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ORIGEM VULCÂNICA PARA O TONSTEIN DA JAZIDA DO FAXINAL (RS): ESTUDOS MINERALÓGICOS, PETROGRÁFICOS E DE PALINOFÁCIES.

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À minha mãe Paulina Wagner Simas
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RESUMO

Análises mineralógicas, petrográficas e de palinofácies são registradas em um leito de tonstein associado a camadas de carvão na Jazida do Faxinal, Rio Grande do Sul, Brasil. A integração dos dados revestiu-se de grande importância para atribuir uma origem vulcânica para este argilito caolinítico. O tonstein é uma rocha quase monominerálica, composta predominantemente por caolinita antigênica. Dispersos na massa caolinítica ocorrem os minerais piroclásticos: paramorfos de quartzo-ß bipiramidais euédricos, "splinters" de quartzo transparente, zircão idiomórfico, apatita euédrica, alanita e pseudomorfos de sanidina, os quais são considerados como uma suíte restrita de minerais vulcânicos de tonsteins distais que preservaram durante a diagênese. Os minerais primários e suas feições texturais, bem como as relações de campo, indicam uma origem vulcânica de queda para essa camada. O estudo de palinofácies, inédito para este tipo de rocha, evidenciou uma composição diferenciada da matéria orgânica estruturada ao longo do perfil do tonstein. Análises estatísticas do querogênio de diferentes níveis da camada de tonstein indicaram altas percentagens de fitoclastos (xilema e epiderme) associados à menor representatividade de palinomorfos. Análises microestratigráficas destes níveis demonstraram que a saturação e a precipitação dos palinomorfos foram altamente influenciadas pelo intenso processo de queda de cinzas. O nível basal caracteriza-se por densos aglomerados de esporos e polens, enquanto o topo é marcado pela preservação de fragmentos de colônias de algas Botryococcus evidenciando uma deposição subaquosa desta camada. Alguns fragmentos de epiderme (cutículas) evidenciam, por sua coloração, acentuada alteração termal. Esses dados possibilitaram vincular as peculiaridades do mecanismo de deposição e preservação da matéria orgânica com o processo de formação do tonstein relacionado à rápida precipitação de cinzas vulcânicas. O tonstein intercalado em camada de carvão indica um episódio de sedimentação de tefra durante a deposição da seqüência portadora de carvão no Permiano Inferior no sul da Bacia do Paraná.

Palavras Chave: Tonstein, Cinzas vulcânicas, Mineralogia, Petrografia, Palinofácies, Permiano Inferior, Bacia do Paraná.

ABSTRACT

Mineralogical and palynofacies analyses are reported from a tonstein layer interbedded with coal seams in the Faxinal coalfield, Rio Grande do Sul, Brazil. Integration of data has far reaching significance for attributing a volcanic origin for this kaolinitic claystone bed. The tonstein is almost monomineralic rock, composed mainly by authigenic kaolinite. Scattered in the kaolinitic mass primary pyroclastic minerals occur: euhedral beta-quartz paramorphs and water-clear quartz splinters, idiomorphic zircons, apatite, allanite and sanidine pseudomorphs; considered as a restricted suite of silicic volcanic minerals of the distal tonsteins which preserved during diagenesis. The primary minerals and their textural features, as well as the field relations, indicate a volcanic air-fall origin. Analyses of the kerogens from different levels of tonstein layer indicate high percentages of phytoclasts combined with very low palynomorph percentages. Microstratigraphic analyses of the tonstein profile demonstrated that saturation and precipitation of palynomorphs were highly influenced by the intense ash-fall process. The preservation of *Botryococcus* colonies at the top of the tonstein evidenced the subaqueous deposition of this bed. The brown color of several cuticle fragments and tracheids was linked to thermal alteration. The tonstein interbedded in a coal seam indicates an episode of tephra sedimentation during the deposition of the coal-bearing sequence of the Lower Permian in the southern Paraná Basin.

Keywords: Tonstein, volcanic air-fall origin, mineralogy, petrography, palynofacies, Lower Permian, Paraná Basin

SUMÁRIO

Texto explicativo da estrutura da dissertação

O documento aqui apresentado, obrigatório para a obtenção de título de Mestre em Geociências 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 dissertações e teses na forma de artigos publicados e/ou submetidos pelo aluno em periódicos científicos, sendo aqui sintetizados os procedimentos utilizados na estruturação do Documento Final submetido à avaliação.

Constam desse documento Resumo e Abstract que sintetizam os objetivos e os resultados obtidos com o desenvolvimento do projeto de pesquisa. O capítulo 1 - Introdução - corresponde a uma compilação de dados sobre a presença de leitos de tonstein associados a camadas de carvão no Permiano Inferior da Bacia do Paraná, datações radiométricas obtidas a partir de análises em zircões procedentes dessas rochas e correlações estratigráficas com outras seqüências gonduânicas. Considerando a necessidade de confirmar a origem vulcânica para o tonstein do Faxinal através de estudos petrográficos e de palinofácies foi delimitado o problema e formulados os objetivos: Generalidades, Objetivos, Estado da Arte, Contexto Estratigráfico, Metodologia, Análise Integradora, Bibliografia e Anexos.

No Estado da Arte é apresentado um histórico abrangente dos trabalhos publicados sobre o tema, abordando as diferentes concepções a respeito da gênese do tonstein. Na Metodologia são caracterizadas as técnicas utilizadas na preparação e análise do material, de acordo com as diferentes metodologias de estudo, ou seja, estudos de Petrografia, Mineralogia e Análises de Palinofácies.

No Contexto Estratigráfico é apresentada uma síntese estratigráfica regional, usando critérios e estratigrafia de seqüências.

A Análise Integradora é formulada a partir dos objetivos inicialmente formulados e dos resultados atingidos com o desenvolvimento do projeto de mestrado. A integração dos resultados de análises petrográfica, mineralógicas, geoquímicas e de palinofácies possibilitou estabelecer conclusões inéditas a respeito do processo de deposição do tonstein, ratificando sua origem vulcânica.

O capítulo 2 - Corpo Principal da tese é composto pelo capítulo onde é apresentado o artigo "*Mineralogy and palynofácies analyses in the Tonstein of Faxinal Coalfield, an altered volcanic-ash layer from the Lower Permian of Paraná Basin, Brazil*" submetido durante à realização do mestrado, no qual a mestranda é a primeira autora, precedido da carta de aceitação da submissão por parte do periódico *International Journal of Coal Geology.*

Compõem o capítulo 3 - referente aos Anexos (a carta de Aceitação da Submissão do artigo, o resumo "*A Roof Shale Flora da Mina do Faxinal (Sakmariano do Rio Grande do Sul): Uma nova concepção sobre o processo tafonômico*" e dois artigos "*Geochronological data from the Faxinal coal succession, southern Paraná Basin, Brazil: a preliminary approach combining radiometric U-Pb dating and palynostratigraphy"* e *"Peat-forming environment of Permian coal seams from the Faxinal coalfield (Paraná Basin) in southern Brazil, based on Palynology and Palaeobotany"* publicados durante o desenvolvimento do mestrado, focados em seqüências portadoras de carvão da Bacia do Paraná, que forneceram subsídios importantes para a dissertação.

As Referências Bibliográficas estão organizadas por ordem alfabética no final desse documento e referem-se exclusivamente ao capítulo 1.

