasional droughts during the growing period. Fossil woods show uneven sequences of growth ring development indicating fluctuations in growing conditions over several growth periods. Taking into account the lower latitudes and the sedimentologic characterization of the outcrop, the cause is likely to be variations in water availability. Nevertheless, the growth rings were formed, suggesting a more or less annual cyclicity or seasonality in wet/dry variations. Thus, although there is evidenced broad annual cyclicity in water supply, this also varied markedly over time, and perhaps it could have been several years in succession when water supply was reduced, materialized in thin growth rings.

Fossil wood analysis from different palaeolatitudes have been demonstrated the validity of using dendrological data to confirm Lower Cretaceous palaeoclimate. Gérards et al. (2007) concluded that during the Early Cretaceous (Berriasian), the Mons Basin (Belgium), located at 30-35°N in palaeogeographic models (Scotese, 2003), presumably in a tropical climate, was characterized by a succession of marked dry and wet seasons, under unstable palaeoenvironmental conditions.

Otherwise, evidence of seasonal climate in the southern mid latitude was obtained in growth ring analyses by Jefferson (1982) in the Lower Cretaceous (Alexander Island - Antarctic) that indicate moderate to high seasonality. Falcon-Lang and Cantrill (2000) also registered for the Alexander Island (Albian) similar wood patterns, from *Araucarioxylon* (invalid genera), *Podocarpoxylon* and *Taxodioxylon* morphotypes. The unusual conditions which allows the generation of growth rings in plants close to the paleopoles and those from the tropics in Early Cretaceous, are generally interpreted in terms of a high carbon-dioxide greenhouse world (Chaloner and McElwain, 1997).

In the case studied the unexpected evidence of wider growth rings in large fossil woods, associated to the low percentage of latewood and the gradual transition early-latewood allowed inferring conditions interpreted to have manifested as accentuated growing periods. These parameters contrasting with different palaeoclimatic models, might be explained by the combination of extrinsically and endogenous factors.

Anatomical analysis have shown relevant botanic affinities of the entire wood assemblage with extant Pinaceae, which are one of the most drought–tolerant conifer, with greater resistance to water stress for survival to more xeric habitats (Atzmon et al., 2004). These evergreen gymnosperms, which dominated low latitudes during times of global warm (Spicer and Chapman, 1990), are today native to most of the Northern Hemisphere, ranging north to just over 70 to 12°N, mainly in regions with good soil drainage. Some species are particularly well adapted to growth in hot, dry semi-desert climates (e.g. Sumatra), just crossing the Equator, at 2°S (Richardson, 1998).

Under nutrient poor, drought-stressed conditions, the low efficiency of the vascular system of conifers, and their small leaves are advantageous, acting conservatively under potential damaging conditions (Kershaw and McGlione, 1995). Otherwise, Pinõl and Sala (2000) showed for several extant Pinaceae in the Pacific USA that species extending into drier habitats compensated less resistance to water cavitation via different adjustments of physiological nature (stomata control) and structural nature, by the increased relative biomass allocation to sapwood.

Different geological data indicates that the conifer assemblage on study was developed during the climax of a greenhouse phase (Fischer, 1984; Frakes et al., 1992), with increasing atmospheric $CO_2$ (Tajika, 1999). Controlled experiments with vegetation in greenhouses developed by Ruddiman (2001) to test growth ring signals as tools for climate science, shows that plant growth is enhanced by higher levels of $CO_2$, used by plants for photosynthesis. Thus, $CO_2$ fertilization may have a factor in faster tree growth in dry regions, regardless of other climatic parameters. Consequently, the particular endogenous and extrinsic factors that could be involved with the production of wider growth rings in the studied assemblage suggest that growth ring width is not related to latitude in a simple a way as has been previously supposed by Creber and Chaloner (1984).

Mean percentage latewood parameter lead to identifying the wood type E of Creber and Chaloner (1984), included by Brison et al. (2001) in the "progressive woods" i.e. those with a progressive transition from earlywood from latewood. They are registered in Early Cretaceous at middle latitudes for both hemispheres, occurring with a higher frequency in the Southern Hemisphere. Wood statistical data are not available for desert biome at lower latitudes (15 - 25°) for the Early Cretaceous time interval; nevertheless, a contrast between growth ring signatures of the present paper and defined biomes for this interval is clearly indicated by palaeoclimatic models of Rees et al. (2000) which is represented in figure 11.

This discrepancy can be ratified by using Dennes (1989) calculation, based in features highly related with environmental characters. This calculation evidenced the earlywood-latewood pattern which was characterized by narrow growth ring boundary with 1-3 rows of narrower tracheids. Typical latewood zone characterized by wall thickenings and reduction of lumen size was not found. The small amount of latewood in growth rings, characterized mainly by narrow cell diameter with no wall thickening in a tropical-desert niche, would be likely caused by limited water availability and resultant reduction in photosynthesis. According Falcon Lang and Cantril (2000), the occurrence of small percentage of latewood in each ring is linked to the preservation of leaves in evergreen conifers, a result that is generally consistent with earlier findings that weakly correlated deciduous phenology with accentuated percentage latewood production.

## 5 - CONCLUSIONS

1. The record of a coniferous wood association from aeolian sandstones at the northern portion of the Botucatu Formation (Paraná Basin, Brazil) at the Early Cretaceous is an evidence of some moisture in that dune paleoenvironment.

2. The presence of humidity in the north part of the Paraná Basin can be explained by palaeowind pattern that allowed the transport of humidity from Tethys Ocean to interior of the Gondwana continent.

3. The presence of growth rings as a common character indicates cyclical variation in tree growing conditions; nevertheless, typical latewood zone characterized by wall thickenings and reduction of lumen size was not found.

4. Quantitative parameters controlling growth ring development were highly related with environmental characters and not only a single consequence of climate. Thus growth rings were not determined by extrinsically factors alone; taxonomic and physiologic parameters were decisive as a response to environmental constrains.

5. Conifer assemblages with Pinaceae affinities evidenced to be adapted to xeric habitats since the Early Cretaceous;

6. The monotypic character of the whole association excludes competitive interaction. This evidence is consistent with some extant Northern Hemisphere Pinaceae, which grows in monotypic communities, adapted to particular ecological conditions.

7. Integration between dendrologic, palaeogeographic and sedimentological data allows detecting that tropical-desert climatic conditions in “greenhouse ecosystems” at the early Cretaceous have no modern analogs in present “icehouse world”.

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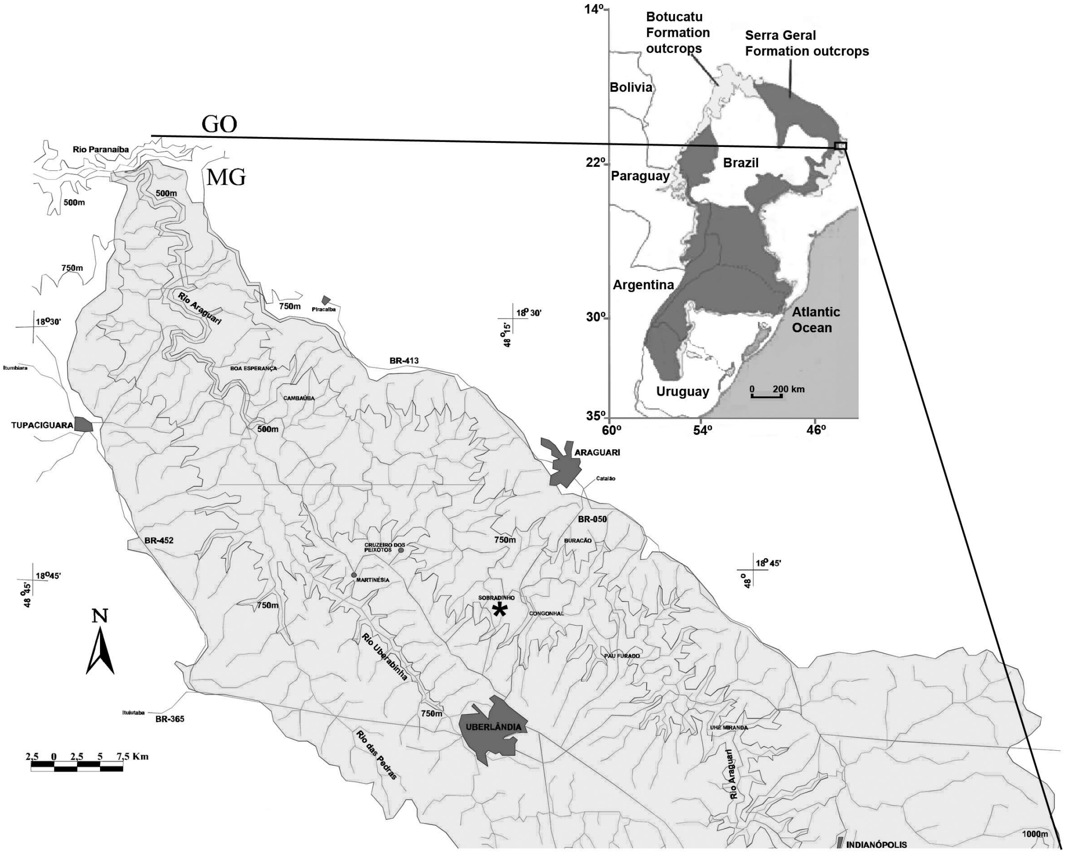


**Figure 1:** Location map of Fazenda Sobradinho Outcrop (*) - Botucatu Formation – in the Paraná Basin.

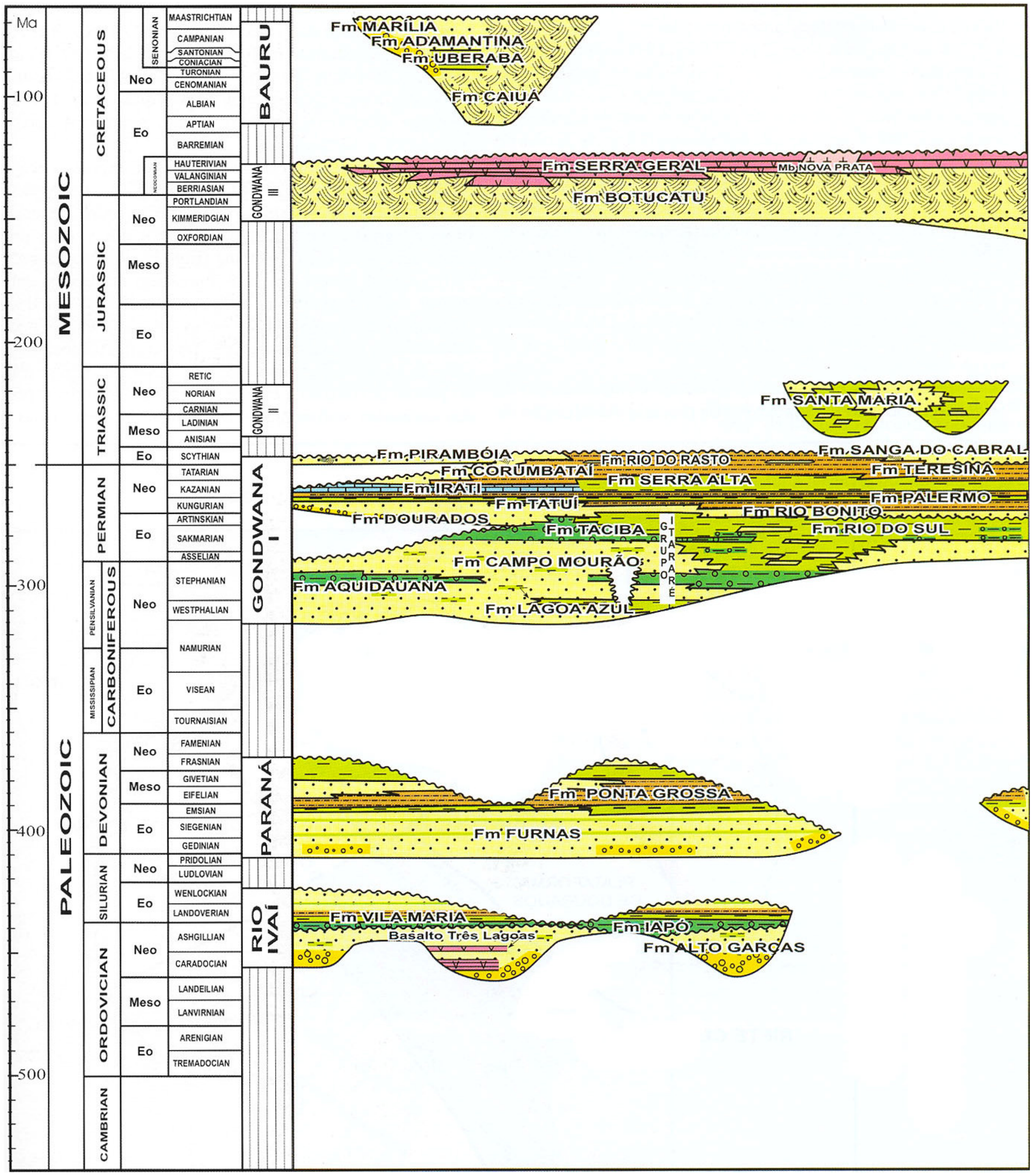


**Figure 2:** Stratigraphic chart of Paraná Basin (Modified by Milani, 2004).

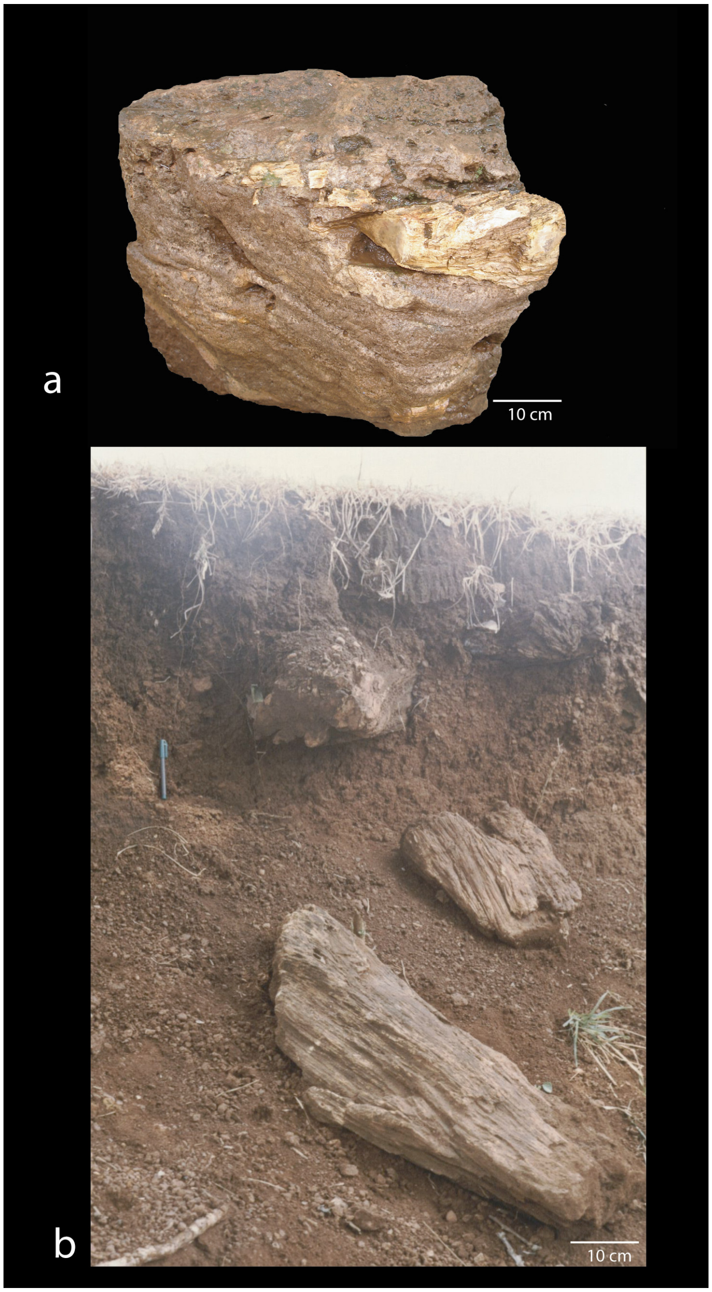


**Figure 3:** **a**. silicified wood fragment included in cross-bedded, coarse grained sandstone; **b.** silicified log included in altered sandy soil.

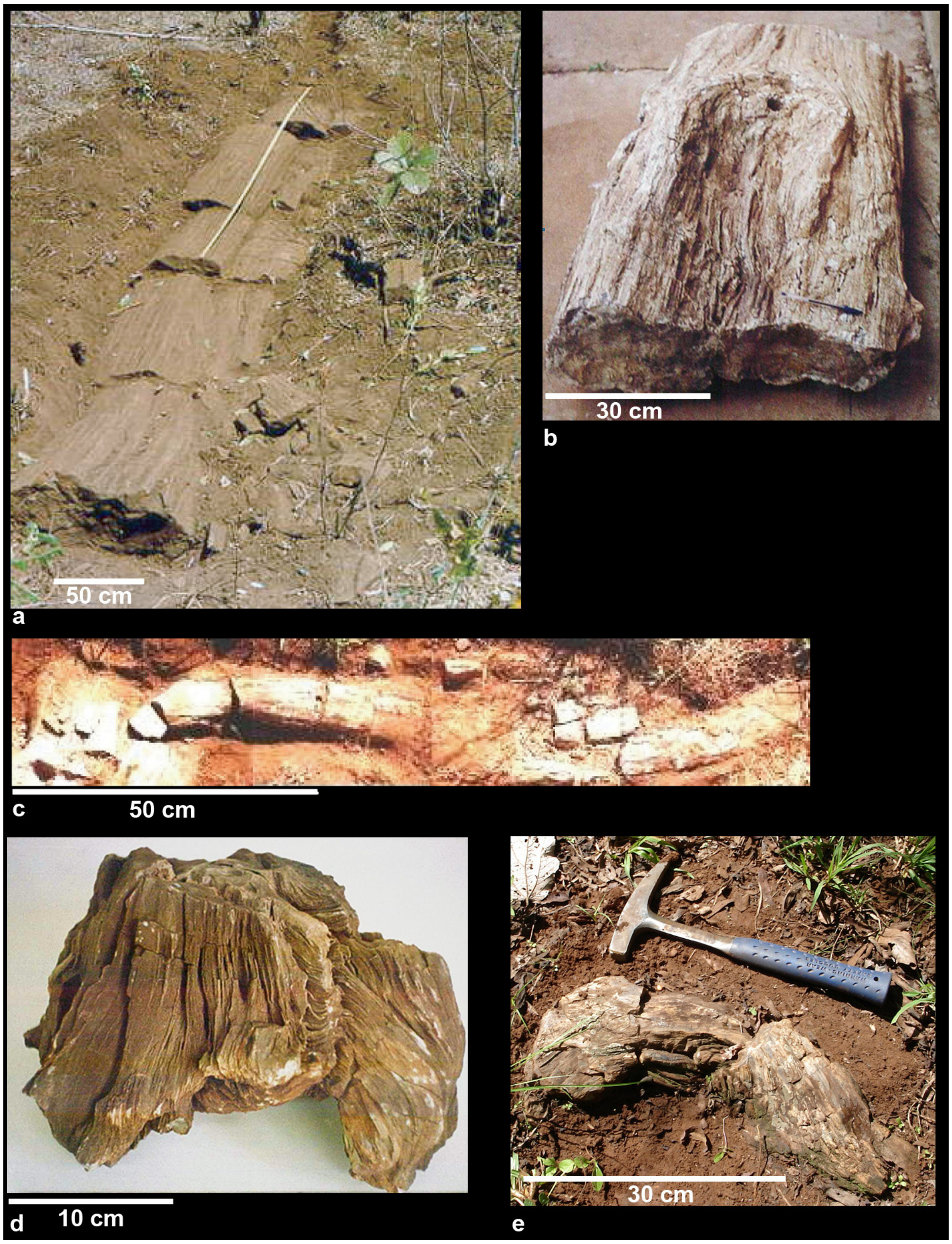


**Figure 4: a.** prostate log compressed and segmented included in altered sandy soil; **b.** prostate log compressed; **c.** putative *in situ* main axis of roots included in sandstone; **d.** basal flared stem; **e.** putative *in situ* main axis of roots included altered sandy soil.