1 - INTRODUÇÃO

1.1 - Generalidades

A ocorrência de leitos de argilito identificados como tonsteins em jazidas de carvão no sul da Bacia do Paraná (Formação Rio Bonito, Grupo Guatá) é extensiva distribuindo-se no Rio Grande do Sul, desde bacias da borda leste (Faxinal, Leão) até a área da jazida de Candiota. De acordo com modelo geocronológico proposto para a Bacia, com base em estratigrafia de seqüências de alta resolução (Milani, et al. 1998), o intervalo portador de carvões ocorre na base da seqüência de segunda ordem Carbonífero-Triássico Inferior (Fig.1).

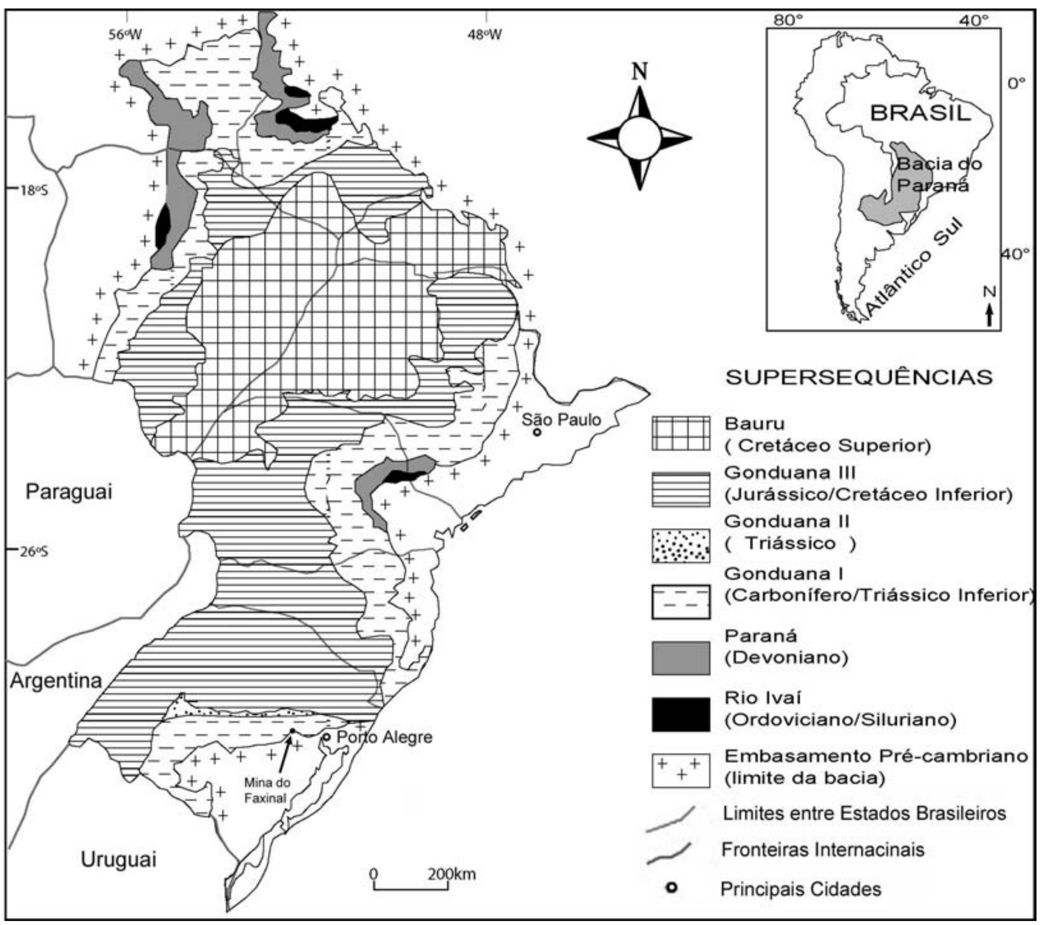

Figura 1 - Mapa geológico simplificado da Bacia do Paraná no Brasil com os maiores elementos tectônicos, e referências geográficas (modificada de Milani, 2003).

Leitos de tonstein podem ter ampla distribuição regional, e, por suas características mineralógicas, freqüentemente podem ser datados através de estudos isotópicos. A distribuição geográfica dessas camadas, por outro lado, está limitada a ambientes potencialmente favoráveis à sua deposição como, por exemplo, ambientes lacustrinos. Sua ocorrência muito freqüente em camadas de carvão está relacionada ao condicionamento geológico das bacias carboníferas e à energia deposicional do paleoambiente. A possibilidade de integrar estudos petrográficos, geoquímicos e isotópicos em tonsteins com dados bioestratigráficos de rochas associadas os caracteriza como marcadores isócronos no registro sedimentar.

Na jazida de Candiota camadas de tonstein distribuem-se em uma área que corresponde aproximadamente a 300 Km2 de extensão. Com base em estudos mineralógicos e químicos, além de relações de campo, Corrêa da Silva (1973), sugeriu que as camadas argilosas na jazida de Candiota corresponderiam a *stratotonstein* de acordo com sistema classificatório de Bouroz, ou *dichtertonstein* conforme nomenclatura proposta por Schüller, sendo sua origem detrítica. Dela Fávera et al. (1992) concordam com essa origem, considerando os tonstein*s* de Candiota como indicadores de clima seco. Análises geoquímicas detalhadas nos tonsteins intercalados na Camada Candiota Superior e na Camada Inferior de carvão em Candiota, realizadas por Formoso et al. (1999) indicaram para esses leitos, uma origem vulcânica relacionada à dispersão de cinzas por via aérea, de acordo com os critérios de Bohor e Triplehorn (1993).

O arcabouço palinoestratigráfico do Paleozóico Superior na Bacia do Paraná, estabelecido detalhado mais recentemente por Souza e Marques-Toigo, (2005), utilizado em crono-correlações de caráter local, torna-se restritivo no estabelecimento de correlações em escala regional na Bacia. Estas correlacões ficam comprometias especificamente dadas as dificuldades de controles faciológicos; desta forma, determinados dados palinológicos utilizados como pararâmetros bioestratigráficos, poderiam corresponder a ecozonas, sem significado temporal. No estabelecimento de correlações com escalas de tempo global, por outro lado, esses parâmetros palinoestratigráficos são também restritivos, levando em consideração as características endêmicas das floras gonduânicas.

A identificação de rochas vulcânicas, que ocorrem intercaladas à camadas de carvão na porção sul da Bacia do Paraná, e a aplicação de técnicas de datação radiométrica essas rochas, oportunizaram o início de programas de estudo com a finalidade de estabelecer o ajuste dos zoneamentos bioestratigáficos a escalas temporais internacionais com base numérica.

Datações IDITIMS U-Pb efetuadas por Matos et al. (2000, 2001) em zircões do Tonstein A intercalado na Camada Candiota Inferior indicaram uma idade radiométrica correspondente a 267.1 ± 3.4 Ma. Cazzulo-Klepzig et al. (2002) analisam o conteúdo palinológico da camada de tonstein e tentam estabelecer uma calibração entre o zoneamento palinoestratigráfico proposto por Marques-Toigo (1991) e essa datação radiométrica, incluindo as palinofloras procedentes do tonstein e carvões associados na subzona palinoestratigráfica *Caheniasaccites ovatus*, até então datada como Artinskiano/Kunguriano, a qual ficou restrita ao intervalo Kunguriano/Roadiano (267 ± 4 Ma.), de acordo com Jin et al. (1997). Esses resultados, porém, mostraram-se significativamente discordantes em relação a modelos geocronológicos estabelecidos para toda a sucessão permiana na Bacia do Paraná, utilizando diferentes metodologias (Lavina e Lopes, 1987; Milani et al., 1998).