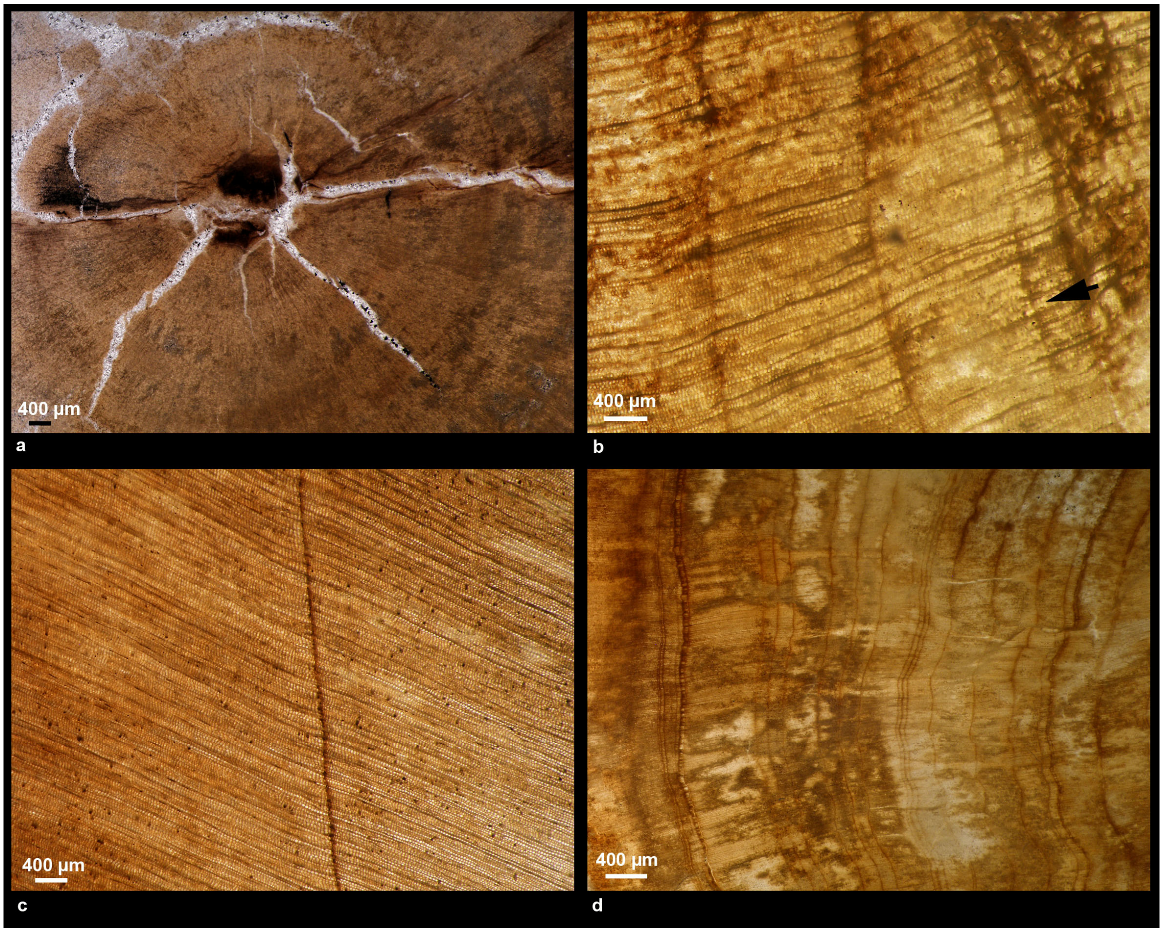


**Figure 5:** Cross sections of fossil woods, **a.** central portion showing circular pith; **b**. wider growth rings and a false growth ring (arrow); **c.** boundary of growth ring with secretor canals; **d.** sequence of growth rings showing the width variability.

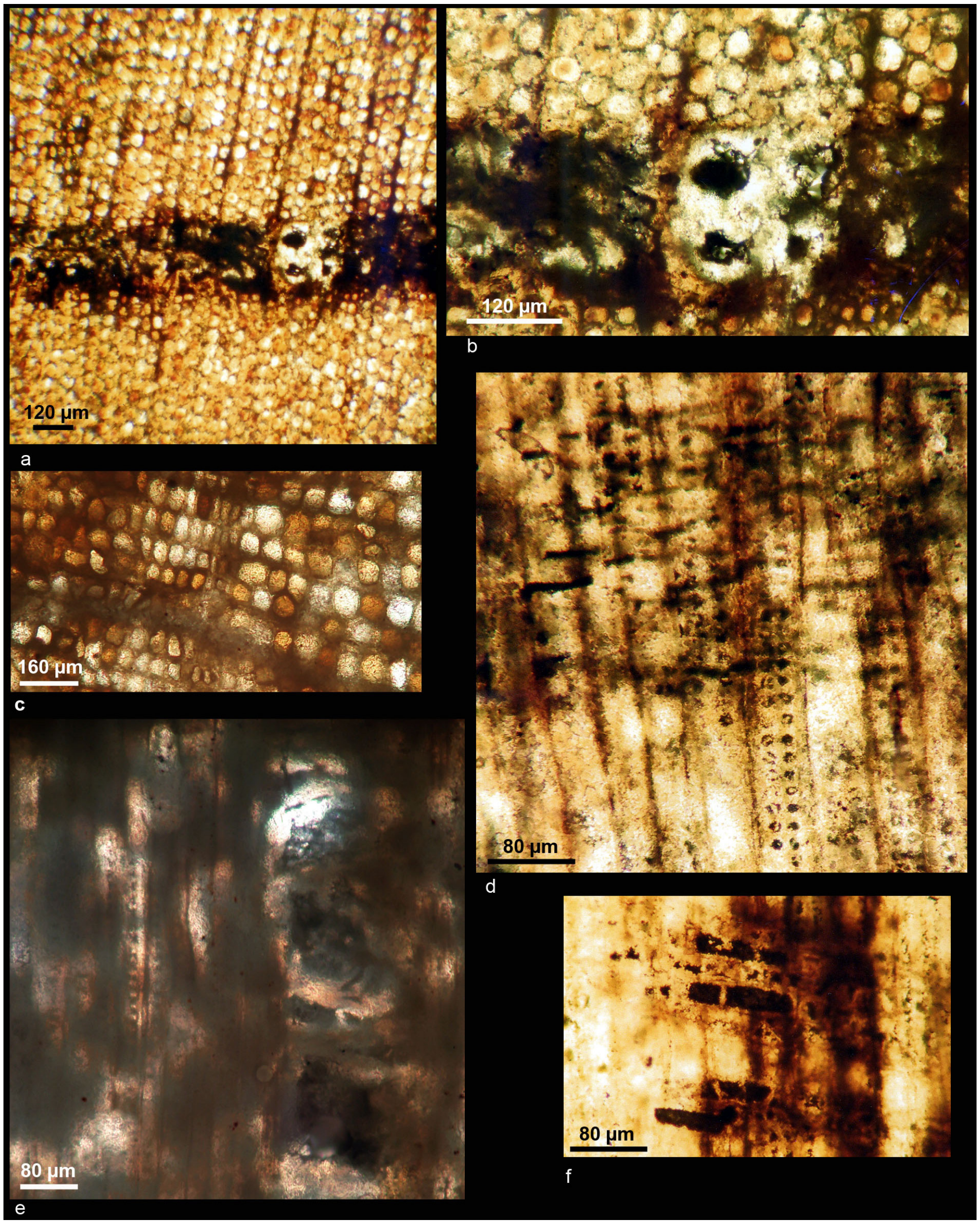


**Figure 6:** Thin-sections of fossil woods, **a.** cross section of growth ring boundary with secretor canals; **b.** detail of figure 6a; **c.** earlywood-latewood transition showing reduction of radial size of tracheids; wall thickening not observed; **d.** radial section showing bisserial sub-opposite bordered pits and horizontal secretor ducts; **e.** radial section viewing secretor canal and unisserial bordered pits in tracheids wall; **f**. radial section showing cross-field with horizontal ducts.

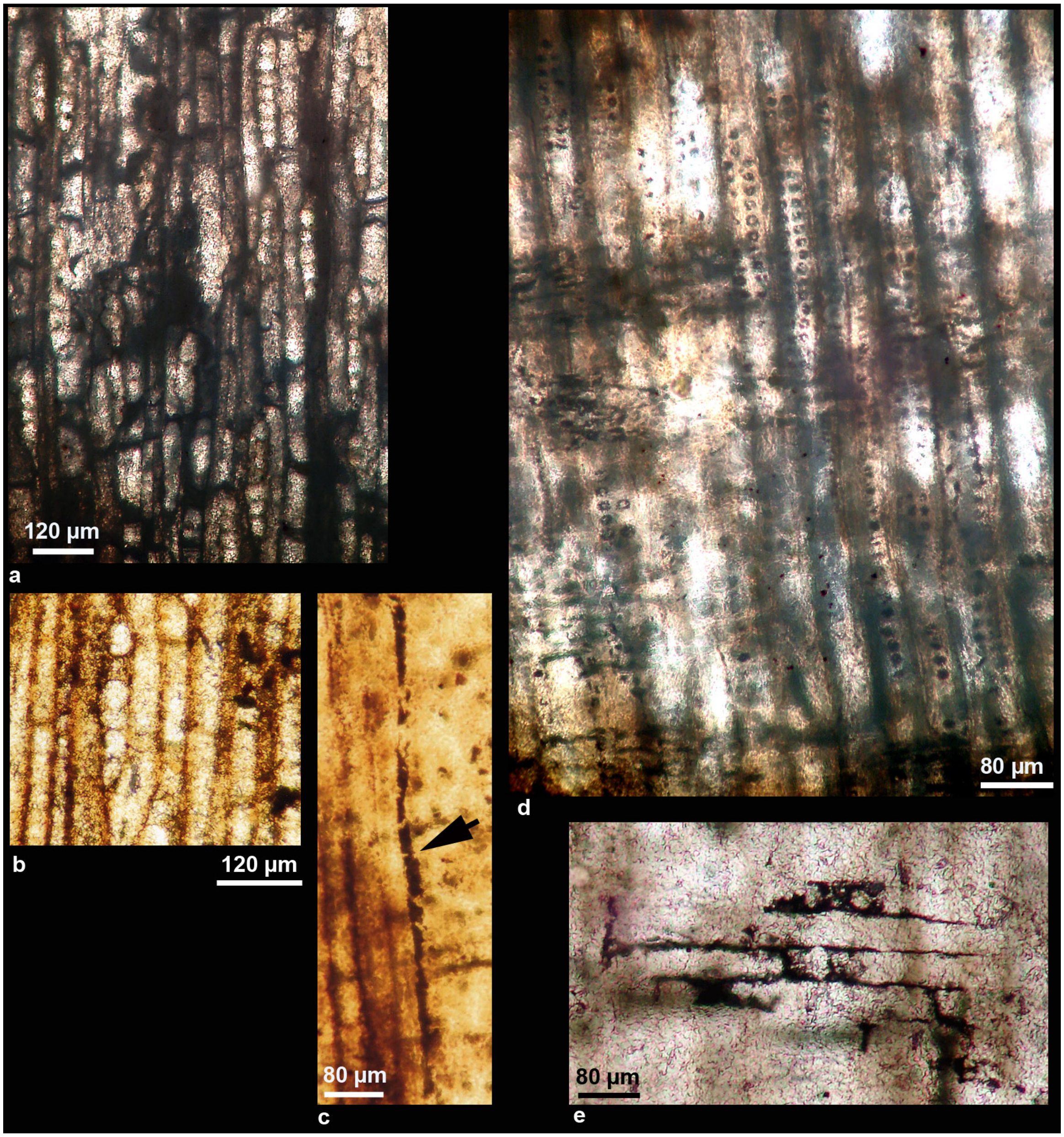


**Figure 7:** Thin-sections of fossil woods, **a.** tangential section with unisserial rays; **b.** radial section showing a vertical secretor duct; **c.** tangential section showing unisserial ray, composed of parenchyma (arrow) and tracheids cells; **d.** radial section viewing mixed type of bordered pits on tracheids walls; **e.** radial section viewing cross field with bad preserved pitting (pinoid?).

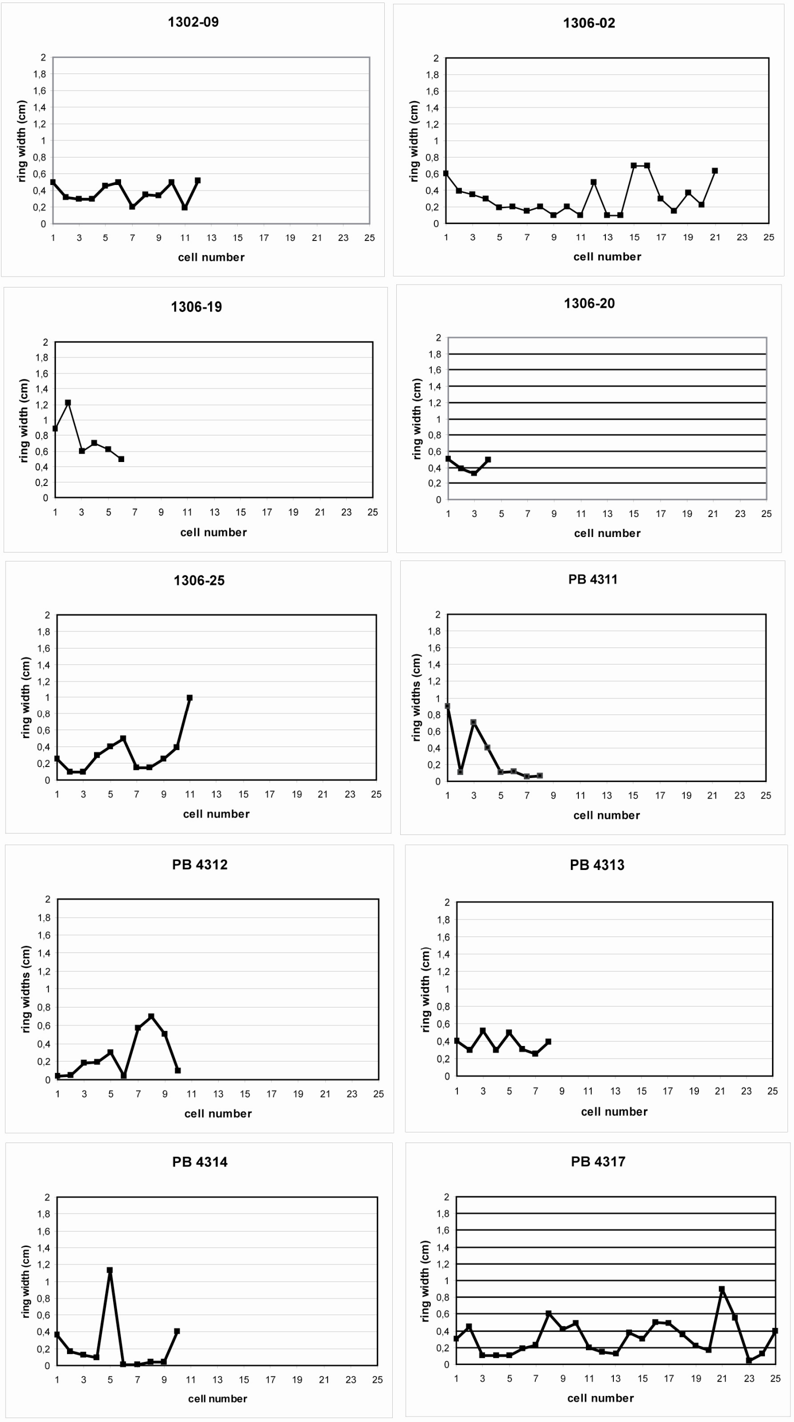


**Figure 8:** Growth ring widths graphics.

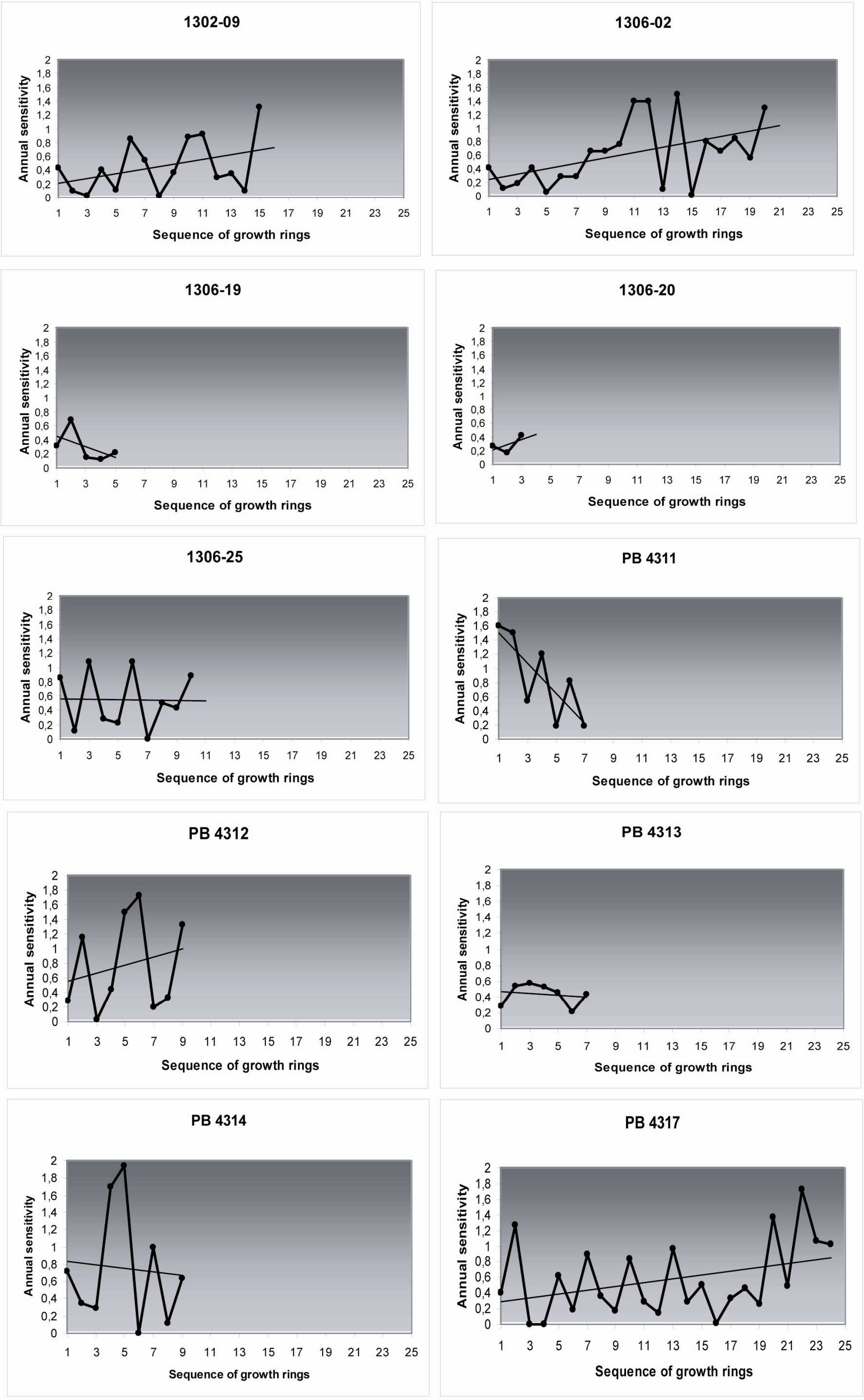


**Figure 9:** Annual sensitivity graphics.

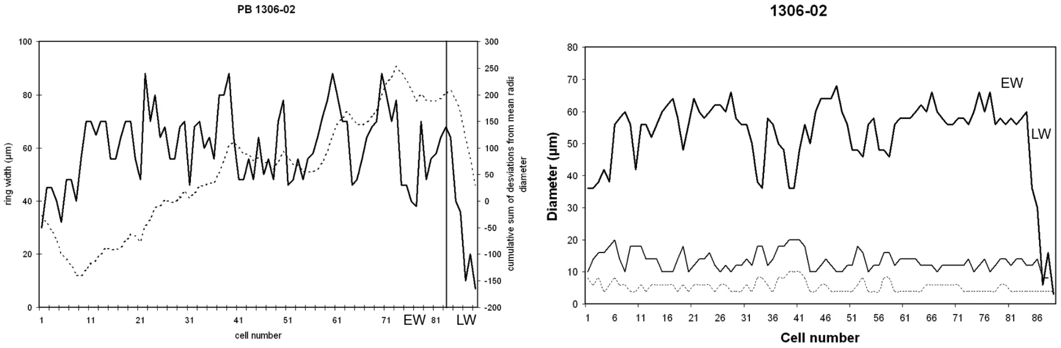


**Figure 10**: **a.** Graphic based on methodology of Creber and Chaloner (1984) showing the variation in cell radial diameter along selected growth ring (solid line) and cumulative sum of deviations from mean radial diameter (dashed line); vertical line separates earlywood (EW) from latewood (LW); **b.** graphic based on methodology of Mork (1928) and Denne (1989) showing the variation in a single growth ring in relation to: i. cell radial diameter along selected growth rings (more thick line); ii. thickness of two adjacent tracheids walls (intermediary line); and iii. thickness of single tracheids walls (more thin line); EW – earlywood, LW – latewood.

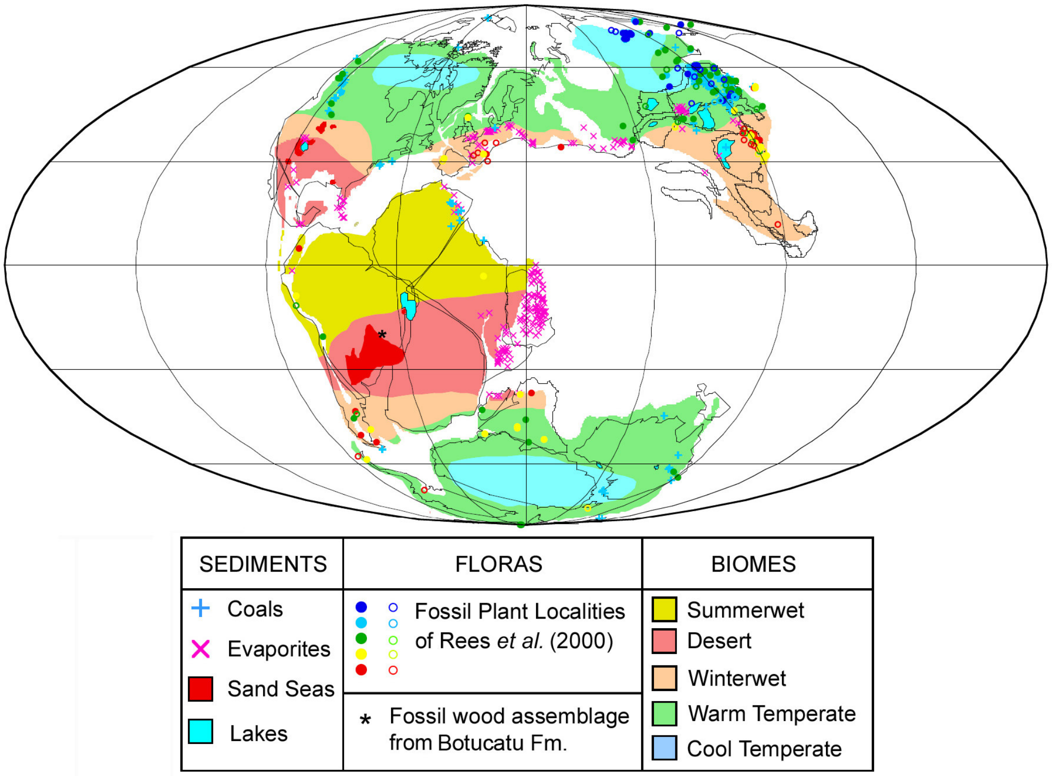
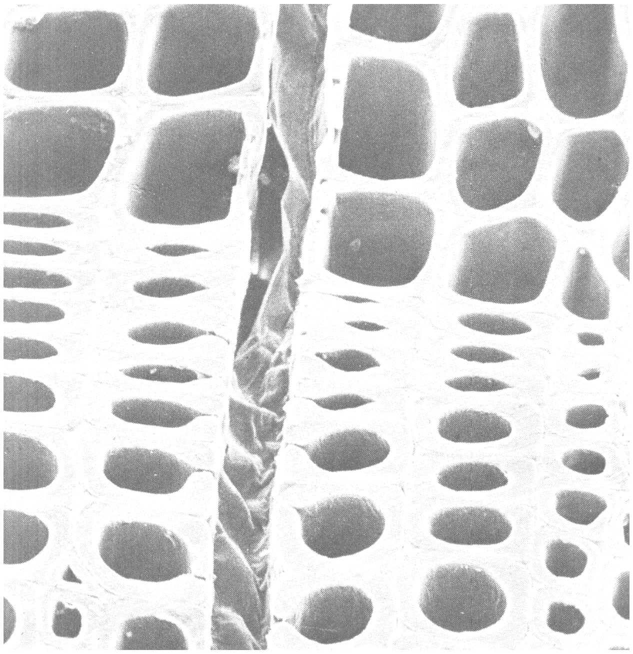


**Figure 11**: Paleoclimatic map from the Jurassic-Cretaceous transition (Tithonian-Berriasian) with the localization of fossil wood assemblage of Botucatu Formation (modified by Rees et al., 2000).

| | **Samples** | **Number of growth rings** | **Minimum ring width (cm)** | **Maximum ring width (cm)** | **Mean ring width (cm)** | **Mean sensitivity MS** | **Minimum annual sensitivity** | **Maximum annual sensitivity** |
|---|---|---|---|---|---|---|---|---|
| 1 | 1302-09 | 16 | 0.19 | 1.10 | 0.46 | 0.449 | 0.029 | 1.308 |
| 2 | 1306-02 | 21 | 0.09 | 0.70 | 0.30 | 0.618 | 0.105 | 1.494 |
| 3 | 1306-19 | 06 | 0.50 | 1.22 | 0.75 | *0.297* | 0.121 | 0.681 |
| 4 | 1306-20 | 04 | 0.32 | 0.50 | 0.42 | *0.288* | 0.171 | 0.420 |
| 5 | 1306-25 | 11 | 0.09 | 1.00 | 0.32 | 0.544 | 0 | 1.077 |
| 6 | PB 4311 | 08 | 0.05 | 0.90 | 0.30 | 0.862 | 0.186 | 1.600 |
| 7 | PB 4312 | 10 | 0.03 | 0.70 | 0.26 | 0.778 | 0.026 | 1.722 |
| 8 | PB 4313 | 08 | 0.25 | 0.52 | 0.36 | 0.432 | 0.214 | 0.568 |
| 9 | PB 4314 | 10 | 0.04 | 1.12 | 0.24 | 0.861 | 0 | 1.704 |
| 10 | PB 4317 | 25 | 0.04 | 0.90 | 0.31 | 0.565 | 0 | 1.729 |
| Total/mean | | **119** | | | **0.37** | **0.569** | | |

**Table 1**: Results of growth rings analysis; complacent values in italic.

# 3 – Análise Integradora



# 3- ANÁLISE INTEGRADORA

## 3.1. Análise Integradora

Durante o Cretáceo, a configuração continental global alterou-se profundamente, desde o típico padrão Mesozóico, caracterizado pela presença de dois supercontinentes (Laurásia e Gondwana) separados por um oceano equatorial (Thetys), até a configuração de diferentes continentes, que se estendem desde o Equador até altas latitudes, separados por diferentes oceanos. Diversas evidências geológicas têm demonstrado que durante esse período, diferentes biotas desenvolveram-se em condições "*greenhouse*", em um mosaico de ambientes terrestres, marinhos rasos e oceânicos (Spicer, 2003).

Em ambiente terrestre, mesmo sob a vigência de temperaturas médias muito elevadas, as condições não eram monótonas. Diferentes zonas climáticas foram delineadas (Ziegler 1990; Willis e McElwain, 2002; Rees et al., 2000; Scotese, 2003) a partir de base de dados paleobotânicos, associada à determinação de litologias climaticamente sensíveis (e.g. carvões, evaporitos, depósitos de sal) comparáveis aos biomas definidos por Walter (1985) para floras atuais.

No Cretáceo Inferior, durante a fase pré-rifte, as massas continentais da África e América do Sul foram incluídas no Cinturão Tropical-Equatorial por Chumakov (1995), no bioma "Deserto" por Rees et al. (2000) e no Cinturão de Clima Árido por Scotese (2003), sem evidências da presença de condições de umidade suficiente para o desenvolvimento de florestas.

A integração de resultados obtidos em análises dendrológicas de lenhos fósseis provenientes de diferentes bacias sedimentares brasileiras no Cretáceo Inferior, estabelecida no presente estudo, levou à inferências importantes sobre a periodicidade de produção de lenho, e consequentemente, sobre a periodicidade do crescimento das plantas em um contexto considerado como árido-tropical no Cretáceo Inferior.

Análises dendrológicas em uma associação de lenhos silicificados composta por dois tipos de lenhos gimnospérmicos provenientes do Afloramento Grota Funda, Formação Missão Velha (Bacia de Araripe) em latitude de aproximadamente 8° S, foram efetuadas a partir de dados estatísticos de sensibilidade media e anual (*sensu* Douglas, 1928), e de peculiaridades anatômicas dos anéis de crescimento (Creber e Chaloner, 1984a).

Os padrões anatômicos reconhecidos são: tipo 1 – cupressóide/podocarpóide, que se caracteriza pela presença de traqueídeos arredondados (diâmetro radial - 40-44 µm), pontoações unisseriadas contíguas e achatadas e campos de cruzamento com 1-2 pontoações cupressóides; tipo 2 – araucarióide, com traqueídeos quadrados (diâmetro radial 48-72 µm), pontoaçõs uniseriadas a bisseriadas, isoladas ou contíguas, e campos de cruzamento com 2-12 pontoações araucarióides por campo.

Os dados resultantes de análises de sensibilidade média indicaram condições variáveis no ambiente de crescimento. Por outro lado a sensibilidade anual acima de 0.7 indica a ocorrência de eventos climáticos extremos. Esses parâmetros indicam que o clima vigente durante o desenvolvimento das plantas foi caracterizado pela alternância cíclica de períodos secos e chuvosos, controlado por precipitações, mas com vigência de condições irregulares no ambiente de crescimento, com pluviometria variável ano a ano. As chuvas periódicas corresponderiam à fase de crescimento das plantas e consequentemente ao mais importante fator de controle de seu crescimento.

A pequena quantidade de lenho tardio e a morfologia das células sugerem a transição muito rápida de estágio de crescimento para o estágio de dormência cambial, sem a ocorrência de decréscimo gradual (Spicer, 2003). A transição entre o lenho inicial e o lenho tardio está diretamente relacionada com a diminuição de disponibilidade de água no solo. A presença de falsos anéis de crescimento reflete fatores externos que afetaram o ciclo de crescimento, tais como a secas ocasionais e infestação de insetos.

As evidências de fitofagia na associação de lenhos são descritas pela primeira vez para a Bacia do Araripe (Formação Missão Velha - Berriasiano) através da descrição da interação artrópode-planta. O complexo sistema de canais ocorrentes nos lenhos, construídos por invertebrados, associado à presença de coprólitos com morfologia diagnóstica, permitiu estabelecer a afinidade dos organismos produtores com organismos herbívoros da família Oribatidade - Ordem Isoptera, a qual tem seu registro inicial no

Cretáceo Inferior (Grimaldi e Engel, 2004), corroborando a idade Berriasiano estimada por Arai (2006) para o topo da Formação Missão Velha.

Modelos de simulação dos climas vigentes na Pangéia indicaram a vigência de sistema de monção durante a fase pré-rifte (Kutzbach, 1994). De acordo com Scherer e Goldberg (2007), as condições de sistema de monção gonduânicas tornaram-se mais suaves a partir do Jurássico Superior, cessando ao final do Cretáceo Inferior. Todavia, dada a imensa extensão geográfica do continente, os modelos climáticos sugerem condições secas para o interior da Pangéia, na ausência da influência moderadora do clima vigente nas regiões mais costeiras (Rudddiman, 2001). Dessa forma, tomando como referência os dados dendrológicos e paleogeográficos, um clima de savana é inferido para o intervalo de desenvolvimento das plantas. Esse clima, definido por regimes pluviométricos e de temperatura, caracteriza-se por uma longa estação seca (inverno) e uma estação úmida, chuvosa (verão), quando o crescimento da planta é rápido e intensificado. Tal como o clima de monções, o clima de savana é sazonal quanto à pluviometria, a qual, porém é mais restrita na estação úmida do que no sistema de monções (Ritter, 2006).

Os dados obtidos na análise da associação de lenhos provenientes da seção tipo da Formação Missão Velha (afloramento Grota Funda) comprovam a eficiência de análises dendrológicas como subsidio para a definição de zoneamentos paleoclimáticos. Os resultados obtidos corroboram o zoneamento paleoclimático estabelecidos por Rees *et al.* (2003) para o limite Jurássico-Cretáceo, que delimita um bioma “Verões Úmidos” (Summer Wet) vigente na faixa peri-equatorial durante o Cretáceo Inferior. Os dados obtidos no presente estudo também confirmam os resultados obtidos por Da Rosa e Garcia (2000), os quais permitiram subdividir a Depressão Afro-Brasileira em duas regiões, com o subsídio de análises de paleocorrentes, proveniência e diagênese. A abundância de lenhos silicificados na Formação Missão Velha na Bacia do Araripe sugere o desenvolvimento de uma floresta de coníferas durante o Berriasiano na margem de terras altas úmidas da porção norte da bacia, separadas pelas condições áridas a semi-áridas vigorantes no sul da bacia, evidenciadas pela presença de extensivas fácies eólicas.

Como decorrência da intensificação da fragmentação do Gondwana, no intervalo Tithoniano-Berriasiano, bacias rifte formam-se nas porções sul e nordeste da

América do Sul, enquanto que na Bacia do Paraná acumulou-se um espesso depósito de arenito, associado eminentemente à deposição de dunas eólicas, e secundariamente a processos fluviais (Scherer and Goldberg, 2007). A deposição da Formação Botucatu, incluída no bioma "Deserto" (Sand Sea) dentro do esquema global proposto por Rees et al. (2000), tem sido relacionada a um período de estabilidade climática associada a condições hiper-áridas (Scherer and Goldberg, 2007). Dessa forma, a presença de uma densa associação monotípica de grandes lenhos de coníferas, ocorrente em afloramento dessa seqüência sedimentar, localizado na porção nordeste da Bacia, vem de encontro a predições climáticas (Scherer, 2000; Scherer and Lavina, 2006; Scherer and Goldberg, 2007) que indicam condições de umidade insuficiente para o desenvolvimento de florestas.

A presença de anéis de crescimento nesses lenhos constitui critério qualitativo de sazonalidade de crescimento e a presença comum de falsos anéis indica perturbações freqüentes nesse ritmo. A aplicação de análises estatísticas nesses lenhos objetivando particularizar critérios climáticos quantitativos indicou padrões muito peculiares, relacionados, sobretudo, a grande flutuação inter-anual e as condições de crescimento altamente estressantes durante o ciclo de vida das plantas. Tomando como referência dados paleogeográficos e sedimentológicos, a causa de tais variações pode ser atribuída à disponibilidade hídrica restrita. Embora os anéis demonstrem evidência de periodicidade no suprimento de umidade, esse fator também varia marcadamente ao longo do tempo, podendo ter ocorrido inclusive, muitos ciclos em que o suprimento hídrico ocorreu muito restritamente, o que se reflete em séries de anéis muito estreitos.

Uma característica muito importante na caracterizarão anatômica dos anéis de crescimento constitui-se na ausência de espessamento das paredes do lenho tardio, onde ocorre apenas a redução do diâmetro radial dos traqueídeos. Esse caráter, incomum em lenhos atuais de diferentes latitudes, deve estar relacionado às condições particulares de desenvolvimento da associação de plantas em um bioma de deserto durante a vigência de condições "*greenhouse*" (Frakes et al., 1992), com grande disponibilidade de $CO_2$ atmosférico (Tajika, 1999). Nessas condições, o crescimento vegetal é potencializado, sendo o $CO_2$ utilizado para a fotossíntese (Ruddiman, 2001). Dessa forma, a fertilização com $CO_2$ pode ter se constituído em um fator de intensificação do crescimento nessa região árida, peri-equatorial, no Cretáceo Inferior, independentemente de fatores climáticos. Por outro lado, a grande quantidade de xilema secundário poderia ter sido gerada através de processo semelhante ao que ocorre em determinadas coníferas atuais, adaptadas a habitats áridos as quais compensam processos de cavitação através de ajustes fisiológicos nos estômatos, e também pelo aumento de biomassa do xilema (Pinõl e Sala, 2000).

A associação monotípica de lenhos apresenta padrões taxonômicos afins às Pinaceae atuais, que se constituem no grupo de coníferas mais tolerante à restrição hídrica, com grande resistência a stress aqüífero, sobrevivendo em habitats xéricos. Algumas espécies perenes desse grupo, restrito atualmente ao Hemisfério Norte (70 a 12°N), adaptam-se a habitats semi-desérticos, peri-equatoriais (Atzmon et al., 2004)

Com base nos resultados obtidos na análise dendrológica de lenhos do Cretáceo Inferior, na Formação Missão Velha, na Bacia do Araripe, e Formação Botucatu na Bacia do Paraná, ficam evidentes as diferenças estruturais nos diferentes padrões de anéis de crescimento. O processo sazonal de crescimento da associação de lenhos procedentes da Formação Missão Velha (8° S), gerou anéis de crescimento típicos de floras desenvolvidas em savanas atuais, na vigência de condições *"icehouse"*. Por outro lado, a associação procedente da Formação Botucatu (18°S) apresenta anéis distintos daqueles relacionados a biomas ocorrentes atualmente em diferentes latitudes. Tomando como referência as diferentes reconstituições paleoclimáticas estabelecidas para o intervalo estudado, os resultados obtidos no presente estudo são mais adequadamente enquadrados na proposta de Rees *et al.* (2000). Neste esquema, a deposição da Formação Missão Velha é relacionada ao bioma "Verões Úmidos", em condições marcadamente cíclicas de disponibilidade hídrica. Por outro lado, as condições estáveis vigentes na deposição da Formação Botucatu relacionada ao bioma "Deserto", não possibilitariam o desenvolvimento de associações florísticas com desenvolvimento de anéis de crescimento nesse ambiente com condições irregulares quanto ao suprimento hídrico. Condições cíclicas abióticas parecem ter sido importantes no controle do crescimento e consequentemente, na definição dos padrões de anéis de crescimento. Por outro lado, condições bióticas (adaptabilidade ecológica e vinculação taxonômica) demonstraram ter sido determinantes, especialmente para a sobrevivência e para a definição dos padrões de crescimento da associação de coníferas desenvolvida no bioma "Deserto", onde ocorriam condições efêmeras de disponibilidade hídrica.