Com a finalidade de obterem dados mais consistentes sobre as relações estratigráficas entre as diferentes jazidas de carvão e os modelos deposicionais já existentes, foram desenvolvidos diferentes estudos. Os resultados permitiram definir o intervalo de geração de carvões no Rio Grande do Sul e calibrar dados palinoestratigráficos, tendo como base, análises radiométricas (IDITIMS U-Pb; SHRIMP U-Pb) realizadas em tonsteins das jazidas de Candiota e Faxinal. (Guerra-Sommer et al., 2006, in press-a,b,c). Os dados radiométricos indicaram que a idade média das camadas de tonstein é de 290.6 ± 1.5 Ma. (Guerra-Sommer et al., in press-c) correspondente ao Sakmariano Médio de acordo com os critérios de Gradstein et al. (2005). O intervalo máximo para a geração dos carvões na porção sul da Bacia do Paraná restringe-se a ± 2 Ma (Fig. 2), pouco expressivo em termos de tempo geológico, oportunizando a hipótese de que possa representar um marco estratigráfico.

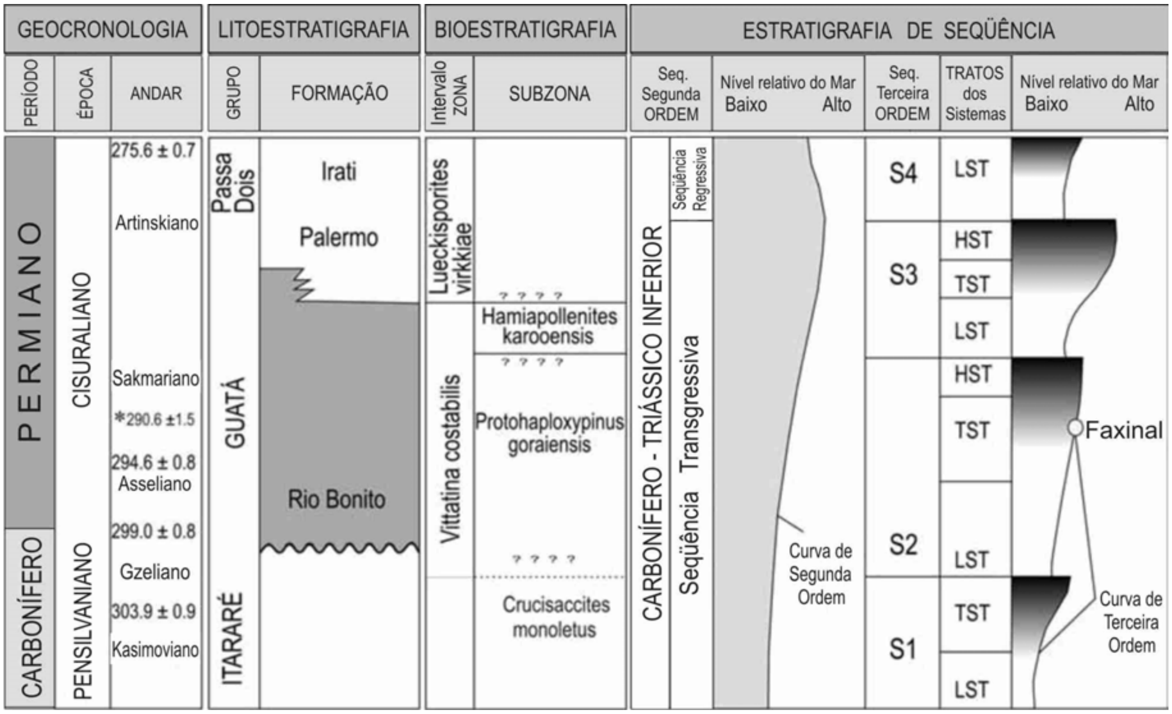

Figura 2 - Integração dos resultados obtidos entre a datação radiométrica, dados bioestratigráficos e de estratigrafia de seqüências (modificada de Guerra-Sommer et al (in press-c).

As idades numéricas obtidas nas jazidas de Candiota e Faxinal podem ser consideradas equivalentes àquelas obtidas em rochas bioestratigráficamente controladas na Bacia de Paganzo, datadas entre 302 ± 6 Ma e 288 ± 7 Ma., calibrados à zona *Pakhapites fusus* - *Vittatina subsaccata* (FS) registrada também na Formação Tasa Cuna e na parte superior da Formação El Imperial (Césari, 2007).

Na Bacia do Karoo a equivalência pode ser estabelecida com datações radiométricas de tufos procedentes de seqüências da porção inferior da Formação Prince Albert do Grupo Ecca com datação de 289.6 ± 3.8 Ma. até 288 ± 3 Ma. (Bangert et al., 1999).

Para López-Gamundi (2006) os horizontes de tufos identificados ao longo das margens continentais nas bacias de San Rafael, Souce Grande, Paraná e Karoo indicam um intervalo produtor de tufos vulcânicos entre 280 e 260 Ma. relacionado à fase ácida riodacítica a riolítica do vulcanismo de Choiyoi. Os dados gerados por idades radiométricas SHRIMP U-Pb para as jazidas de Candiota e Faxinal, indicam idades entre 292 e 288 Ma., mais antigas, portanto, para o evento vulcânico, relacionado por Guerra-Sommer et al. (in press-c) a fase andesítica do referido vulcanismo.

A camada de tonstein do Faxinal é enfocada no presente trabalho por suas peculiaridades: constituí-se em uma camada única, facilmente reconhecível, lateralmente contínua em toda a jazida; esse leito contém uma densa associação de plantas fósseis magnificamente preservadas; a presença de um nível carbonático contínuo em sua base distingue esse leito dos demais já descritos para a Jazida de Candiota.

Análises petrográficas preliminares desenvolvidas no tonstein do Faxinal (Guerra-Sommer et al., in press-a), com base nas características texturais e mineralógicas dos minerais primários, permitiram estabelecer uma hipótese de origem vulcânica para esta rocha. Todavia, o detalhamento analítico desse tonstein, estabelecido através da integração de análises petrográficas, mineralógicas e de palinofácies permite inferir novos dados a respeito de sua gênese e sugere uma fonte vulcânica mais próxima como origem das cinzas.

Visando documentar essas inferências, foram propostos para o presente estudo os objetivos abaixo relacionados.

1.2 - Objetivos

- Caracterizar a petrografia, a composição mineralógica e palinofaciológica do tonstein intercalado à camada de carvão **S** da Jazida do Faxinal, visando obter assinaturas das rochas para confirmar a origem vulcânica e estabelecer comparações com possíveis fontes piroclásticas.
- Integrar os resultados das diferentes metodologias com a finalidade de confirmar a origem vulcânica para essa camada argilosa, designada como tonstein (sensu Bohor and Triplehorn, 1993).

1.3 - Estado da Arte

A história da investigação dos tonsteins inicia-se com o trabalho pioneiro de Bischof (1863), que assim designa os leitos de argilitos associados a camadas de carvão nas jazidas da Saxônia, Silésia e Saar, sem, contudo, atribuir conotação genética ao termo conforme referem às revisões terminológicas de Bouroz, et al. (1983) e Williamson (1970a). Esta designação foi introduzida no período conhecido como "pré-microscópico", quando as características mineralógicas diagnósticas eram reconhecidas apenas com recursos que permitiam observações visuais das rochas. Todavia, mesmo com estas limitações, muitas dessas características foram posteriormente confirmadas através de estudos petrográficos, os quais se tornaram efetivos somente com o desenvolvimento da microscopia.