## 3.2. Conclusões

- A presença de anéis de crescimento em lenhos de coníferas procedentes de biomas relacionados a diferentes latitudes no Cinturão Equatorial durante o Cretáceo Inferior indica fases periódicas de crescimento das plantas. Essas diferenças estão, de forma ampla, relacionadas a diferentes condições de disponibilidade hídrica vigentes no Pangéia no intervalo estudado.

- Os dados dendrológicos foram congruentes com modelo paleoclimático proposto para o intervalo Cretáceo Inferior (Berriasiano), que define, para o cinturão equatorial, biomas distintos (Verões Úmidos e Deserto).

- Evidências inéditas de interação artrópode-planta na associação de lenhos fósseis proveniente da Formação Missão Velha (Bacia do Araripe) permitiram vincular o padrão de ataque à família Oribatidae (Isoptera), corroborando a idade Berriasiano para a deposição dessa seqüência estratigráfica.

- Análises estatísticas geraram parâmetros eficientes na definição de paleoclimas durante a vigência de condições "*greenhouse*", no bioma "Verões Úmidos", onde a periodicidade hídrica ocorreu em intervalos regulares. Esses parâmetros possibilitaram a comparação com padrões de anéis de crescimento encontrados em biomas atuais.

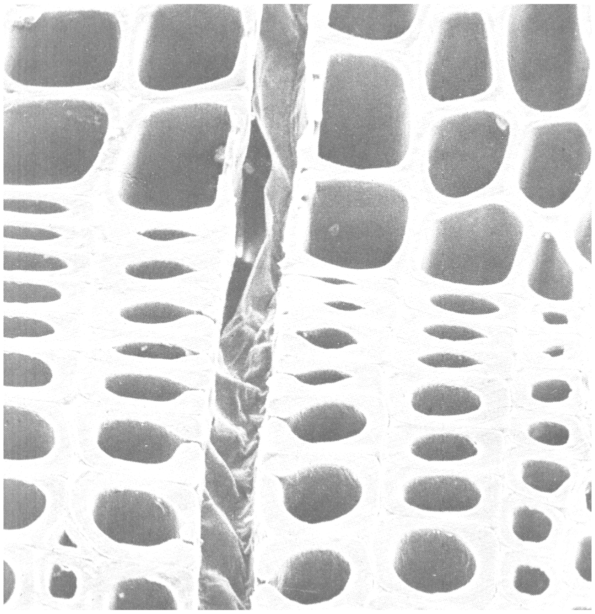
- Determinadas características bióticas (vinculação taxonômica e adaptação ecológica) e abióticas (alta disponibilidade de $CO_2$ atmosférico e temperatura) revelaram-se como fatores controladores do crescimento no bioma "Deserto", onde os ciclos revelaram-se muito irregulares e o stress hídrico foi intenso.

- A integração de dados dendrológicos, sedimentológicos, paleogeográficos e zoneamentos paleoclimáticos propostos para o intervalo estudado, permite inferir que as condições que oportunizaram o desenvolvimento de associações florísticas em bioma

Deserto no Cretáceo Inferior, em intervalo "*greenhouse*" não encontram analogia em biomas atuais, em intervalo "*icehouse*".

- A integração de diferentes dados indica que parâmetros quantitativos que controlam o crescimento dos anéis de crescimento podem estar relacionados a caracteres ambientais e não somente a fatores climáticos. Dessa forma a relação entre a produção de anéis de crescimento e cinturões latitudinais, de forma ampla, não pode ser aplicada em lenhos fosseis, indistintamente.

# 4 – Anexos



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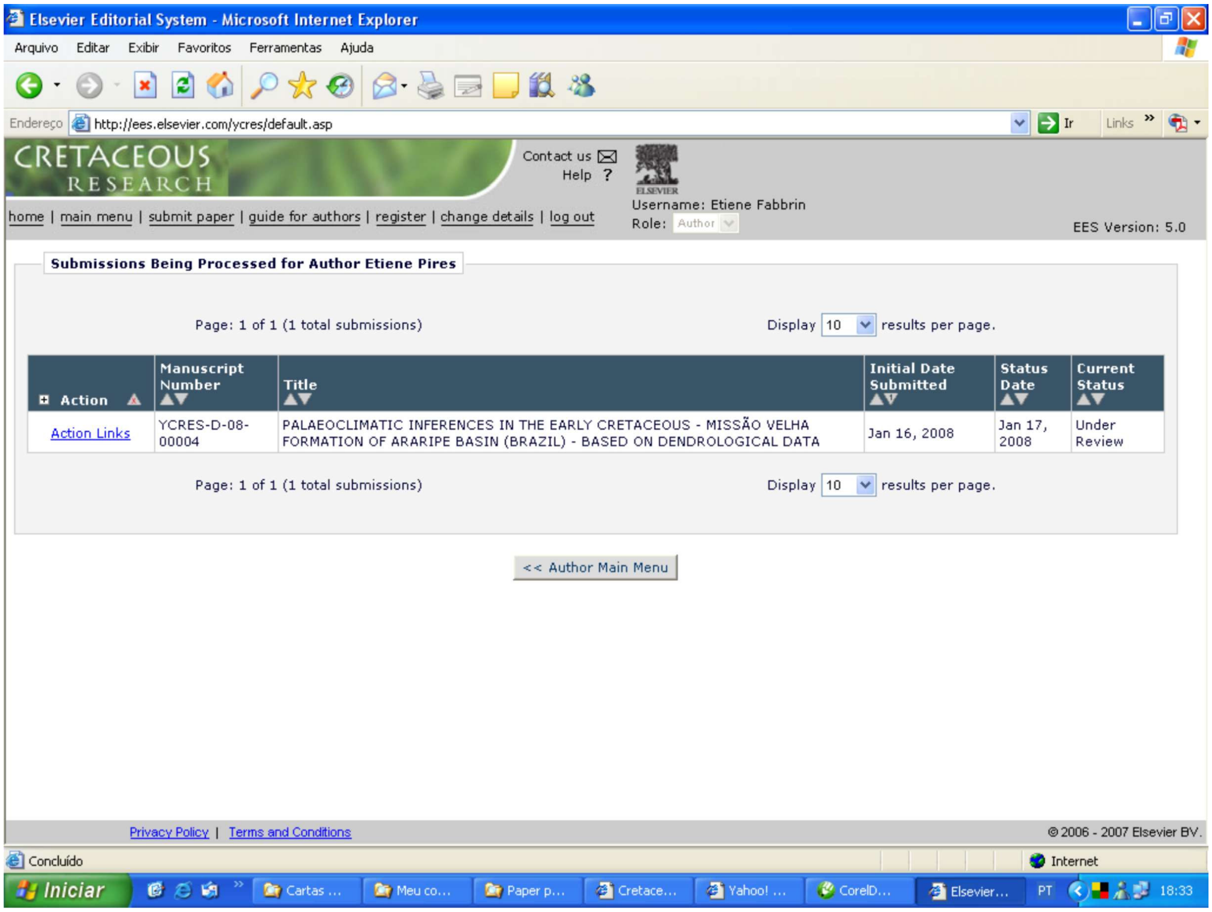

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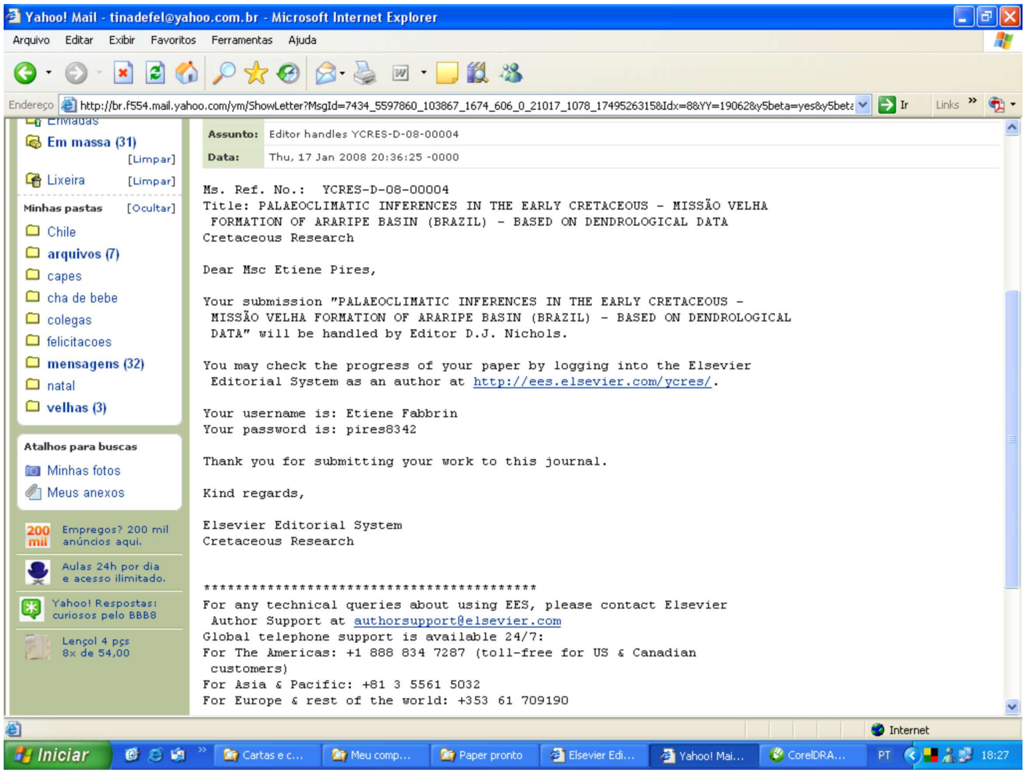

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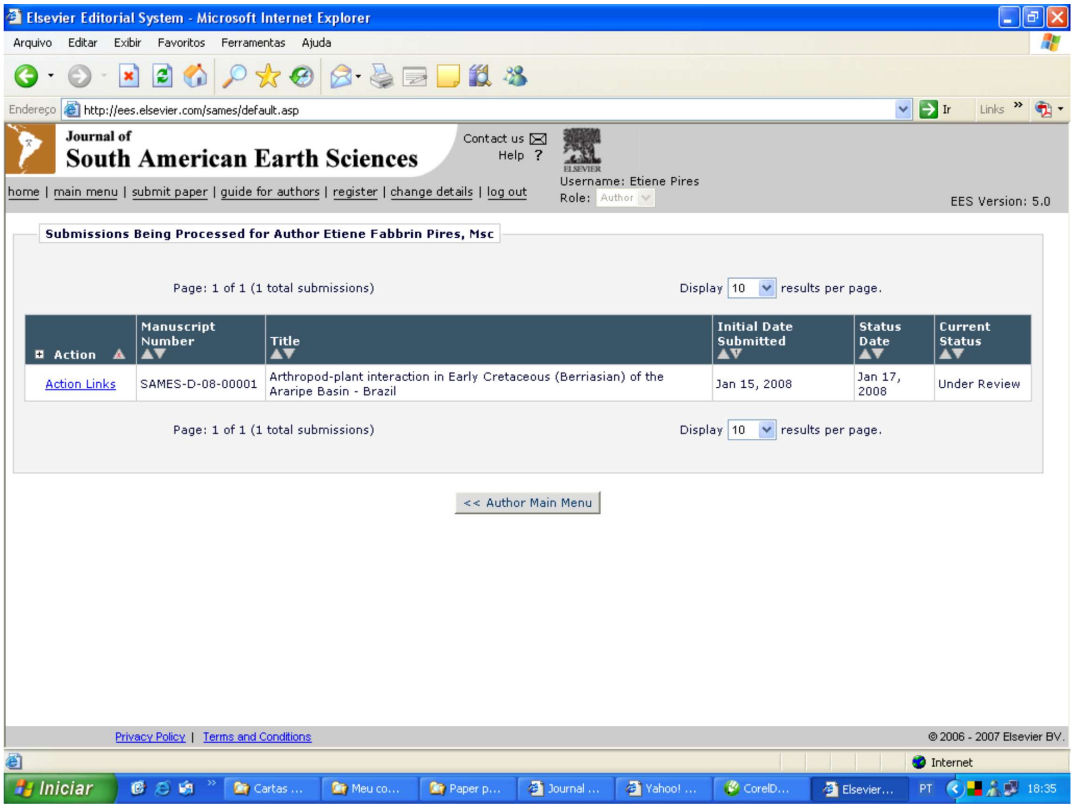

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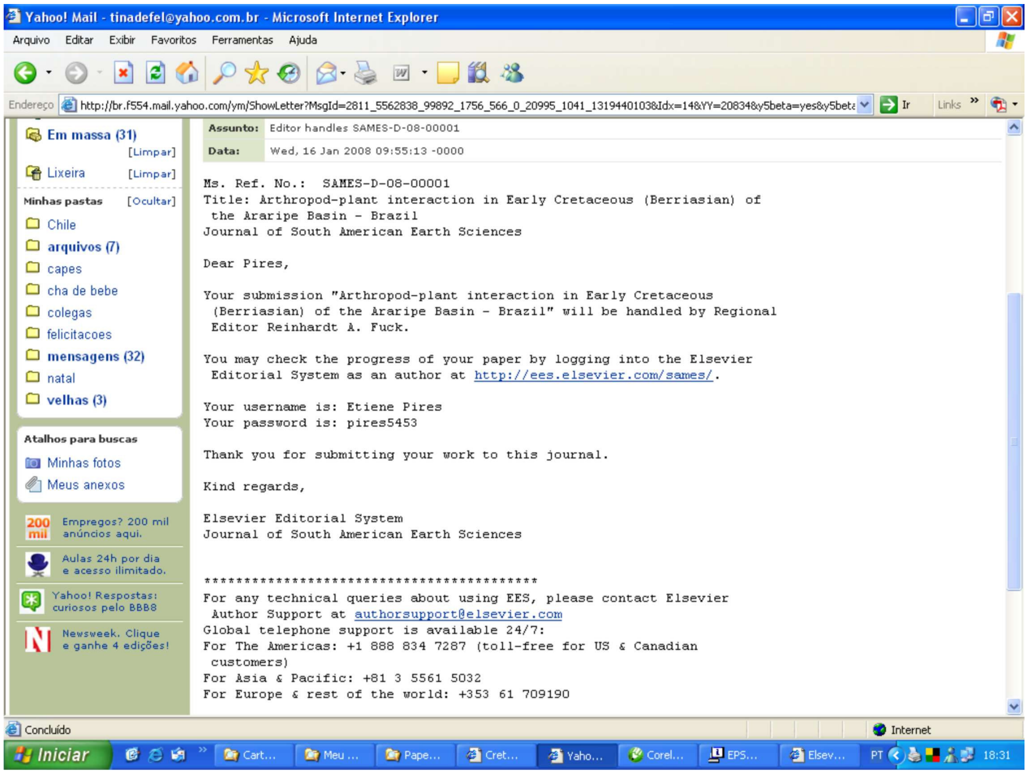

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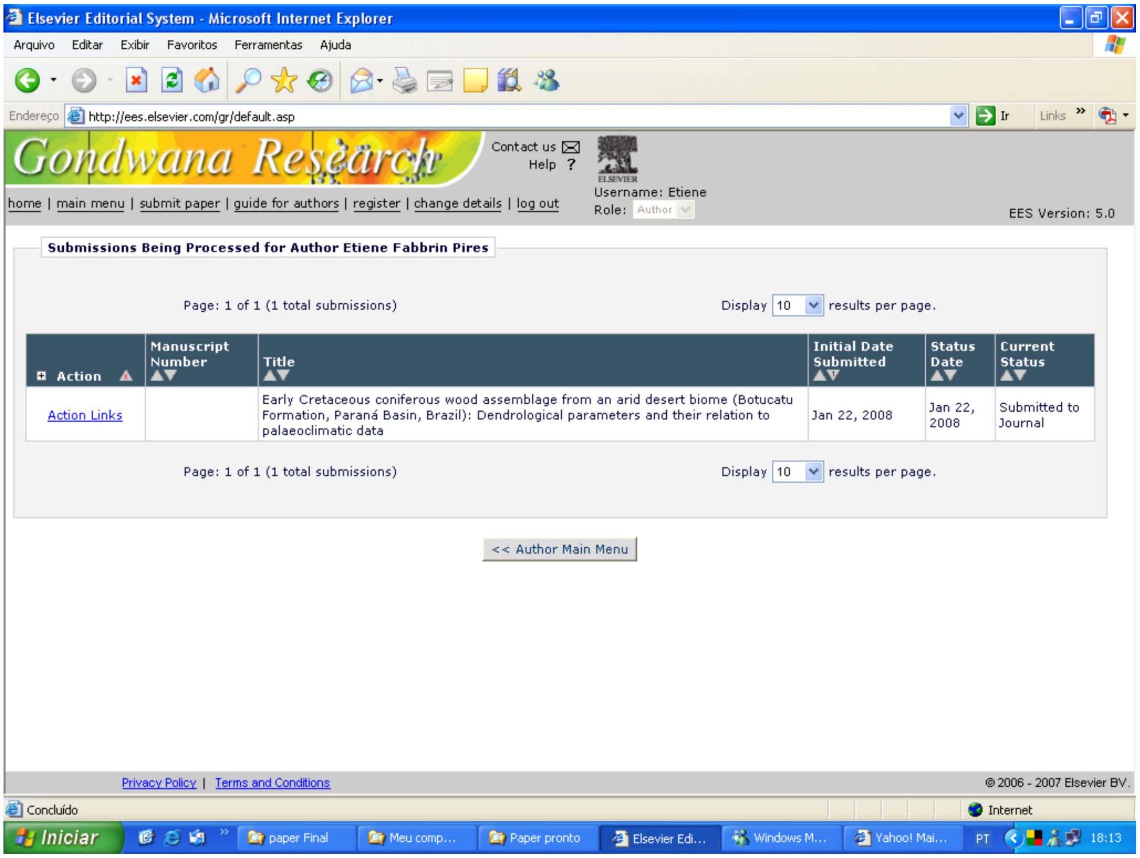

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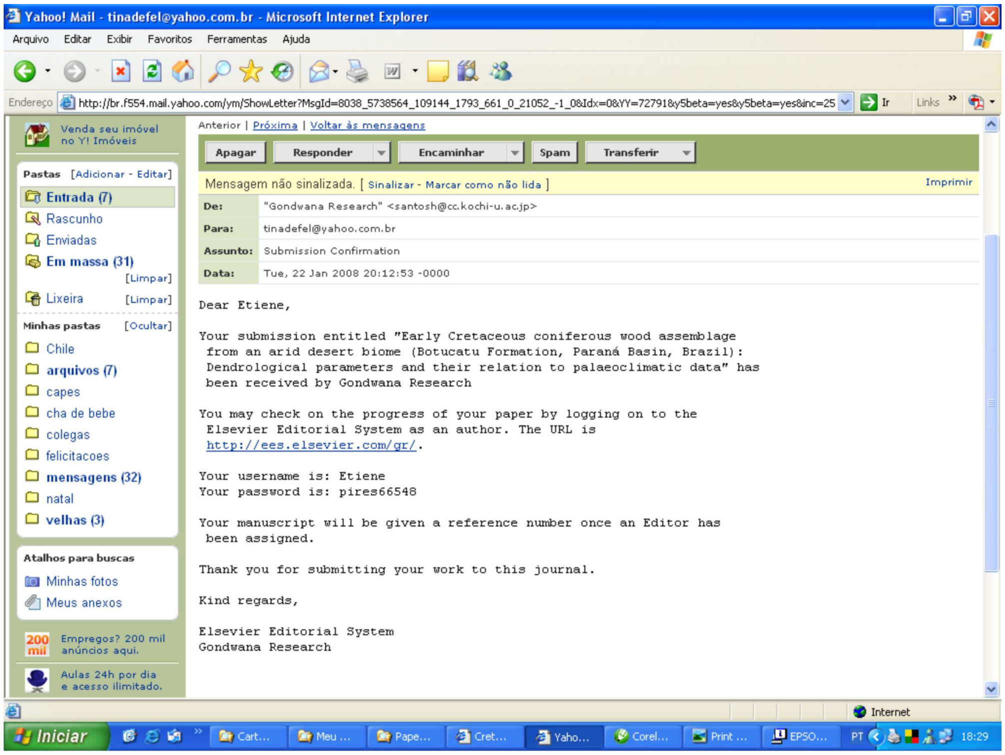

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Anais da Academia Brasileira de Ciências (2004) 76(3): 595-609
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# *Sommerxylon spiralosus* from Upper Triassic in southernmost Paraná Basin (Brazil): a new taxon with taxacean affinity

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## ABSTRACT

The anatomical description of silicified Gymnospermae woods from Upper Triassic sequences of southernmost Paraná Basin (Brazil) has allowed the identification of a new taxon: *Sommerxylon spiralosus* n.gen. et n.sp. Diagnostic parameters, such as heterocellular medulla composed of parenchymatous and sclerenchymatous cells, primary xylem endarch, secondary xylem with dominant uniseriate bordered pits, spiral thickenings in the radial walls of tracheids, medullar rays homocellular, absence of resiniferous canals and axial parenchyma, indicate its relationship with the family Taxaceae, reporting on the first recognition of this group in the Triassic on Southern Pangea. This evidence supports the hypothesis that the Taxaceae at the Mesozoic were not confined to the Northern Hemisphere.