Termier (1889, 1890) faz as primeiras descrições microscópicas e petrográficas da composição dos tonsteins considerando elementos de suas texturas reliquiares e identifica grandes prismas vermiculares de um mineral na matriz criptocristalina, o qual denominou como “leverrierite”, considerando-o como uma variedade transicional entre caolinita e mica. Este termo foi usado por um longo tempo em estudos de tonsteins. No mesmo período Schmitz-Dumont (1894) descobre, em tonsteins, texturas indicando uma origem vulcânica do material primário e utiliza esses dados para o estabelecimento da hipótese vulcanogênica para a origem dessas rochas. Esses estudos foram realizados nas camadas de carvão do Carbonífero Superior da região de Saar. Essa concepção tornou-se, posteriormente, no conceito genético mais aceito pela comunidade científica.

No inicio do século XX, a petrografia finalmente é caracterizada como uma ciência autônoma. A maioria dos estudos petrográficos, porém, dedicaram-se às rochas ígneas, concentrando-se na investigação de suas microtexturas. As pesquisas de Rosembush e seus colaboradores neste campo foram destacadamente representativas. Estudos em rochas sedimentares já haviam sido desenvolvidos por Sorby (1877, 1880) quando é referida a importância da luz polarizada para análise dessas rochas e descreve texturas pelíticas, utilizando-as para interpretação genética (Levison-Lessing, 1923).

Ao longo do século XX, a geologia, mineralogia e petrografia das argilas passam a ser estudadas com detalhe (Ginzburg, 1912, 1915, Zemyatchenskii, 1923) e a moderna concepção das argilas, com ênfase em seus aspectos mineralógicos, é formulada inicialmente por Vernadskii (1954).

O intensivo estudo que se fez nesse período no sentido da compreensão da gênese das argilas ignorou, por outro lado, as rochas caracterizadas como tonsteins, sendo sua investigação ocasional e irregular, sobretudo quanto aos seus litotipos. Tomando como referência os estudos realizados em argilas, Ginzburg (1912) propõe três hipóteses para a origem dos tonsteins: pós-vulcânica, relacionado a ambiente paludal e por processo intempérico. Essa última hipótese consolida seu status de teoria com os trabalhos de Polynov (1956) e Ginzburg (1963).

A hipótese de uma gênese vulcânica para essas rochas recebeu, todavia, confirmações adicionais através de diferentes estudos (Rogers, 1914; Termier, 1923; Stützer, 1931; Hartung, 1942; Petracheck, 1942; Bederke, 1943), mais tarde, substanciada por Lapparent, 1934 e desenvolvida por Stach (1950). Este conceito é consistente com aquele estabelecido para as bentonitas (Knight, 1898), "produzidas *in situ* pela transformação de cinza vulcânica".

Hoehne (1953a) apresenta uma visão discordante, caracterizando os tonsteins, como produtos de intemperismo de sedimentos comuns em um ambiente paludal. Uma sinopse do desenvolvimento da hipótese sedimentar é apresentada em seu último artigo, publicado postumamente (Hoehne, 1964).

Nesse período, hipóteses alternativas para a para a origem dos tonsteins são consolidadas por Diessel (1965), Petrov (1967) e Millo (1968), embasada nos estudos de Hoehne segundo a qual essa rocha seria produzida pelo transporte de caolinita para a bacia de sedimentação, desde o local de proveniência. De acordo com ela, tonsteins representam uma "laterita argilosa" composta de material transportado em estado coloidal e precipitado de soluções devido à coagulação (conceito quimiogênico).

Apesar do caráter irregular das investigações, em meados do século XX, duas propostas alternativas, vulcanogênica ou detrítica, encontram apoio litogenético e respaldo na comunidade científica. As análises eram, porém, eminentemente descritivas e sistemas classificatórios não haviam ainda se estabelecido, inexistindo hipóteses a respeito de correlações regionais e espaciais entre leitos de tonstein. Consequentemente, a compreensão das possibilidades de aplicação do estudo dessas rochas para a solução de problemas geológicos não havia ainda sido concebida.

O estabelecimento de sistemas classificatórios para os tonsteins foram elaborados por Schuller (1951), Bouroz (1962), Masek (1963), Burger (1979, 1985) e Stach et al. (1982), mas a maior parte destes sistemas é descritiva e geralmente baseada na textura, morfologia de grãos dos argilominerais, e pseudomorfos; isto é, feições principalmente relacionadas aos processos pós-deposicionais e não à origem. Dado que essas feições são secundárias e frequentemente variarem lateralmente dentro de uma única camada, elas pouco contribuem ao entendimento genético ou mineralógico dos tonsteins.

Outros nomes foram propostos para as antigas camadas de cinza vulcânica não-marinha, tais como "cineritos" (Bouroz, 1962) e "bentonitas caoliníticas" (Spears e Rice, 1973), mas o termo "tonstein" foi mais aceito e é amplamente utilizado.

O termo "cinerito", proposto por Bouroz (1962), aplica-se geralmente a qualquer deposito de cinzas vulcânicas de queda, independente do seu estado de alteração, ambiente deposicional, ou composição mineralógica presente. Burger (1979) usou o termo "Kaolin-coal tonstein" para essas camadas, mas esta designação excluía os tonsteins em camadas de carvão que não são originalmente compostos por caolinita. "Noncoal tonstein" refere-se de acordo com Burger (1979) a camadas de cinzas vulcânicas alteradas, não-marinhas, não interacamadadas ou em contato com camadas de carvão.

O termo "tufo" utilizado para definir cinzas vulcânicas consolidadas (Fisher e Schminke, 1984) deveria, de acordo com Bohor e Triplehorn (1993), ser aplicado para caracterizar leitos não marinhos de cinzas vulcânicas não associadas com carvões. Fisher e Schmincke (1984) sugeriram que o termo tonstein fosse eliminado e que o termo bentonita fosse usado em um senso amplo para representar todas as camadas ricas em argilas de provável origem vulcânica, delgadas, muito espalhadas, independente de sua composição de argilomineral ou ambiente deposicional.

O incremento de estudos desenvolvidos na Europa e nos Estados Unidos comprovou que essas rochas não são restritas somente a bacias paleozóicas, como se julgava, mas ocorrem também em seqüências portadoras de carvão do Mesozóico e Cenozóico em diferentes continentes (Addisson et al., 1983; Batchelor, 1995; Cheng et al., 1996; Diessel, 1985; Burger, 1979; Weiss et al., 1992).

Esses estudos demonstraram que os tonsteins, antes considerados como efêmeros, constituem-se em rochas típicas de seqüências portadoras de carvões, sendo ocorrências comuns, embora quantitativamente pouco representadas nos perfis estratigráficos.

Pesquisadores europeus passaram a aceitar a teoria vulcânica, na segunda metade do século XX, culminando na monografia detalhando a natureza vulcânica de tonsteins, apresentada por Dopita e Kralik, (1977). Uma importante contribuição à consolidação da teoria vulcânica foi a descrição de tonstein proveniente de seqüências recentes, contendo inequívocos minerais primários vulcânicos e mesmo vidro vulcânico (Triplehorn e Bohor, 1986). Essas evidências sobre origem de tonsteins são atualmente aceitas por quase toda a comunidade cientifica, mesmo pelos mais devotados discípulos de Hoehne (cf. Burger, 1985b).

A confirmação da hipótese de que tonsteins representam camadas não-marinhas de cinzas-vulcânicas alteradas, análogas às bentonitas marinhas, foi extremamente importante para o estabelecimento dos seus usos geológicos. Masek (1963) demonstrou a relação genética entre estes dois tipos de camadas de cinzas delineando a transformação lateral de bentonitas para tonsteins em carvões da porção central da Bacia da Bohemia.

A equivalência entre estes dois tipos de camadas vulcânicas indica que os tonsteins também podem ser usados do mesmo modo que bentonitas i.e., como isócronas, marcadores de horizontes, calibradores de biozonas fósseis, e fontes de minerais primários vulcânicos apropriados à datação radiométrica.