**Key words:** fossil wood, taxacean affinity, Upper Triassic, Paraná Basin.

## INTRODUCTION

The petrified woods from several paleontological sites in the central portion of Rio Grande do Sul State (Brazil) have been ascribed to distinct ages and correlated to different stratigraphic units, such as the Rosário do Sul Formation – Triassic according to Gamermann (1973), the Caturrita Member of the Botucatu Formation with an age Jurassic as suggested by Bortoluzzi (1974), the Caturrita Formation of a Upper Triassic age according to Andreis et al. (1980) and the Mata Sandstone referred to the Rhaetian by Faccini (1989). Fossil woods occur as silicified fragments that are usually found as rolled pieces in sedimentary rocks, although they seldom occur included within the sedimentary deposits. The fossil record comprises mainly conifer-related gymnosperm forms and possibly represents a mesophytic flora originated when climate changes took place during the Meso-Neotriassic transition. The so called Conifer Flora is supposed to correspond to a younger association that the *Dicroidium* Flora, represented by impressions referred to the Asselian-Ladinian sedimentary sequences of the Santa Maria Formation (*sensu* Bortoluzzi 1974).

These occurrences of petrified wood in the Mesozoic of southernmost Paraná Basin have been know from more a century. They have been generally included by different authors in the genus *Araucarioxylon* Kraus (1870) and have been considered as indicative of Coniferales. According to Gram-

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bast (1960), Greguss (1967), Lepekhina (1972) and Mussa (1982), this genus is broad defined, encompassing almost all the possible variation in characters, and thus embracing a large group of plants. Consequently this taxon doesn't have taxonomic and phytostratigraphic relevance. Bamford and Philippe (2001) ratify that *Araucarioxylon* is illegitimate, and consider that most of wood species included of this genus should be transferred to *Agathoxylon* Harting.

The present study aims to describe and identify an association of silicified wood composed of specimens not decorticated, complete, recovered at the Linha São Luiz outcrop, district of Faxinal do Soturno at Rio Grande do Sul State southernmost Paraná Basin (Brazil). The sedimentary sequence which the outcrop is included, according to Rubert (2003) using litostratigraphic criteria, in the base of Caturrita Formation (*sensu* Andreis et al. 1980). Pires (2003) included the outcropping rocks in the Carnian-Eonorian Sequence according to Scherer et al. (2000). Besides silicified wood, different fossils were identified at this outcrop, represented by vertebrates (fish-scales, procolophonides, dinosaurs, mammals, cinodonts), invertebrates (conchostraceans and insects), icnofossils, shoots and reproductive structures of gymnosperms (Ferigolo and Ribeiro 2000, 2001). Impressions of leaves are included in the genus *Brachiphyllum* Brogniart by Bolzon et al. (2002) and the silicified woods are identified as *Araucarioxylon* Kraus. On the other hand, Dutra and Crisafulli (2002) characterized two different patterns of leaves: type-*Cyparissidium* and type-*Pagiophyllum*.

## MATERIALS AND METHODS

The 31 fragments of wood on which the present study is based, were collected from the same stratigraphic horizont in the Linha São Luiz outcrop (UTM: 22J0262516E/66277528N) in different missions, by researchers of UFRGS, UNIVATES and Fundação Zoobotânica do Rio Grande do Sul. Preservation is usually good, specimens are mostly silicified. Dense impregnation by iron oxide is a common feature. The type material is deposited in the Paleobotanical Sector of the Departamento de Estratigrafia e Paleontologia of the Instituto de Geociências of the Universidade Federal do Rio Grande do Sul, Rio Grande do Sul State, Brazil. The specimens were cut in transversal, radial and tangential planes; observations were made on polished surfaces, with incident light; anatomic details were observed from petrographic slides mounted in Canada balsam, in transmitted light.

## DESCRIPTION

### *Sommerxylon spiralosus* n.gen. et n.sp.

**Holotip –** PB 3784.

**Paratips –** MCN PB 338; MCN PB 339; MCN PB 340; MCN PB 357; MCN PB 366; PB 3779; PB 3789; PB 3790; PB 3810; PB 278.

**Locality –** Linha São Luiz outcrop, (UTM: 22J0262516E/66277528N), Faxinal do Soturno, Rio Grande do Sul State, Brazil.

**Horizon –** basal section of Caturrita Formation (*sensu* Andreis et al. 1980).

**Age –** Upper Triassic.

**Derivatio Nominis –** generic name: is attributed in honor to Dr. Margot Guerra Sommer; specific epithet – to derive from the presence of spiral thickenings in the radial wall of the tracheids.

## DIAGNOSIS

### *Sommerxylon* n.gen.

Gymnospermous wood consisting of pith, primary xylem, secondary xylem, phloem and cortex. Pith solid, circular to sub-circular, with occasional large gaps, irregularly shaped heterocellular. Thin walled parenchymatous cells of the pith, rounded or polygonal in cross section, grouped in solid nests. Thick walled sclerenchymatous cells, polygonal, walls heavily pitted, single and isolated or in small nests, not oriented. Protoxylem endarch, centrifugal, wedge shaped. Growth rings distinct, large, with a gradual transition from early to late wood; early wood wide. Bordered pits in radial walls of secondary xylem uniseriate (99%), isolated or contiguous, locally biseriate (1%) alternate or opposite. Medullary ray homocellular, uniseriate. Cross-field pits single, small, 1–4 pits per cross-field, irregularly disposed. Radial spiral thickenings single in radial walls, inclination against the wall of tracheids 40–45°. Wood parenchyma and resinous canals absent. Phloem not differentiated in primary and secondary phloem, showing parenchymatous cells with dark contents and phloematic rays; resinous canals absent. Cortex with parenchymatous cells and canals.

### *Sommerxylon spiralosus* n.gen. et n.sp.

Gymnospermous wood consisting of pith, primary xylem, secondary xylem, phloem and cortex. Pith almost circular, with irregular boards, small to medium size (2,5–7,75 mm in diameter), heterocellular, composed by parenchymatic and sclerenchymatic tissues. Medullar parenchyma comprising thin walled cells irregularly rectangular to sub-circular grouped in nests. Sclerenchymatous cells thick walled, heavy pitted, polygonal interposed singly or in irregularly nests with parenchymatic tissue. Large mesh gaps of irregular shape not orientated dispersed in the pith. Primary xylem easily distinguished in transverse section, endarch, dispersed in wedge shaped bundles at the periphery of the pith composed by cells thin walled. Secondary xylem centrifuge, radially disposed. Distinct growth rings 1,12-6 mm wide, showing a gradual transition from early to late wood. Early wood 58-150 cells (1-4 mm), tracheids wide, polygonal lumen almost rectangular. Late wood narrow 6-20 cells (0,08-0,95 $\mu$m), compressed radially with a compressed lumen, rectangular in shape. False growth rings not continuous all over the diameter are frequent. Radial walls of tracheids with bordered pits, mainly uniseriate (99%), circular, isolate or contiguous flattened; partially biseriate (1%), alternate or opposite. Medullary rays homocellular, uniseriate, cells oval in tangential view, 1-22 cells high (average height 6 cells). 1-4 circular and small pits per cross-field; pit pore is usually centric, circular to sub circular. Spiral thickenings in radial walls of tracheids, distance between the bands 10 to 28 $\mu$m, running parallel, about 2 $\mu$m in thickness; individual bands are flat, inclination against the walls 40° to 45°. Wood parenchyma and resinous canals absents. Phloem not differentiated in primary and secondary phloem, showing parenchymatous cells with dark contents and phloematic rays; resinous canals absent. Cortex with circular cells (parenchymatous cells) and canals.

The material corresponds of fragments of petrified wood, measuring 2-10 cm in length and 2-8,5 cm in diameter (Fig. 1,a), cylindrical, sometimes slightly compressed in transversal view.

All the specimens are composed by pith, primary xylem, secondary xylem, phloem and cortex. The pith is circular (Fig. 1,d), centric or eccentric, small to medium (2,5-7,75 mm), solid (Fig. 1,d), or with mesh gaps in some levels, which are irregularly shaped and disposed without any kind of organization, probably originated by cellular decay (Fig. 1,c; Fig. 3,e).

The pith is heterocellular, composed by parenchymatic and sclerenchymatic tissues (Fig. 1,d). Parenchymatous cells are circular to sub-rectangular or polygonal in shape, of different sizes. Large cells occur dispersed trough the pith (D: 24-40 $\mu$m) and smaller ones forms solid clusters (D: 18-22 $\mu$m) (Fig. 3,e).

The sclerenchymatous cells are either single or grouped in nests dispersed all over the pith without any kind of arrangement (Fig. 1,c). These cells vary in size (42-180 × 32-150 $\mu$m) are usually isodiametric in transverse section (Fig. 1,b) and rectangular in longitudinal view. Their walls show several layers of thickenings and are heavy pitted, radial canals can be observed running from the external radial walls to the lumen (Fig. 1,b).

The primary xylem encircles the pith disposed in wedge shaped bundles, and in some places projects into the pith. It is endarch and can be distinguished from secondary xylem in transverse section having thinner walls and tracheids being circular to sub-circular in shape (Fig. 1,c). The endarch dispo-

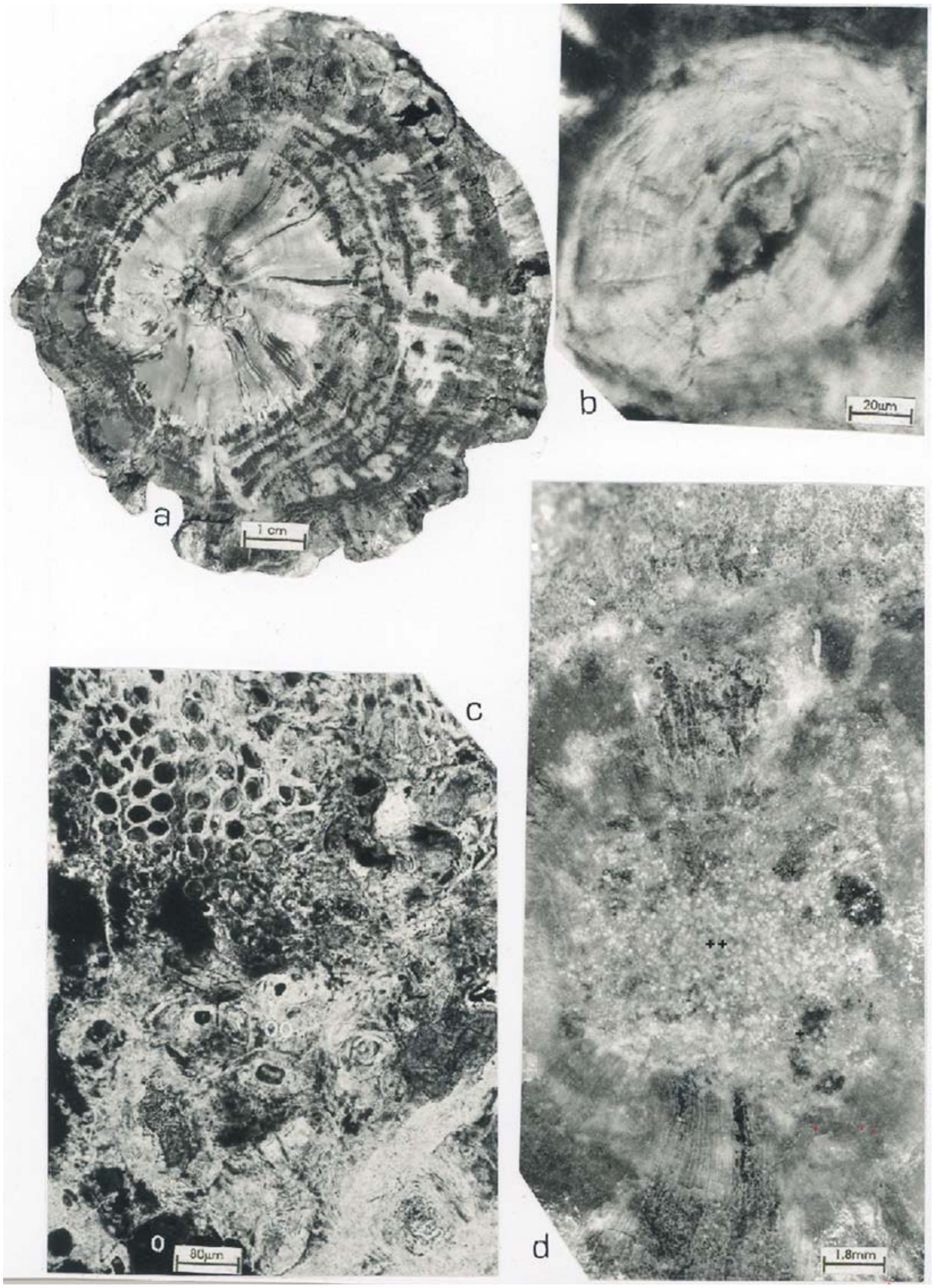

Fig. 1 – *Sommerxylon spiralosus* n.gen. et n.sp. Transverse section **a:** distinct growth rings, represented by clear and dark bands – Pb 278. **b:** Sclerenchymatous thick walled cell, heavy pitted. **c:** primary xylem endarch, wedge shaped, outlying the periphery of the pith, nest of sclerenchymatous cells irregularly gaps. d: solid pith heterocelular – PB 3782.

sition was not confirmed in the radial longitudinal section, where primary xylem was not preserved.

The secondary xylem is centrifuge, radially disposed; growth rings are distinct (Fig. 1,a), with gradual transition from early to late wood (Fig. 4,a). The circular cross-section of the growth rings indicated a possible relation of the specimens with vertical stems according the criteria of Schweingruber (1996). Rings 62-170 tracheids wide, 1,12-6 mm broad.

Early wood in each ring is wide, 58 to 150 cells deep; the width of the early wood varies from 1 to 4 mm; the tracheids are rectangular in transverse section (20-50 $\mu$m) with circular lumen (4-32 $\mu$m).

Late wood is narrow, 6 to 20 cells deep and the tracheids are radially compressed (10-30 $\mu$m) and have a small lumen (2-30 $\mu$m), rectangular in shape. The width of the late wood varies from 0,08 to 0,95 $\mu$m.

False growth rings are common along different levels of the secondary xylem, characterized by being not uniform and continuous rings around the transverse section.

Radial walls of tracheids have bordered pits showing dominantly uniseriate disposition (99%), closely spaced (Fig. 2,b,c) or contiguous slightly flattened (Fig. 2,e). When the pits are separated, they are more or less circular (D: 8-11 × 26-50 $\mu$m) with a spacing of 2 to 4 $\mu$m. The disposition partially biseriate altern or opposite were very rarely observed (1%) (Fig. 2,a,d). The pit pore is usually centric, circular to sub-circular (D: 2-4 $\mu$m) (Fig. 2,e).

Spiral thickenings are common on radial walls of tracheids (Fig. 3,a,b,c) rarely in longitudinal walls. The individual bands are flat, wide, single, running parallel; the distance between the bands of the spiral is about 10-28 $\mu$m. In some tracheids the individual bands of the spiral thickenings are superposed, resembling as double (Fig. 3,c). The inclination of different spirals against the wall of the tracheids is 40 to 45°. Tangential walls of tracheids are unpitted.

Medullary rays are homocellular, parenchymatous, smooth, uniseriate, 1 to 22 cells high (average 6 cells) (Fig. 3,d); their thick varies from 7 to 26 $\mu$m and their height from 114 to 496 $\mu$m. Ray cells are oval to sub-circular in tangential view. The density of the rays is 4 to 6 per millimeters square.

Cross-field pits are badly preserved (Fig. 2,f), varying from 1-4 pits per field (Fig. 2,g), and seems to be ordered in irregularly rows; they are circular, small (2 to 4 $\mu$m in diameter) with a round central pore (Fig. 2,h).

Axial parenchyma and resinous canals were absent in the secondary xylem.

Cellular elements of the cambium have collapsed, giving the appearance of a continuous, all around gap, in transversal section.

Due to poor preservation not much is know about the phloem and cortex. The phloem and cortex have partially decomposed and only little information is available about its structures. The phloem is not differentiated in primary and secondary phloem; parenchymatous cells with dark contents are observed and phloematic rays are represented as dark bands (Fig. 4,b); resinous canals and fibers were not visualized. The cortex is characterized by circular cells (parenchymatous cells?) and the presence of canals (Fig. 4,c).

## DISCUSSION

The main features presented by the studied specimens are heterocellular pith with sclerenchymatic nests in a parenchymatic matrix, endarch protoxylem, uniseriate pits in radial walls of tracheids, medullary rays homocellular uniseriate, spiral thickenings in radial walls of tracheids, absence of axial parenchyma and resiniferous canals.