O estudo das texturas do tonstein foi associado à caracterização mineralógica e petrográfica, constituindo a base da classificação dos tonsteins. A análise das prototexturas demonstrou que os tonsteins das bacias paleozóicas eram correlacionados com acumulações eólicas de cinzas vulcânicas. Essas texturas reliquiares são encontradas em muitos tipos de argila e reforçaram a hipótese vulcanogênica para os tonsteins (Chrisfidis e Dunham, 1993; Batchelor, 1995).

Todavia Admakin (1995) com base em estudos realizados em jazidas de carvão da Bacia de Moscou e na Bacia de Irkutsk (Admakin e Portnov, 1987), propõe a ocorrência de tonstein detrítico, composto de caolinita epiclástica montmorilonítica, além do tonstein vulcanogênico. Para designar essas rochas Martinec et al. (1989) sugeriu o termo "paratonstein". A concepção de Admakin (1995) caracteriza indicadores litogenéticos para subdividir os tonsteins, de acordo com sua composição inicial, discriminando alternativamente duas categorias genéticas de tonstein: os "orthotonsteins" representariam o produto da transformação diagenética de cinza vulcânica transportada pelo vento, enquanto que os "paratonsteins" seriam produzidos por acumulação de material caolinítico liberado de crostas intempéricas erodidas. Admakin (1995) afirma que, embora as propriedades genéticas dos diferentes grupos sejam similares, é importante elaborar critérios objetivos para distingui-los. Os critérios diagnósticos incluem a associação entre minerais estáveis e protominerais pseudomórficos, texturas reliquiares e características específicas das camadas de carvão, nódulos de titânio e a paragenêse dos tonsteins com rochas geneticamente relacionadas na seqüência portadora de carvão.

O conhecimento das características e dos processos genéticos relacionados à geração de tonsteins propiciou a solução de diferentes problemas geológicos. Dessa forma, esses leitos passaram a ser utilizados em correlações intrabacinais e interbacinais, em seqüências portadoras de carvões. Esse método foi usado para reconhecer camadas de carvão sincrônicas na França, Bélgica e Grã-Bretanha (Bouroz, 1966; Hoehne, 1951, 1953, 1957; Burger, 1979; Spears and Kanaris-Sotiriou, 1979) como também no estabelecimento de correlações entre seqüências portadoras de carvões nos Estados Unidos e Europa (Burger, 1985b). Leitos de tonsteins também têm sido utilizados como uma importante ferramenta para caracterizar a extensão de zonas formadoras de carvão em determinadas seqüências estratigráficas. Por outro lado, a análise desses leitos tem também propiciado registro e datação de eventos eruptivos de curta duração e a estimativa de periodicidade em eventos vulcânicos do passado geológico.

A consolidação da teoria vulcânica para a origem dos tonsteins é apresentada no artigo "Tonsteins: Altered Volcanic-Ash Layers in Coal-Bearing Sequences" elaborado por Bohor e Triplehorn (1993). Naquele artigo é apresentada a evolução dos sistemas de nomenclatura e classificação dessas rochas, detalhada descrição da mineralogia primária e secundária, bem como a ocorrência geográfica. Tonsteins são reconhecidos como cinza vulcânica de queda alterada com base nas relações de campo, composição mineralogia e texturas, geoquímica e idade radiométrica. Essa interpretação amplia seu uso em diferentes estudos geológicos. Desta forma, os tonsteins têm sido utilizados como: controle de amostragem geoquímica, estudos de petrografia orgânica e planejamento de mineração. Correlações regionais e intercontinentais entre estratos não marinhos podem ser estabelecidas; datações radiométricas de minerais primários vulcânicos permitem a determinação de idades de camadas de carvão e sua calibração com zonas palinoestratigráficas. Por outro lado, a presença de múltiplas camadas de tonstein em espessas camadas de carvão pode ser usada para estudar o estilo e a história do vulcanismo explosivo. A partir desse estudo, que é considerado um marco com relação à evolução conceitual do estudo de tonsteins, diferentes autores têm estabelecido análises em cinzas vulcânicas alteradas, em diferentes bacias e em distintas províncias paleogeográficas, em amplos intervalos de tempo geológico, desde o Devoniano até o Holoceno (López Gamundí, 1994; Stollhofen et al., 2000; Wüst e Bustin 2001; Creech, 2002; Lopez Gamundí, 2006).

No Brasil, o estudo pioneiro de Correa da Silva (1973), desenvolvido com base em relações de campo, e algumas análises mineralógicas e químicas, classificou os tonsteins de Candiota como "Stratotonstein" de acordo com a classificação de Bouroz, (1962) que atribui a essa rocha uma origem detrítica. Della Favera et al. (1992) concordam com essa interpretação considerando esses tonsteins como indicadores de clima seco.

Todavia, Formoso et al, (1999), através de análises geoquímicas detalhadas indicam para esses leitos, origem vulcânica relacionada a dispersão de cinzas por via aérea, de acordo com os critérios de Bohor e Triplehorn (1993).

Datações radiométricas U/Pb em zircões provenientes de tonsteins da jazida de Candiota (Matos et al., 2000, 2001) indicaram idade de 267 ± 3,4 Ma. Cazzulo-Klepzig et al. (2002) tenta estabelecer uma calibração entre o zoneamento palinoestratigráfico estabelecido por Marques-Toigo (1991) e as idades indicadas; todavia a idade proposta mostrou-se incompatível com os esquemas estratigráficos vigentes para a Bacia do Paraná (Milani, et al. 1998).

Com a finalidade de obter dados mais consistentes que possibilitassem uma melhor correlação com os modelos vigentes, Guerra Sommer et al. (2006, in press-a,b,c) estabelecem datações com base em análises radiométricas IDTMS U-Pb em tonsteins das jazidas de Candiota (296 ± 4,2 Ma.) e Faxinal (285,4 ± 8,6 Ma.). Os resultados obtidos em análises de zircões procedentes de tonsteins das jazidas de Candiota e Faxinal indicaram para os mesmos uma idade média de 290,6 ± 1,5 Ma.

Interpretações de Coutinho et al. (1988) e Coutinho e Hachiro (2005) através de estudos de distribuição, mineralogia, petrografia, e proveniência e significado dos depósitos de cinzas na bacia do Paraná, inferem a proveniência destas cinzas atravessando a patagônia alcançando a Austrália.

Guerra-Sommer et al. (in press-c) com base em dados de Sato e Lhambias (1994), consideram que o vulcanismo do grupo Choiyoi inferior poderia representar a fonte mais provável para a precipitação distal de cinzas no sul da Bacia do Paraná durante o Sackmariano.

1.4 - Contexto Estratigráfico

Eventos tectônicos e eustáticos no sul da Bacia do Paraná no sul do Brasil induziram vários ciclos de terceira ordem de elevação do nível do mar durante a longa duração englobada pela Superseqüência I do Gonduana. Esta superseqüência abrange quatro seqüências denominadas de terceira-ordem, da base para o topo, S1, S2, S3, e S4 (Holz, 1998; Holz et al., 2000). O intervalo estudado focalize-se na Formação Rio Bonito que inclui o estrato portador de carvão e compreende a seqüência S2 e a parte inferior da S3. A seqüência S2 corresponde a um trato de sistema de mar baixo (LST), em sua base, seguido por um trato de sistema transgressivo (TST) e no topo, trato de sistema de mar alto (HST). A parte inferior de S3 representa novamente um LST. O intervalo de topo do S3 pertence à Formação Palermo e representa um TST e um HST. O LST de S2 é composto de duas paraseqüências (Holz et al., 2000) que contém camadas fluvio deltáicas progradantes e umas poucas camadas de carvão. O LST é recoberto por um TST de quatro paraseqüências (pântano associado à barreira/laguna). As camadas de carvão nas três paraseqüências basais são espessas e contínuas, enquanto na paraseqüência superior elas são finas e descontinuas. O HST compreende uma única paraseqüência de fácies marinha (Fig. 2).

A jazida de carvão do Faxinal (UTM N6651.5 / E432.7), minerada pela Companhia de Pesquisas e Lavras Minerais (COPELMI), está localizada perto do Município de Arroio dos Ratos, cerca de 120 km a sudoeste de Porto Alegre e próxima às jazidas de carvão de Água Boa e Sul do Leão (Fig. 3).

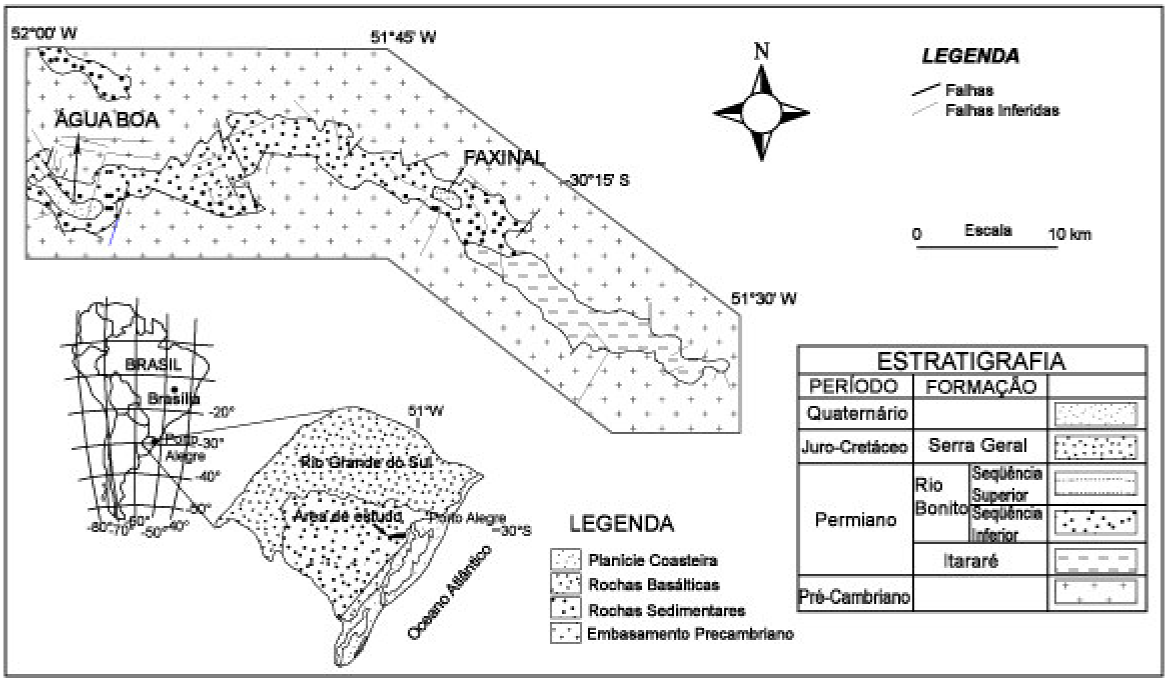

Figura 3 - Mapa de localização da Mina do Faxinal.

Estas jazidas estão situadas em um graben, referido previamente como o paleovale Leão/Mariana Pimentel (Ribeiro et al., 1987). Esta é uma estrutura alongada tendendo a SE-NW em sua porção oriental e E-W para o oeste. O graben, inserido no embasamento, tem 60 km de extensão e até 5 km de largura. As três jazidas de carvão são blocos estruturais abatidos, principalmente controlados por um sistema de falhas N40ºE, e sua extensão é limitada pela erosão subseqüente. A jazida do Faxinal (reserva de 18×10^6 toneladas de carvão) está situada na parte leste do graben. A sucessão do Faxinal inclui cinco camadas de carvão, designadas, da base para o topo: I, IM, M, MS, e S. As camadas são intercaladas com siltitos, lamitos, arenitos e paleosolos (Fig. 4).

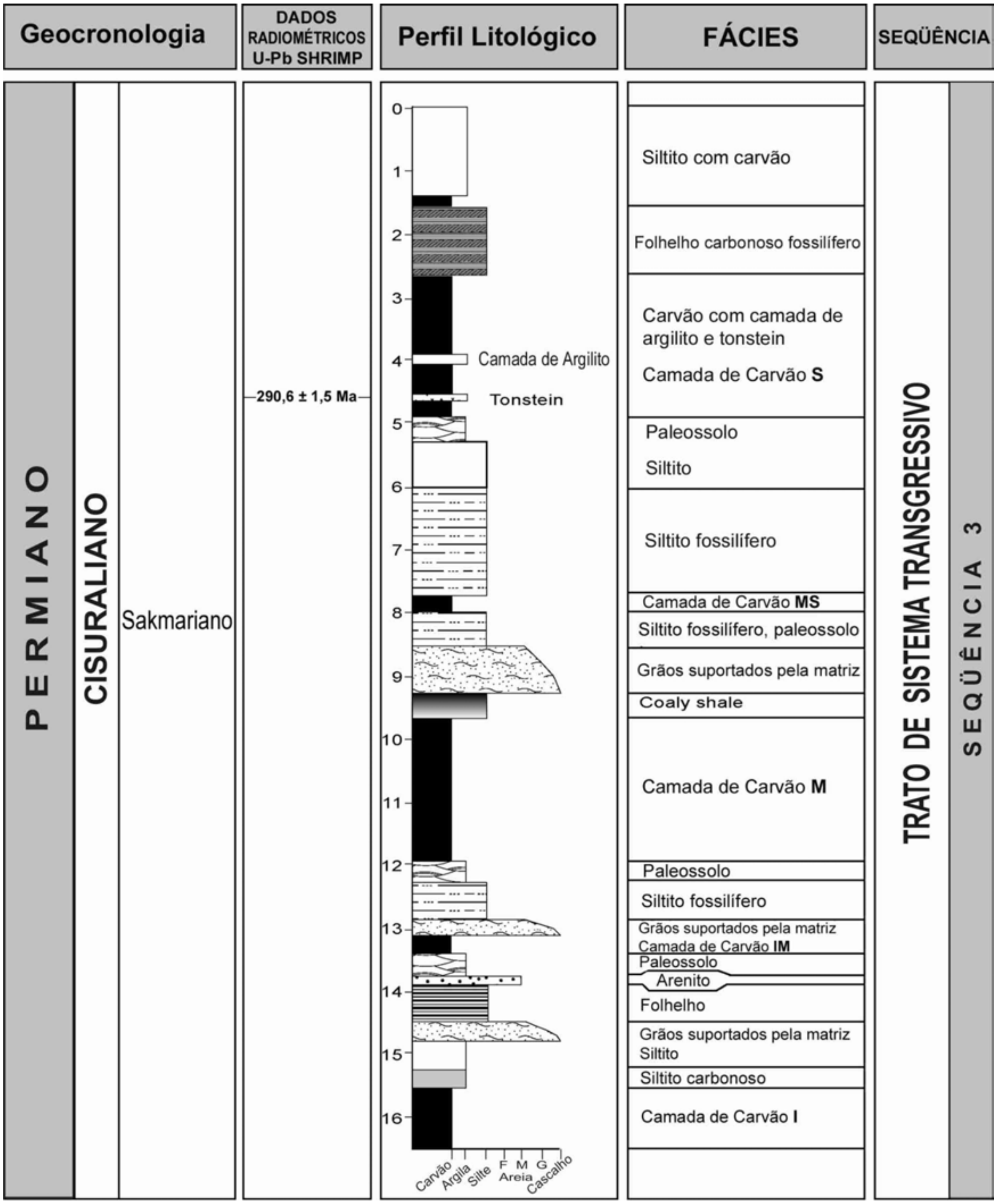

Figura 3 – Perfil litológico, fácies, paraseqüência, geocronologia e dados radiométricos da Jazida do Faxinal (modificado de: Guerra-Sommer, in press-a,c).