*Taxopitys* Kräusel (1928), a Permian gonduanic morphogenus [*Taxopitys Africana* Kräusel (1928), South Africa; *Taxopitys alves-pintoi* Kräusel and Dolianiti (1958) and *Taxopitys jolyi* Mussa (1982), Permian, Paraná Basin, Brazil] besides heterocelular medula with sclerenchymatous nests, presents protoxylem centripetal, mesarch, medullary rays uniseriate, cross-field with little pits, horizontal spiral thickenings and araucarioid pitting in secondary

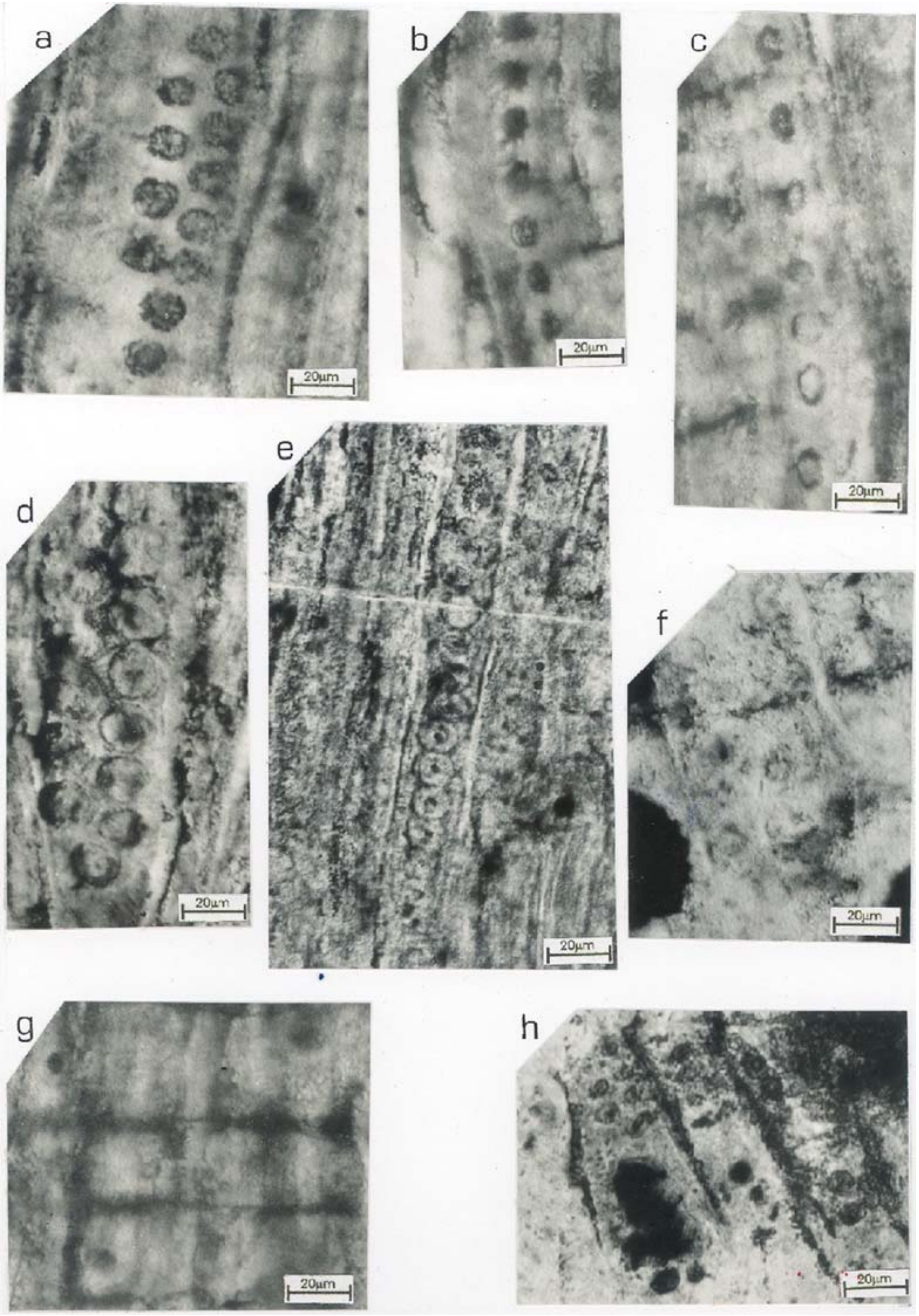

Fig. 2 –*Sommerxylon spiralosus* n.gen. et n.sp. Radial section **a:** tracheid with bordered pits partially biseriate alternate. **b:** tracheid with bordered pits uniseriate isolated. **c:** tracheid with bordered pits uniseriate isolated. **d:** tracheid with bordered pits partially biseriate alternate. **e:** tracheid with bordered pits uniseriate contiguous. **f, g:** cross-fields with not well preserved pits, circular. **h:** cross-field with 1-4 pits in irregularly rows.

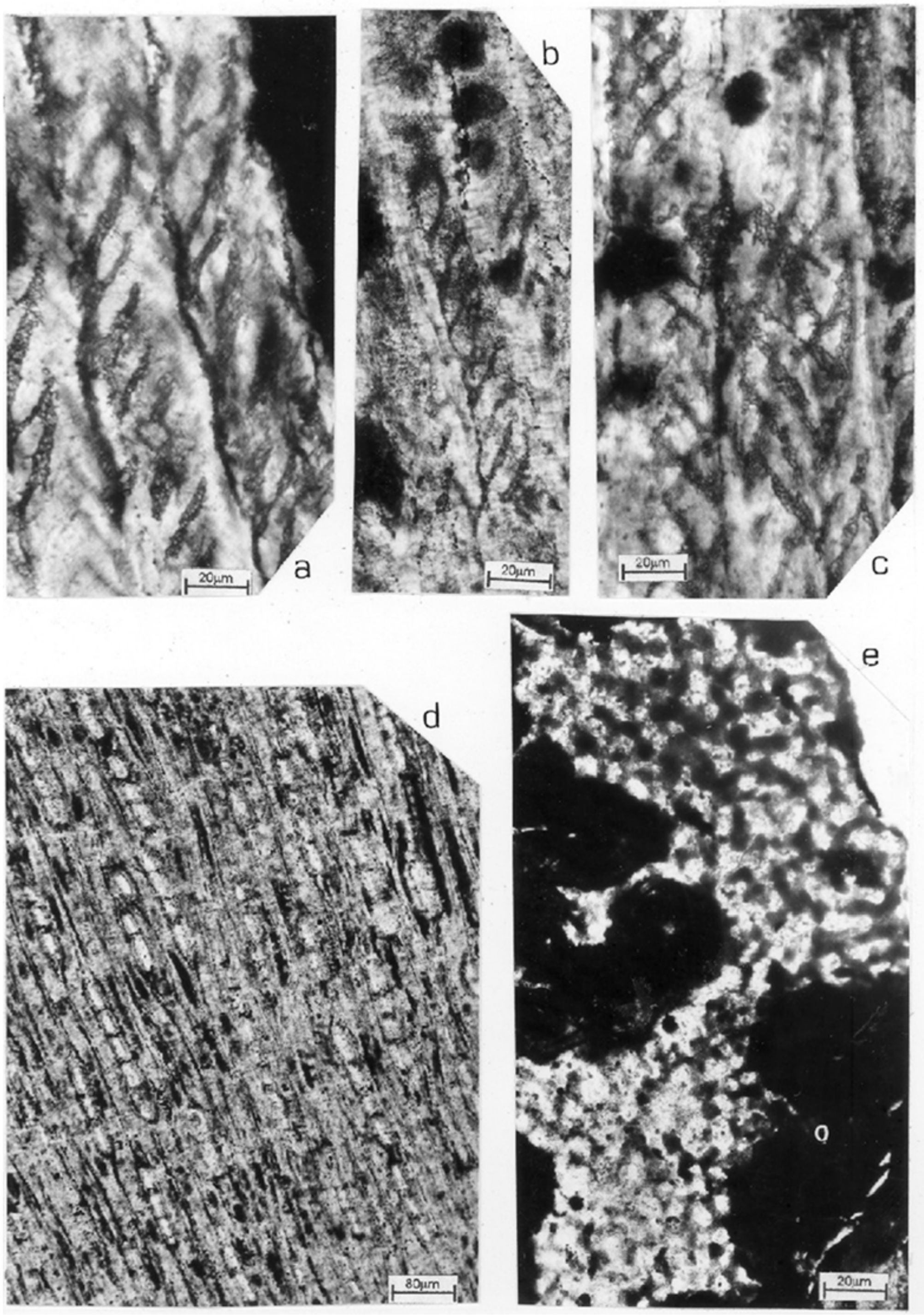

Fig. 3 – *Sommerxylon spiralosus* n.gen. et n.sp. Radial section – **a, b:** detail of simple spiral thickenings in the walls of the tracheids. **c:** spiral thickenings superposed. Tangential section – **d:** medullary rays. Transverse section – **e:** nest of parenchymatous cells in the pith associated to the irregularly gaps.

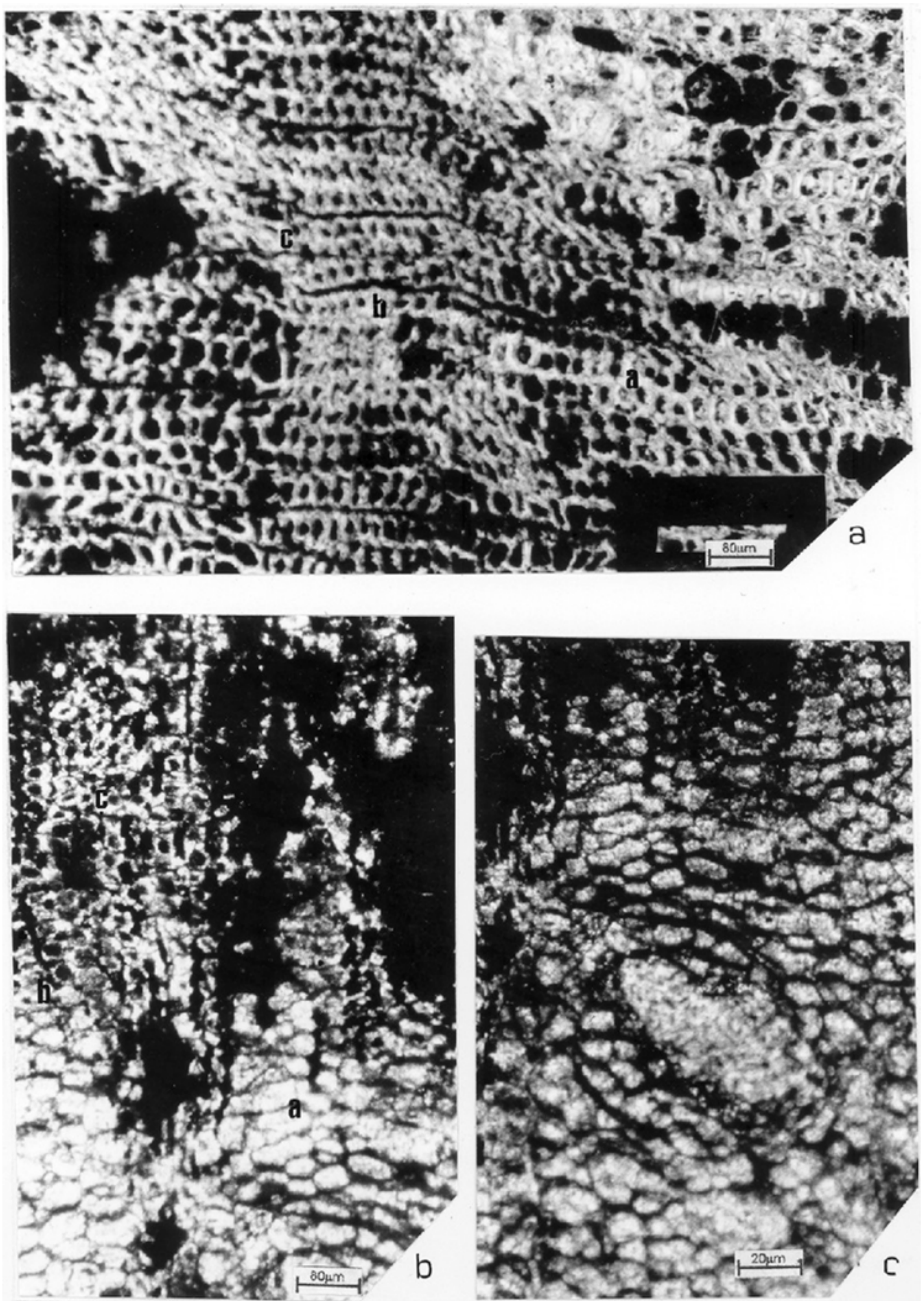

Fig. 4 – *Sommerxylon spiralosus* n.gen. et n.sp. Transverse section – **a:** secondary xylem showing the limit of growth ring; a – early wood; b – late wood; c – limit of the ring. **b:** limit among tissues; a – cortex; b – limit among issues; c – phloem with parenchymatous cells (clear with dark contents) and phloematic rays (dark radial bands). **c:** cortex with circular cells and channel.

xylem. The two last characters are different from the specimens here analyzed. At the same way, diagnostic parameters of the morphogenus *Parataxopitys*, (*P. brasiliana* Maniero (1951) and *P. Americana* Milanez and Dolianiti (1950) of Permian Paraná Basin, Brazil) as araucarioid pitting and the structure of spiral thickenings show distinct in relation to the specimens studied in this paper (Table I-A).

Dutra and Crisafulli (2002) cited *Kaokoxylon zalesskyi* (Sahni) Maheshwari, from the Linha São Luiz outcrop at the same level from were collected the present specimens. Taxonomic diagnostic features are neither cited, nor described or figured. However the characterization of *Araucarioxylon* type of secondary wood and the non-reference of spiral thickenings, indicates distinct taxonomic affinity from the specimen named as *Kaokoxylon* by Dutra and Crisafulli (2002).

Descriptions of homoxylous morphogenera restrict to secondary wood prolififerate in literature mainly in Mesozoic and Cenozoic periods. Table I-B gives complete data and important xylotomical features of this genus compared with the new taxon here proposed. The relevant character for comparison was the presence of true spiral thickenings in secondary xylem. According to Barefoot and Hankins (1982), spiral thickenings are genetic feature and so have diagnostic importance.

*Prototaxoxylon (= Spiroxylon)* Kräusel and Dolianiti (1958) correspond to a morphogenus defined originally from Upper Paleozoic at that time represented by *P. indicum (= Spiroxylon)* (Metha) Prakash and Srivastava (1961) (Permian- India), *P. (= Spiroxylon) africanum* (Walton) Kräusel and Dolianiti (1958) (Permian- Karoo Basin – South Africa), *P. brasilianum* Kräusel and Dolianiti (1958) (Upper Permian – Paraná Basin, Brazil), *Prototaxoxylon (Spyroxylon) intertrappeum* Prakash and Srivastava (1961) (Upper Cretaceous- India) and *Prototaxoxylon andrewsii* Agashe and Chitnis (1971). This wood, besides to be characterized by true spiral thickening on the radial walls of tracheids, differs from the specimens under examination by having radial walls of tracheids characterized by 1-3 seriate circular – slightly horizontally compressed bordered pits. The specimen identified as *P. intertrappeum* by Lutz et al. (1999), from the Upper Triassic of North then Chile, seems to correspond by the characters figurate, to *Taxaceoxylon* Kräusel (1949) instead of *Prototaxoxylon*.

The presence of bars of Sanio and axial parenchyma are important and distinctive characters in the genus *Platyspiroxylon* Greguss (1961) described from the Jurassic of Hungry (*P. heteroparenchymatosum* Greguss 1961) and *P. parenchymatosum* from the Permian of Hungry (Greguss 1967) and Upper Cretaceous of Canada Ramanujam (1972). A comparison with *Torreyoxylon boureaurii* Greguss (1967), Lower Cretaceous from Hungry, make evident important differences, such as the presence of axial parenchyma and spiral thickenings in doubles bands.

The genus *Taxaceoxylon* Kräusel (1949) was proposed in substitution of *Taxoxylon* Kraus (1870) originally described as *Taxites scalariformis* (Goeppert) {= *Taxoxylon Goepperti* Unger = *Taxaceoxylon escalariforme* (Goeppert) Seward (1919)} which was invalidated.

This taxon includes specimens of secondary homoxylic wood with true spiral thickenings and abietinean type of pitting in the radial walls of tracheids, medullary rays homocellular, absence of resiniferous cells or ducts and axial parenchyma. The identification was based only on the characters of the secondary wood; some distinguishing features of the pith corresponding to thick walled polygonal cells dispensed in the parenchymatous tissue, were mentioned by Kräusel (1949), but not included in the diagnosis of the genus.

Kräusel and Jain (1963) have shown that only a few woods described as *Taxaceoxylon (Taxoxylon)* really belongs to the Taxaceae, corresponding to *Taxaceoxylon torreyanum* Shimakura (1936) from Pliocen of Japan, *Taxaceoxylon (=Taxoxylon) antiquum* (Boeshore and Gray) Kräusel (1949) from the Upper Cretaceous of North Caroline (EUA) and *Taxaceoxylon rajmahalense* (Bhandwaj) Kräusel and Jain (1963) from Jurassic of India.

**TABLE I-A**

**Characterization of fossil woods with spiral thickenings in radial walls of tracheids. Fossil with primary structures.**

| Species | Locality / Horizon / age | Cross field | Medullary rays | Bordered pitting | Spiral thickenings |
|---|---|---|---|---|---|
| *Taxopitys africana* Kräusel (1928) | South Africa<br>- Kaoko Formation<br>- Permian | 2 to 8 minute pits per cross field, aperture obliquely oriented | Uniseriate, up to 18 cells high, walls smooth | Uniseriate occasionally biseriate, alternate, aperture circular | Ticklish and forked |
| *Toxopitys alves-pintoi* Kräusel & Dolianiti (1958) | Brazil<br>- Irati Formation<br>- Permian | 1-4 pits per cross field arranged in 2 rows, rarely 6 pits arranged in 3 rows | Uniseriate, 2-6 cells high | Uniseriate occasionally triseriate alternate | Ticklish, horizontal |
| *Toxopitys jolyi* Mussa (1982) | Brazil<br>- Irati Formation<br>- Permian | 1-4 minute pits per cross field, aperture circular or obliquely lenticular | Uniseriate, up to 8 cells high, rarely partly biseriate | Late wood: normally uniseriate and contiguous, compressed in shape with aperture circular; sometimes biseriate alternate, sub-circular to sub-hexagonal | Single, occasionally double, horizontal |
| *Parataxopitys brasiliana* Maniero (1951) | Brazil<br>- Irati Formation<br>- Permian | 4-6 pits per cross field | Uniseriate, 2-7 cells high, in transverse section the average of high is 20,5 $\mu$m | Uniseriate, contiguous, compressed in shape, 10-20 $\mu$m in diameter; occasionally biseriate, alternate, 14-16 $\mu$m in diameter; border circular, aperture 1-2 $\mu$m in diameter; | Ticklish, horizontal, sometimes with a forked thicken distance 6-8 $\mu$m |
| *Parataxopitys americana* Milanez & Dolianiti (1950) | Brazil<br>- Irati Formation<br>- Permian | 4-6 pits per cross field | Uniseriate | Uniseriate rarely biseriate alternate | Ticklish, horizontal |

After the revision of Kräusel and Jain (1963) new species were described *T. cupressoides* Sharma (1970), from Jurassic Sequences of India, *T. japonomesozoicum* Nishida (1973), from Cretaceous of Japan e *T. mcmurrayensis* Roy (1972) registered from Lower Cretaceous of Canada.

Bamford and Philippe (2001) revised the generic names of Jurassic/Cretaceous homoxylons wood, applying the roles of the International Code of Botanical Nomenclature (Greuter et al. 1999), and indicate that *Taxoxylon* should be abandoned and *Taxaceoxylon* preferred.