O presente estudo focaliza-se em uma camada argilosa de coloração cinza clara, de aproximadamente 10 cm de espessura, fossilífera, intercalada na camada de carvão (S). A camada está exposta ao longo dos cortes da mina a céu aberto e mostra, principalmente, limites superior e inferior abruptos (Fig. 5).

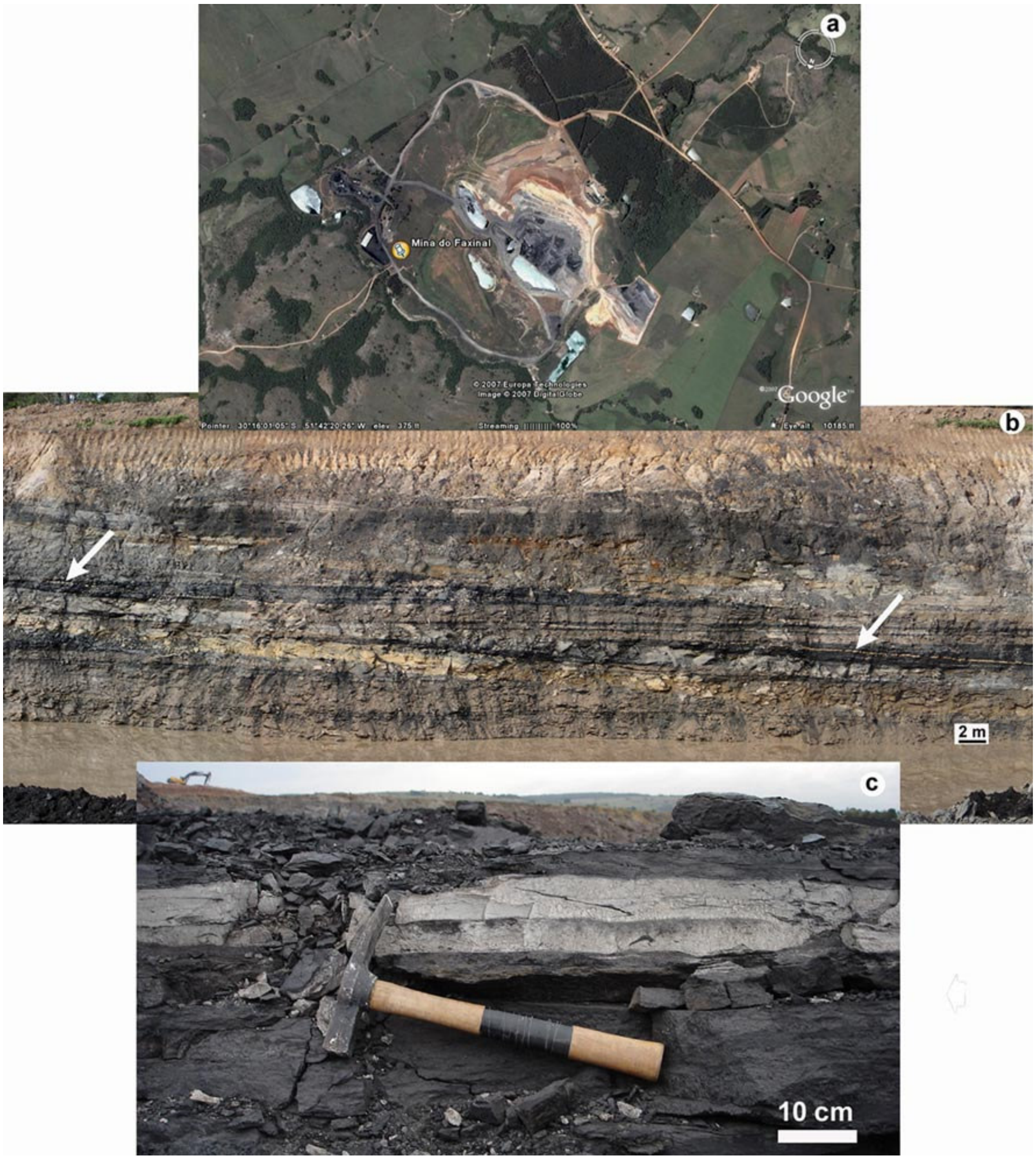

Figura 5 – Em a) vista aérea da Mina do Faxinal (imagem de satélite – Google Earth 2007); b) vista de perfil do corte 8, onde as setas indicam a fina camada de tonstein; c) detalhe da camada de carvão S, com o tonstein intercalado.

1.5 - Metodologia

1.5.1 - Material

Sete amostras integrais da camada de tonsteins foram coletadas aleatoriamente de diferentes pontos da frente de lavra da Mina do Faxinal, no Corte 8 (UTM N6652,3/E431,3) em uma extensão de 100 m. As amostras são denominadas: FX-0, FX-1, FX-2, FX-3, FX-4, FX-5, FX-7, conforme constam nas figuras 6, 7 e 8. Em cada amostra tonstein, de cerca de 10 cm de espessura, foram identificados três níveis distintos, mesoscópicamente observáveis e confirmados por análises petrográficas e de difração de raios X. Estes níveis, aqui denominados níveis microestratigráficos, constituem-se de: nível basal (**b**) correspondente a um carbonato calcítico com caolinita; o nível intermediário (**m**) composto por um argilito caolinitico com siderita, pirita e calcita; e o nível de topo (**t**) corresponde a um argilito caolinítico (Fig. 6)