A detailed comparison with regard to the nature of bordered pits, spiral thickenings, medullary rays, number of cross-field pits and absence of resin ducts and axial parenchyma (Table IA-B) shows that the studied specimens are more closely comparable to the genus *Taxaceoxylon*. The identification however is impossible because the diagnosis of *Taxaceoxylon* is based exclusively in characters of secondary wood. On the other hand, the specimens, under study presents distinguished features of the

**TABLE I-B**

**Characterization of fossil woods with spiral thickenings in radial walls of tracheids. Fossils restricted to secondary wood.**

| Species | Locality / Horizon / age | Cross field | Medullary rays | Bordered pitting | Spiral thickenings |
|---|---|---|---|---|---|
| *Prototaxoxylon indicum* (Metha) Prakash & Srivastava (1961) | India<br>- Permian | 6-7 pits per cross field, border elliptical, 6-8×3-4 $\mu$m in size | Uniseriate, 1 cell high, fairly thick walled, squarish, 20 $\mu$m vertical height | Uniseriate or irregularly biseriate (then alternate or opposite), contiguous (occasionally separate); circular or horizontally elliptical in shape, 14,5×15,5 $\mu$m (in early wood), smaller pits 4 $\mu$m in diameter | 1-2 seriate, passing in between the pits or across the borders of contiguous pits |
| *Prototaxoxylon brasilianum* Kräusel & Dolianiti (1958) | Brazil<br>- Estrada Nova Formation<br>- Permian | 1-4 pits per cross field, broadly oval, slit like oblique opening | Uniseriate, often biseriate, 1-6 (1-2) cells high, cells broadly oval | Single series (usually crowded) occasionally biseriate and alternate | Close, narrow and nearly horizontal, bands across the pits, look like scalariform pitting |
| *Prototaxoxylon africanum* (Walton) Kräusel & Dolianiti (1958) | South Africa<br>- Permian | 2-8 pits per cross field | Almost uniseriate 1-18 cells high, average height 31 $\mu$m | Normally uniseriate and contiguous, occasionally biseriate (mostly alternate an rarely opposite), often vertically compressed, 11-13 $\mu$m in size | 1-2 seriate, confined to the wall between the pits |
| *Prototaxoxylon intertrappeum* Prakash & Srivastava (1961) | India<br>- Deccan Intertrappean Series<br>- Upper Cretaceous | 1-10 pits per cross field, 6-11 $\mu$m in size, scattered or arranged in 1-3 horizontal rows; aperture circular or obliquely lenticular | 1-3 seriate (usually 1-2 seriate, exceptionally triseriate), 2-30 cells high (often up to 50); cells usually oblong, average height 24 $\mu$m, horizontal and tangential walls smooth and unpitted | Normally uniseriate and contiguous, sometimes biseriate (mostly alternate, occasionally opposite), circular or vertically compressed in shape (sometimes hexagonal), 13-20 $\mu$m in size, circular or obliquely lenticular aperture | 2-3 seriate, 5-11 $\mu$m thick, close, both left and right-handed, inclined at 50-70°, pass usually across the borders of contiguous pits or trough the space between the separate pits or become thin and pass trough the rim of the pore |

pith, primary xylem, phloem and cortex. Consequently, considering the restrictions of the International Code of Botanical Nomenclature (Greuter et al. 1999), a new taxon is proposed: *Sommerxylon spiralosus* nov. gen. et. nov. sp. The present wood possesses all the general anatomical characters of a taxacean wood, as it was referred by Kräusel (1949), and Kräusel and Jain (1963) based in Florin (1940). It's important to observe that, even not including pith studies in the diagnosis, Kräusel (1949) refers to the

**TABLE I-B (continuation)**

| Species | Locality / Horizon / age | Cross field | Medullary rays | Bordered pitting | Spiral thickenings |
|---|---|---|---|---|---|
| *Prototaxoxylon andrewsii* Agashe & Chitnis (1971) | India<br>- Barakar Stage<br>- Lower Permian | 2-6 pits per cross field; pits round to horizontally oval; type cupressoid; 8-10 $\mu$m, with circular to oblique pore (2 $\mu$m) | 1-2 seriate, predominantly uniseriate, 1-8 cells high; vertical diameter 29-40 $\mu$m | 1-3 seriate slightly horizontally compressed; biseriate are contiguous, alternate, subopposite or opposite; triseriate are alternate and contiguous; 10-12 $\mu$m in diameter | 3-11 $\mu$m in thickness, closely spaced, run clockwise or anticlockwise, single or double |
| *Platyspiroxylon heteroparenchymatosum* Greguss (1961) | Hungry<br>- Lower Jurassic | 1-6 pits callitroids per cross field, broadly elliptical | 40 cells high, smooth walls | Uniseriate, occasionally biseriate circular, contiguous or isolated, aperture oval | Parallel, large and compressed lines, type-callitoid, with bars of Sanio |
| *Platyspiroxylon parenchymatosum* Greguss (1967) | Hungry<br>- Permian<br>Canada<br>- Upper Cretaceous | 1-6 pits callitroids per cross field, pits broadly elliptical | 3-8 cells high, 25-30 $\mu$m in diameter; radial diameter 170-200 $\mu$m; smooth walls | Uniseriate occasionally biseriate circular, contiguous or isolated, aperture oval | Parallel, large and compressed lines, type-callitoid, with bars of Sanio |
| *Torreyoxylon boureaui* Greguss (1967) | Hungry<br>- Lower Cretaceous | Broadly triangular, squarish or polygonal | Uniseriate, 1-8-10 cells high, 18-20 $\mu$m in diameter, walls smooth and unpitted | Uniseriate, occasionally locally biseriate opposite, aperture obliquely | Rare, ticklish, single or double, distance 15-20-30 $\mu$m |
| *Taxaceoxylon torreyanum* Shimakura (1936) | Japan<br>- Kanagawa Basin<br>- Pliocene | — | — | Uniseriate isolated rarely opposite | Single, occasionally double |
| *Taxaceoxylon antiquum* (Boeshore & Gray) Kräusel (1949) | United States of America<br>- Upper Cretaceous | 2-4 pits per cross field | 1-21 cells high, mostly uniseriate but with paired cells in place; lateral walls with small round pits, 2-4 per tracheid | Uniseriate occasional biseriate | 2-4 series in the early wood and placed at approximately 45° angles with the long axis of the tracheids (tangential section) |
| *Taxaceoxylon rajmahalense* (Bardwaj) Kräusel & Jain (1963) | India<br>- Rajmahal Stage<br>- Jurassic | Not preserved | Simple, uniseriate, rarely partly biseriate, 1-22 cells high, tangential walls smooth | Uniseriate, circular, 10 $\mu$m in diameter, aperture circular, 6 $\mu$m wide | Visible both on the radial and tangential walls, sometimes single but mostly double, running parallel, distance 10-30 $\mu$m, inclination against the wall of the tracheid 40-70° |

**TABLE I-B (continuation)**

| Species | Locality / Horizon / age | Cross field | Medullary rays | Bordered pitting | Spiral thickenings |
|---|---|---|---|---|---|
| *Taxaceoxylon cupressoides* Sharma (1970) | India -Rajmahal Stage - Jurassic | 1 or rarely 2 large pits simple or bordered per cross field vertically arranged, circular or ovoid, 5-7,5 $\mu$m in long diameter | Uniseriate sometimes partially biseriate, 1-14 cells high, tangential walls smooth, radial walls with simple or bordered pits | Uniseriate or biseriate, opposite separate or contiguous, rounded with circular apertures | Single or double |
| *Taxaceoxylon japonomesozoicum* Nishida (1973) | Japan - Cretaceous | 1-2 pits per cross field, circular or ovoid, vertically arranged | Oblong or rectangular in tangential section, 18-25 $\mu$m and 9-14 $\mu$m in vertical height and horizontal width respectively, pitted only on the radial walls | Uniseriate, 11-13 $\mu$m in diameter, circular apertures with 5 $\mu$m in diameter | Single spirals solitary running with a pith of 7-15 $\mu$m, sometimes 20 $\mu$m |
| *Taxaceoxylon mcmurrayensis* Roy (1972) | Canada - McMurray Formation - Lower Cretaceous | 4-6 minute pits per cross-field, generally cupressoid, ocassionally tending to be taxodioid, aperture obliquely, horizontal walls smooth, thick, without any pits | Uniseriate, occasionally biseriate; 2-12 cells high, 15-20 $\mu$m in diameter | Uniseriate, circular, discrete, vestured, pores circular or oblique | One or two helices; nearly perpendicular to the vertical axis or at an acute angle to it |

similarity between the pith nature of *Taxaceoxylon* and that one of the extant genus *Torreya*. The same structures can be found in the pith of the specimens under the examination, and this evidence ratifies the botanical affinity between extant and fossil forms.

The occurrence of fossil representatives of the extant Taxaceae are mainly concentrated on the bases of leaf branches, the oldest one corresponding to *Paleotaxus rediviva* Nathorst (1908), from Upper Triassic of South Sweden; on the other hand, the oldest dated Taxacean petrified wood up till now was *Taxaceoxylon rajmahalense* (Bardwaj) Kräusel and Jain (1963) from Middle Jurassic from India. The identification of *Sommerxylon spiralosus* nov. gen. et nov. sp. in Upper Triassic sequences of southern Pangea supports the hypotheses of Kräusel and Jain (1963) based on Florin (1940) and Studt (1926) that in the Mesozoic the Taxaceae were not confined to the Northern Hemisphere.

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## RESUMO

A descrição anatômica de lenhos silicificados de Gymnospermae em seqüência do Triássico Superior no sul da Bacia do Paraná (Brasil), possibilitou a identificação de um novo taxon: *Sommerxylon spiralosus* n.gen. et n.sp. Parâmetros diagnósticos tais como medula heterocelular, composta por células parenquimáticas e esclerenquimáticas, xilema primário endarco, xilema secundário com pontoações areoladas unisseriadas dominantes, espessamentos espiralados nas paredes radiais dos traqueídeos, raios lenhosos homocelulares, ausência de canais resiníferos e de parênquima axial, indicam a sua vinculação à família Taxaceae, constituindo-se em reconhecimento inédito da presença deste grupo no Triássico Superior no sul do Pangea. Esta evidência suporta a hipótese de que a família Taxaceae não estava confinada ao Hemisfério Norte durante o Mesozóico.

**Palavras-chave:** lenho fóssil, afinidade com taxaceae, Triássico Superior, Bacia do Paraná.

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# Late Triassic climate in southernmost Parana Basin (Brazil): evidence from dendrochronological data

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## Abstract

Dendrochronological methods were used to study a fossil wood assemblage identified as *Sommerxylon spiralosus* Pires et Guerra-Sommer from outcropping sandstone fluvial sequences (Late Triassic of southernmost Parana Basin, Brazil). The climate signal from fossil woods, supported by sedimentary evidence, indicates a seasonal climate. Analysis of preserved growth rings has yielded information about the peridiodicity of growth related to seasonal cycles. The growth phase in each cycle developed at a slow rate, and the growing period was relatively uniform; in contrast, the periodic phases of growth restriction were not very extensive. These seasonal cycles were interrupted by occasional droughts during the growth season, reflected by the presence of false growth rings. These data match recent global climate patterns from the Late Triassic.

*Keywords:* Fossil wood; Growth rings; Late Triassic; Paraná Basin; Brazil; Paleoclimatology

## 1. Introduction

Fossil wood is an important component of Triassic floras from southern Parana Basin (Brazil) and, in some stratigraphic sequences, is the only plant material preserved. In Mesozoic sedimentary sequences of Rio Grande do Sul, fossil woods occur as silicified fragments that usually are found as rolled pieces on sedimentary outcrops, though they seldom occur within the sedimentary deposits. The petrified woods found in several paleontological sites have been ascribed to distinct ages and correlated with different stratigraphic units (Rosário do Sul Formation, Triassic, Gamermann, 1973; Caturrita Member of Botucatu Formation, Jurassic, Bortoluzzi, 1974; Caturrita Formation, Upper Triassic, Andreis et al., 1980; Mata Sandstone, Rhaetian interval, Faccini, 1989). The fossil record comprises mainly conifer-related gymnosperms and may represent a mesophytic flora that originated when climate change took place during the Meso-Neotriassic transition. This flora is supposed to correspond to a younger association than the *Dicroidium* flora, according to leaf impressions recovered from Asselian-Ladinian sedimentary sequences (Guerra-Sommer et al., 1985) of the Santa Maria Formation (*sensu* Bortoluzzi, 1974).

The anatomical description of silicified gymnosperm woods from the Linha São Luiz outcrop, Faxinal do Soturno, Rio Grande do Sul, has enabled the identification of *Sommerxylon spiralosus* Pires et Guerra-Sommer (2004). Diagnostic parameters of the wood, such as heterocellular medulla composed of parenchymatic, secretory, and sclerenchymatic cells; primary xylem endarch; secondary xylem with dominant uniseriate pits; spiral thickenings in the radial walls of tracheids; an absence of resiniferous channels; and axial parenchyma indicate its relationship with the family Taxaceae and its first recognition in the Triassic of southern Pangea.

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This evidence supports the hypothesis of Kräusel and Jain (1963) that the Mesozoic Taxaceae were not confined to the Northern Hemisphere.

Ferigolo and Ribeiro (2000, 2001) refer to different fossils in the Linha São Luiz outcrop, represented by vertebrates (fish scales, procolophonides, dinosaurs, mammals, cinodonts), invertebrates (conchostraceans, insects), ichnofossils, fossil woods, shoots, and reproductive structures of gymnosperms. Bolzon et al. (2002) identify the impressions of leaves as *Brachyphyllum* Brogniart and the silicified woods as *Araucarioxylon* Kraus. However, Dutra and Crisafulli (2002) characterize two different patterns of leaves identified as type *Cyparissidium* and type *Pagiophyllum,* referring to *Kaokoxylon zalesskyi* (Sahni) Maheshwari for the silicified wood. Bonaparte et al. (2003) describe two new derived cinodonts from this outcrop: *Brasilodon quadrangularis* Bonaparte et al. and *Brasilitherium riograndensis* Bonaparte et al.

Schultz et al. (1994, 2000), Schultz (2001), and Cisneros and Schultz (2003) suggest a Late Ischigualastian–Early Coloradian age (approximately equivalent to Late Carnian-Early Norian of the marine European biochronology) for the fossiliferous bed of Faxinal do Soturno. The outcropping sedimentary sequence is included in either the base of the Caturrita Formation (Rubert, 2003 *sensu* Andreis et al., 1980) or the Carnian-Eonorian sequence (Pires, 2003 *sensu* Scherer et al., 2000).

On the basis of lithostratigraphic studies, Rubert (2003) claims the Ictidosauria assemblage zone (base of Norian) refers to a depositional environment related to floodplain facies in a fluvial system with channels and ephemeral shallow lakes.

In the fossil woods collected at the Linha São Luiz outcrop, the growth rings are distinct with a gradual transition from early to latewood. The study of growth rings in fossil woods allows, in certain conditions, the recognition of climatic tendencies that can be used to infer the environmental conditions during the lifetime of the plant (Creber and Francis, 1999; Parrish, 1999). This dendrochronological analysis provides important contributions for different floristic paleoprovinces (Arnold, 1947; Beck, 1953; Matten and Banks, 1967; Chaloner and Creber, 1973; Fritts, 1976; Francis, 1984; Chapman, 1994; Yao et al., 1994; Falcon-Lang, 1999; Falcon-Lang, 2000).

Bolzon's (1993) preliminary study indicates the presence of false growth rings in some gymnosperm woods from southern Parana Basin in the Mesozoic (Mata sandstone *sensu* Faccini, 1989). The generation of false growth rings was attributed to abrupt changes in the water supply, not necessarily a hot climate that was seasonally humid, annual, or cyclic (Larson, 1969).

This article aims to present new information about the Late Triassic climate in the southern Paraná Basin on the basis of a dendrochronological analysis of the fossil wood assemblage of the Linha São Luiz outcrop.

## 2. Material

The fragments of wood on which the present study is based (11 specimens) were collected during different missions from the same stratigraphic horizon in the Linha São Luiz outcrop, Faxinal do Soturno, Rio Grande do Sul, Brazil (UTM: 22J0262516E/66277528N) (Fig. 1), included either in sedimentary sequences or as rolled fragments in a transect of approximately 30 m. Preservation is usually good, and anatomical details are well preserved; specimens are mostly silicified. The fossil specimens range in size from 2 to 8.5 cm in diameter, and all include primary structures (pith and primary xylem), in addition to secondary xylem, phloem, and cortex. The circular cross-section of the growth rings indicates that they may represent remains of trunks, according to the criteria of Schweingruber (1996). Dense impregnation by iron oxide is a common feature. The type material is deposited in the Paleobotanical Sector, Departamento de Estratigrafia e Paleontologia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil. Observations were made on polished surfaces combined with a graduate scale with incident light; anatomic details were observed from petrographic slides mounted in Canada balsam in transmitted light.

## 3. Facies analysis of outcrop

Using the vertical stratigraphic column (Fig. 2), it was possible to identify two facies associations: (1) massive sandstone and (2) mudstone and sandstone sheets.

### 3.1. Massive sandstone

#### 3.1.1. Description

This facies association is composed of moderately sorted, reddish, medium- to coarse-grained sandstone. The sandstone is massive and displays abundant intraformational mudstone clasts. It forms 5 m thick and more than 30 m wide packages (outcrop maximum size). Tetrapod fossils, related to cinodonts, sphenodonts, procolophonides, and dinosaurs (Ferigolo and Ribeiro, 2000; Bonaparte et al., 2003) and found either articulate or disarticulate, are common.

#### 3.1.2. Interpretation

The massive sandstones may be produced by postdepositional modification related to dewatering and bioturbation or sediment-rich gravity flow (Miall, 1996). The lack of evidence of faint residual sedimentary structures and the occurrence of different vertebrate taphonomic classes suggests fast deposition in sediment-rich gravity flows. Fonseca (1999) interprets this facies association as channel deposits generated by bank collapse.

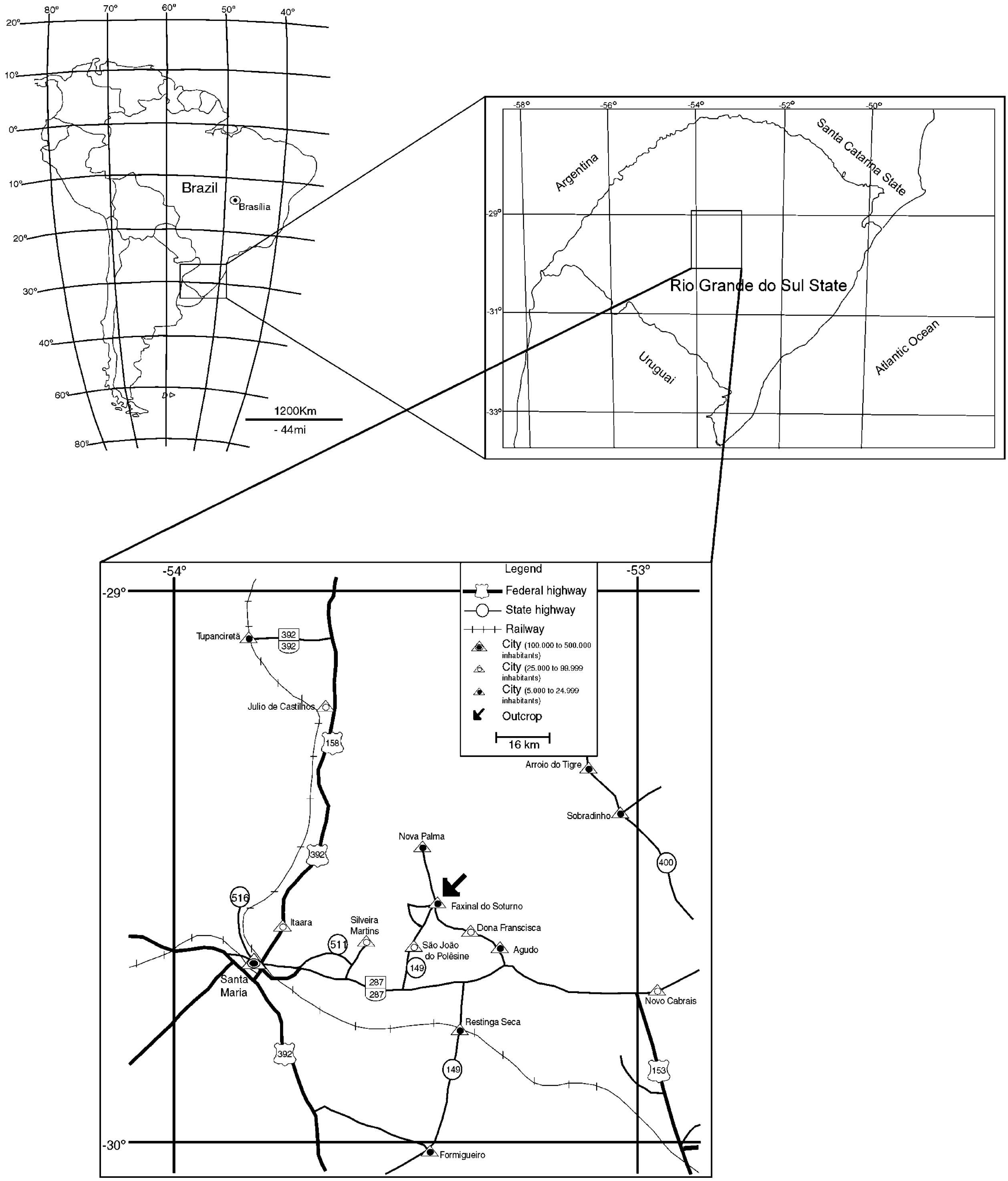

Fig. 1. Location of the studied area. Arrow indicates the fossiliferous locality.

### 3.2. Mudstone and sandstone sheets

#### 3.2.1. Description

This facies association abruptly covers the massive sandstone deposits. The basal surface is slightly undulating with less than 50 cm of relief. The base of the succession is composed of horizontal laminated mudstone with abundant fossil fragments represented by fish scales, conchostraceans, insects, and fossil wood. The upper section consists of sandstones and interbedded mudstone. The sandstone layers are fine to coarse grained and 0.1–0.6 m thick and exhibit ripple cross-lamination and rare trough cross-bedding. Bioturbation is common. Some levels of interbedded mudstone contain mudcracks.

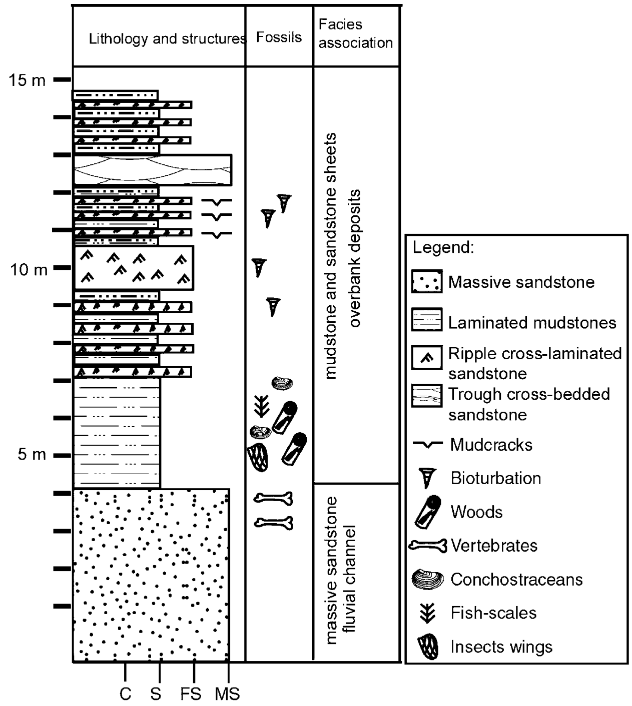

Fig. 2. Stratigraphic column of the Linha São Luiz outcrop.

### 3.2.2. Interpretation

The laminated mudstone from the base of the succession is interpreted as a floodplain deposit. The sandstone-pelitic rhythmic succession from the top of the section is interpreted as a crevasse splay deposit. The cycle coarsening and thickening upward may represent restricted lacustrine deltas associated with the progradation of crevasse splay lobes similar to those described by Kirschbaum and McCabe (1992). The abundance of bioturbation indicates that the crevasse deposits were intensively colonized by invertebrates. The presence of mudcracks in this crevasse deposit suggests alternating wet and dry events.

## 4. Methods

Statistical data from a selection of 11 fossil wood samples were obtained in accordance with Fritts (1976) (based on Douglass, 1928), using mean sensitivity (MS) and annual sensitivity (AS).

Schweingruber (1996) bases his approach on that established by Douglass (1928), which characterizes sensitivity as the degree to which a tree reacts to environmental factors and depends on the species. This sensitivity can be observed in the sequence of growth rings and contemplated in the increase of narrow or wide tree rings or the occurrence of density fluctuations.

According to Fritts (1976), MS is a measure of the variability of growth from year to year. Numerically, MS represents the mean variability in ring widths over a series of rings (for the formula, see Fritts, 1976; Francis, 1984; Creber and Francis, 1999). Values range from 0 to a maximum of 2. An arbitrary value of 0.3 is taken to separate 'complacent' trees that grow under a favorable and uniform climates ($MS \leq 0.3$) from those that are 'sensitive' to fluctuating climate parameters ($MS \geq 0.3$). The AS was calculated for each individual wood specimen and has been arranged into histograms. It shows that two woods may have the same MS but different patterns of AS.

For fossil growth analysis, it was assumed that relative ring width is a simple proxy for climate, in which narrower rings indicate cooler climates and wider rings suggest warmer climates (Fritts, 1976). The presence of false growth rings was considered a parameter that has climatic significance, in that it evinces interruptions of growth during a growing season.

Studies related to the determination of the index of MS in fossil woods demand many samples of the same taxon. Therefore, the use of this methodology is quite uncommon because of the rare occurrence of suitable fossils and even rarer discovery of a great number of monospecific individuals. Only a few authors (Creber and Chaloner, 1984; Francis, 1984; Brea, 1998; Francis and Poole, 2002) have used MS as tool for paleoclimatic analysis.

## 5. Results

The presence of distinct growth rings in the wood specimens (Fig. 3a) is indicative of a seasonal climate. Growth rings in different specimens are wide; ring widths range from 1.49 to 4.75 mm (mean ring width = 2.84 mm), which suggests a considerable range in growth rates. These data indicate variability in the limiting factors among subsequent cycles.

In each ring, there is a wide zone of earlywood with tracheids of thin cellular walls and wide lumen. A slow decrease of the radial diameter of tracheids is observed along rings. A distinct zone of 6–20 narrow latewood cells, indicating a response to a seasonal change, marks the ring boundaries (Fig. 3b and c). These characteristics indicate slow growth and long phases of cambial activation. The distinct latewood suggests restriction of growth in a small interval of time. The common occurrence of false growth rings within the earlywood of many rings is represented by narrow zones of 2 or 3 smaller, denser cells, almost as small and dense as those of the latewood, and sometimes as a discontinuous ring in relation to the total diameter of the wood. They are not periodic in occurrence but rather occur irregularly. The presence of false growth rings in earlywood (Fig. 3b) is indicative of the onset of adverse conditions during the growing season (Creber, 1977). Studying growth rings of Cheirolepidiaceae conifers in a fossil forest of the Late Jurassic of southern England, Francis (1984) relates the onset of water storage to intermittent droughts during the growing season, when water generally was available for growth.

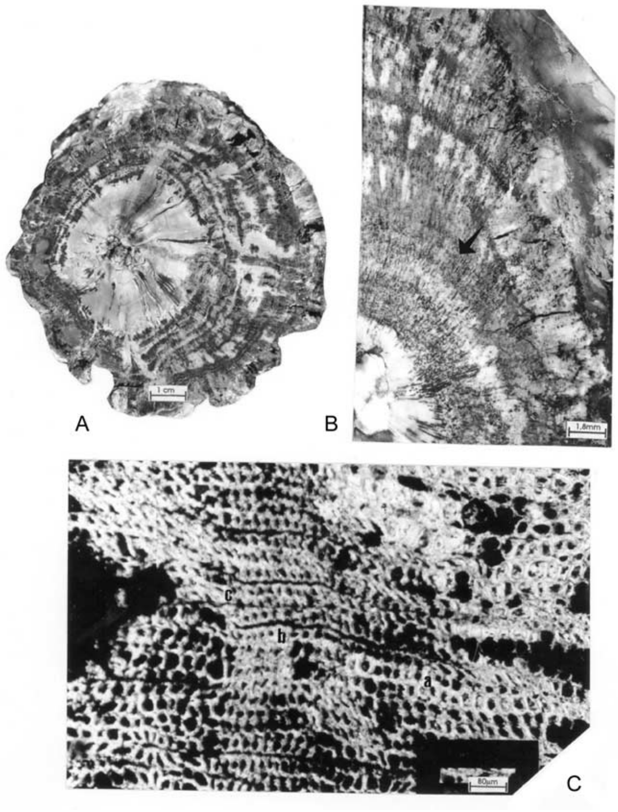

Fig. 3. *Sommerxylon spiralosus*, transverse sections. (a) Distinct growth rings represented by clear and dark bands. (b) Arrow indicates false growth ring. (c) Secondary xylem show the limit of growth ring; a = earlywood; b = latewood; c = limit of the ring.

Statistical data were obtained for 11 series of growth rings, for a total of 94 rings. The average ring width is 2.82; the average MS is 0.46; the average maximum AS is 0.91; and the average minimum AS is 0.09. The mean ring width, MS, and AS results are presented in Table 1, and the AS also is represented in Fig. 4.

Mean sensitivity ranges from 0.23 to 0.70, and the MS of the majority of the individual samples (90.9%) is greater than 0.3, which corresponds to sensitive types. These data indicate that the growing environment was not uniform but rather included significant episodes that caused irregular growth rates. The cyclic conditions of precipitation and water supply were variable during the life of the plant. The AS of 0.7 indicates extreme climatic events.

## 6. Discussion

Dendrochronological studies provide significant data to support climatic models established for the Late Triassic in Gondwanaland. Several authors have postulated a hot climate with a marked tendency toward aridity for the Neotriassic in Pangea (Tucker and Benton, 1982; Benton, 1983). Dickins (1993) synthesizes the paleoclimatic data available for the Devonian-Triassic interval and suggests a globally hot climate. In the Middle and Late Triassic, the occurrence of dry and humid zones suggests a more asymmetric climate than that of the Early Triassic.

Crowley and North (1991) and Crowley (1994) refute the almost cosmopolitan distribution of biota in the Triassic as evidence of a homogeneous climate, as was postulated by Hallam (1985). According to Crowley (1994), the different biotas were adapted to a wide spectrum of environmental conditions related to seasonal cycles. The modeling of the Pangea supercontinent proposes the establishment of longer annual cycles, directly related to the low retention of heat, which occurs on large landmasses.

On the basis of general patterns of models of circulation during the Triassic, Wilson et al. (1994) suggest a precipitation increment in the Carnian (Middle Triassic). This model suggests significant seasonal precipitation in both the south and the north of Pangea. (Fowell et al., 1992; Simms and Ruffell, 1990).

On the basis of sedimentologic, stratigraphic, and paleontological data, Holz and Scherer (1998) infer

Table 1
Results of growth ring analysis

| | Samples | Number of rings | Average of ring widths (mm) | Mean sensitivity (MS) | Annual sensitivity (AS) | |
|---|---|---|---|---|---|---|
| | | | | | Max. | Min. |
| 1 | PB 3785 | 9 | 2.1 | 0.42 | 0.66 | 0.09 |
| 2 | PB 3786 | 12 | 1.49 | 0.56 | 1.57 | 0 |
| 3 | PB 3787 | 5 | 3.9 | 0.23 | 0.1 | 0.28 |
| 4 | PB 3788 | 9 | 3.58 | 0.46 | 1 | 0 |
| 5 | PB 3789 | 7 | 3.07 | 0.32 | 0.66 | 0 |
| 6 | PB 3790 | 7 | 2.71 | 0.63 | 1.2 | 0.28 |
| 7 | PB 3791 | 7 | 3.64 | 0.35 | 0.54 | 0.22 |
| 8 | MCN PB 339 | 13 | 2.46 | 0.48 | 1 | 0 |
| 9 | MCN PB 356 | 9 | 2.6 | 0.46 | 1.33 | 0 |
| 10 | MCN PB 367 | 6 | 2.3 | 0.7 | 1 | 0.18 |
| 11 | PB 278 | 10 | 3.4 | 0.41 | 1 | 0 |
| Total | | 94 | | | | |
| Average | | | 2.82 | 0.46 | 0.91 | 0.09 |

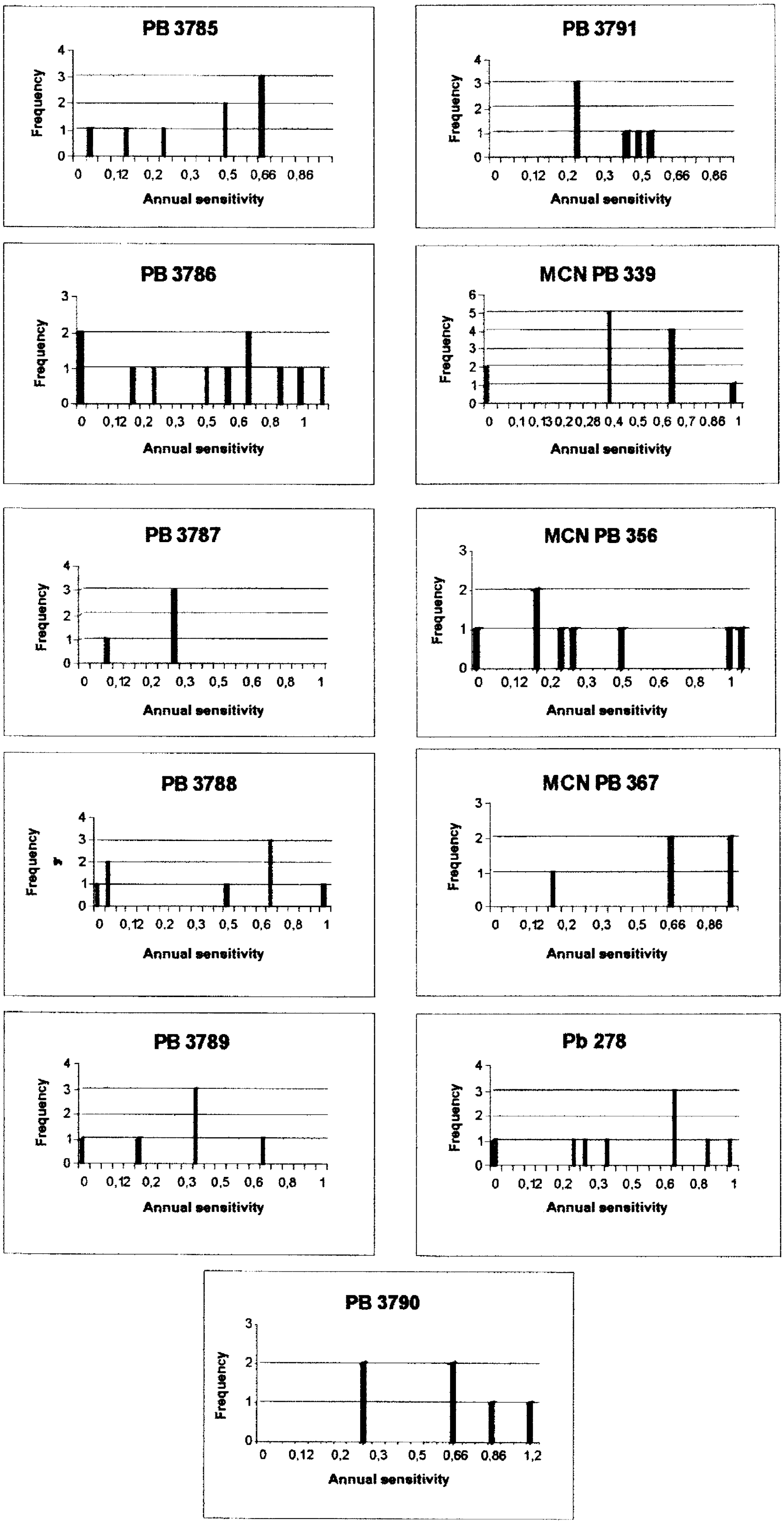

Fig. 4. Annual sensitivity histograms of the specimens of *Sommerxylon spiralosus*. The extension of histograms shows great variability in ring widths over a series of rings.

the general conditions of a humid climate for the Meso-Neotriassic package from the southernmost Parana Basin (Brazil). These sequences were deposited at a paleolatitude of approximately 58°S (Palmer, 1999). Climatic fluctuations between relatively arid and humid conditions were suggested, but the temporal amplitude and cyclicity of these inferred conditions were not discussed by the authors.

Sedimentological data obtained in the Linha São Luiz outcrop agrees with the hypothesis of a humid climate with fluctuating precipitation rates. Facies association indicates a fluvial system with associated floodplain deposits, and the presence of lacustrine sediments suggests wet climatic conditions (Miall, 1996). The occurrence of frequent levels of mudcracks associated with crevasse splay deposits indicates oscillation of the base level, associated with climatic fluctuations between dry and wet conditions.

The presence of conchostraceans in sandstone-pelitic rhythmic successions of the same facies association that contains fossil woods records is important faunal evidence. These invertebrates can be considered an index fossil for very restricted nonmarine facies living in ephemeral ponds and also are good indicators of seasonality. Each assemblage preserved in one rhythmic lamina of sediment is representative of a single season (Tasch, 1969). Francis (1984) ratifies the presence of a seasonal climate in Jurassic mid-latitude sequences with the presence of seasonal crustaceans (conchostraceans) in adjacent sediments, in addition to other paleoenvironmental evidence. Thus, future detailed studies of the vertical distribution of this conchostracean assemblage and the concentric growth lines of their carapaces complement the present dendrochronological data will indicate the length of the wet season.

Dendrochronological methods used to study *Sommerxylon spiralosus* indicate seasonal cycles. The growth phase in each cycle developed at a slow rate, and the growing environment was relatively uniform; however, the periodic phases of growth restriction were not very extensive. The different cycles of growth were affected by external factors. The external cyclic factor that caused the cessation of growth was related to the restriction of precipitation. The irregular supply of water probably accounts for the variable ring width. It is hard to tell if these seasonal cycles reflect different periods of a single year or longer periods, but they were interrupted by occasional droughts in the growing season, as reflected by the presence of false growth rings.

Comparing these results with the selected types of growth rings in fossil woods presented by Creber and Chaloner (1984), it is possible to establish a similarity to their type D. Type D indicates a growing season that is relatively uniform but has a terminal event that represents the cessation or retardation of growth.

The homogenous composition of the fossil wood assemblage, related to a single taxon, did not permit an inference about the influence of genetic and biotic factors in the generation of growth rings. However, diagnostic parameters of the wood indicate its relationship with the family Taxaceae (Pires and Guerra-Sommer, 2004). Currently, this family occurs within the Northern Hemisphere's subtropical to temperate climate regions. The growth rings in extant plants are similar to the taxon analyzed herein.

## 7. Conclusions

The growth ring patterns obtained from the fossil woods of the Linha São Luiz outcrop, southern Paraná Basin, Brazil, indicate that they can detect an external climate signal. This evidence shows that the climate during the deposition of the studied assemblage in the Late Triassic at high latitudes was not equable but rather that marked seasonal variations affected the environment.

Climatic data determined from fossil wood show a distinct pattern of seasonality related to growth cycles with extensive favorable and restricted unfavorable growth periods. The external factors that affected the cycles were mainly related to cyclic restrictions of the water supply. Irregular changes of environmental conditions, probably linked to occasional droughts in the growing season, can be detected using dendrochronological analysis.

The similarity between the growth ring patterns and those obtained from other sedimentological data ratifies the climatic signal, and the general conclusions obtained in our study match recent global climate patterns from the Late Triassic.

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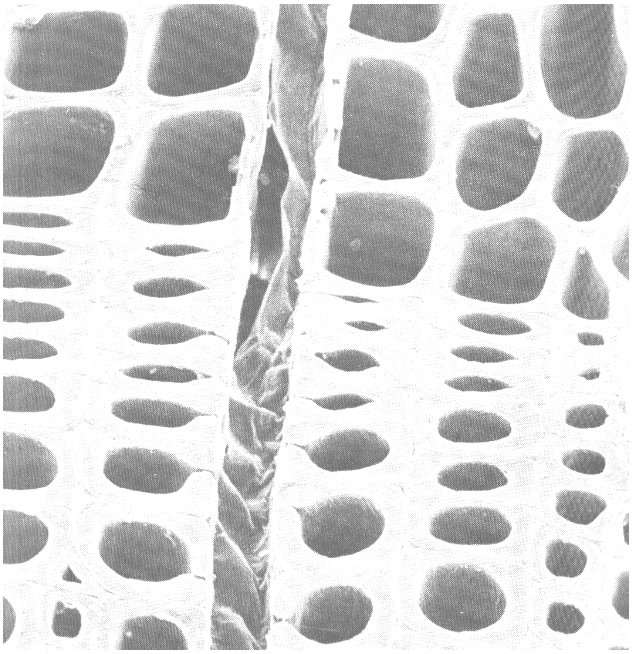

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