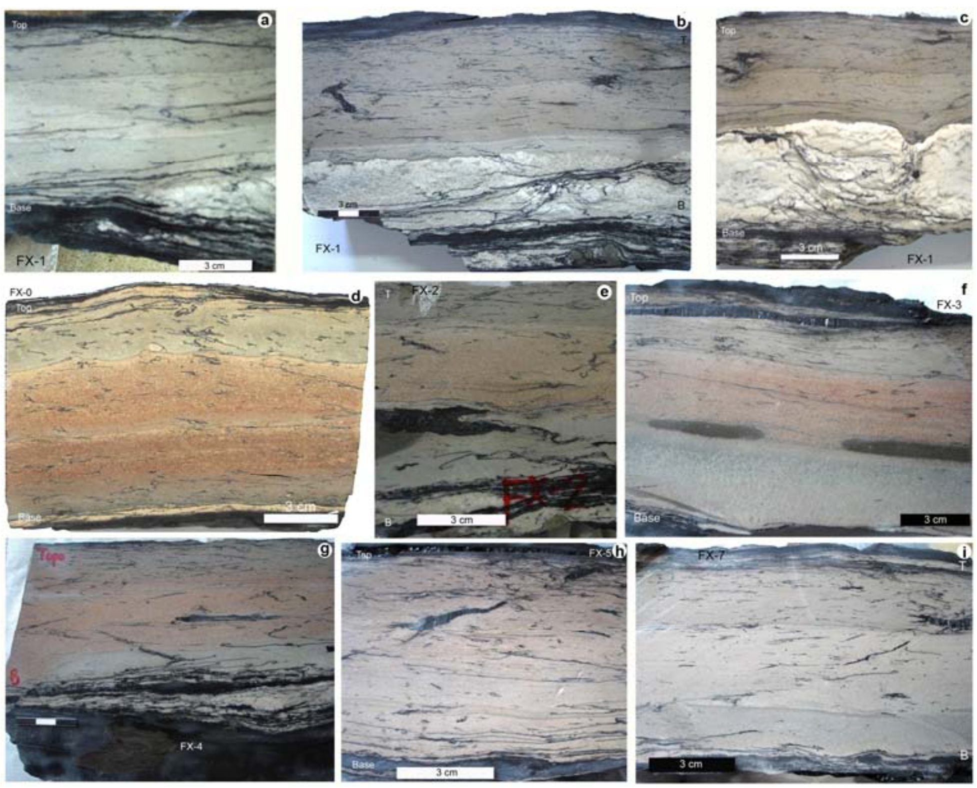

Figura 6 – Perfis das amostras do tonstein da Jazida do Faxinal, mostrando os três níveis microestratigráficos de base, intermediário e topo; laminação primária, matéria orgânica (folhas e ramos fósseis). Na amostra FX-1 (a,b,c) verifica-se uma concreção calcítica lenticular na base; FX-0 (d), FX-2 (e), FX-3 (f), FX-4 (g) apresentam coloração rosada no nível intermediário devido à presença de siderita; FX-5 (h) e FX-7 (i); (c) estrutura de escape de fluídos na concreção calcítica (canto inferior direito); (f) mostra lentes piríticas (c.a. 1cm de espessura) entre os níveis calcítico e siderítico; (g) falhas de deslizamento de pequena escala; em (b,c,e,h,i) perturbação da laminação pela queda de ramos.

1.5.2 – Métodos

1.5.2.1 – Petrografia e Mineralogia

Análises mineralógicas e petrográficas foram desenvolvidas a partir de sete amostras de argilitos selecionadas. A elaboração de quinze lâminas petrográficas foi efetuada no Spectrum Petrographics Inc. (Vancouver, WA, USA) tendo em vista a qualidade necessária para a realização dos estudos propostos.

A microscopia convencional foi a ferramenta fundamental para identificar e caracterizar a mineralogia primária (piroclástica) e secundária (autigênica), bem como as texturas vulcânicas piroclásticas, aspectos deposicionais (microlaminação) e diagenéticos. Para tal análise foi utilizado o microscópio petrográfico (*Leitz* – Laborlux 12 POL S).

As análises de Microscopia Eletrônica de Varredura (MEV) foram obtidos nos Centros de Microscopia Eletrônica: MEV-PUCRS e MEV-UFRGS. Foram obtidas imagens eletrônicas pelos detectores de Elétrons Retroespalhados e de Elétrons Secundários e análises químicas qualitativas pelo EDS (Espectrômetro de dispersão em energia de raios-X) em algumas amostras de tonsteins, em lâminas delgadas e fragmentos de rocha, confirmando os dados já observados ao microscópio óptico petrográfico convencional.

O detalhamento mineralógico realizado a partir de difração de raios-X (DRX), com análises qualitativas e semi-quantitativas de rocha total, foi obtido pelos métodos do pó para sete amostras, cada qual dividida nos três níveis distintos, observáveis a vista desarmada (Fig.7). Para observação dos argilominerais (caolinita) presentes nos argilitos do topo da camada de tonstein, foram preparadas lâminas de sete amostras com material orientado e submetidas à técnica de amostra natural (Fig. 8). Estas análises foram realizadas no Laboratório de Difração de Raios-X do IG-UFRGS, com o difratômetro modelo SIEMENS Bruker AXS D 5000, com radiação Kα em tubo de cobre (Cu) (nas condições 40 kV e 25mA) e filtro de níquel (Ni).

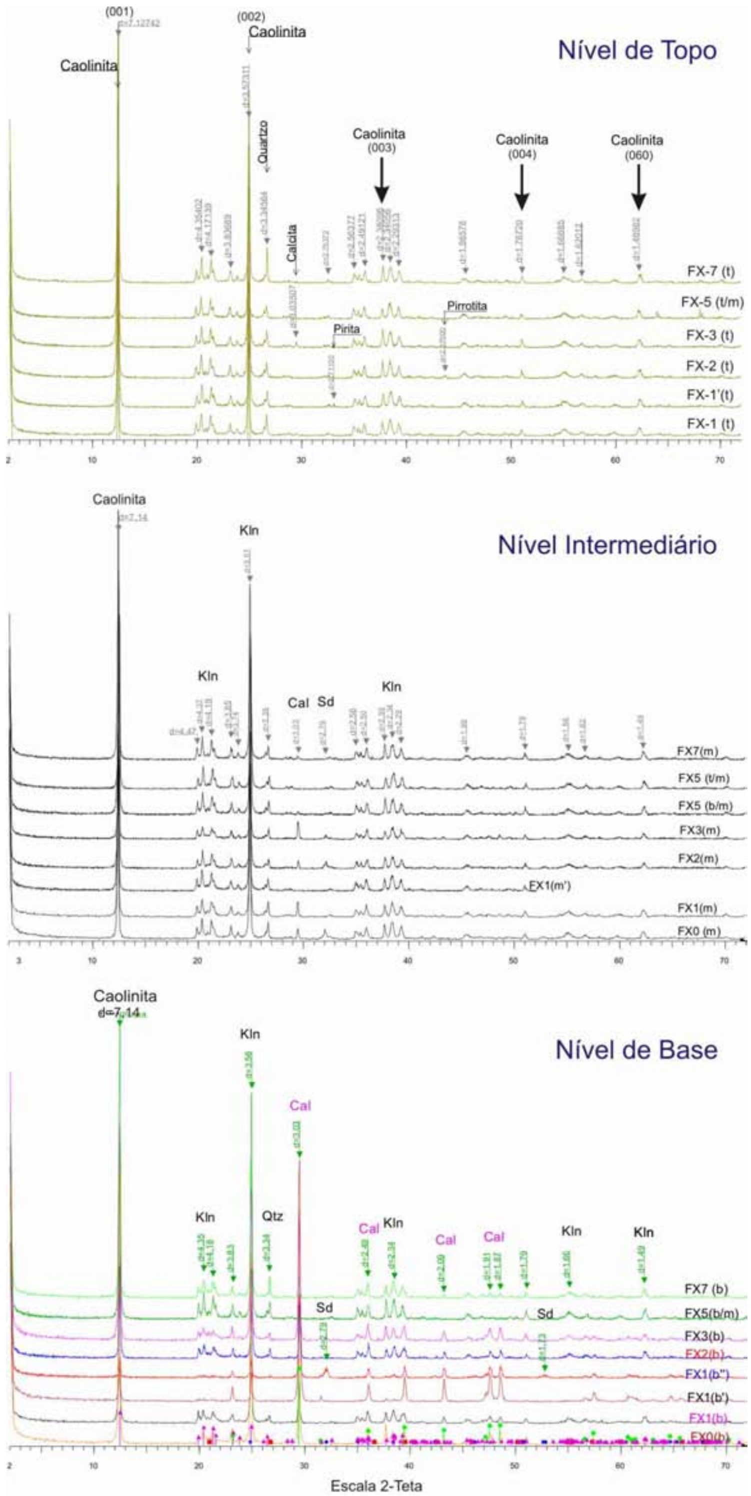

Figura 7 – Padrões de difração de raios-X de rocha total da camada de tonstein mostrando diferentes proporções entre minerais caolinita (Kln), calcita (Cal), siderita (Sd) e Quartzo(Qtz) primário, evidenciando a distinção mineralógica que marca os 3 níveis microestratigráficos.

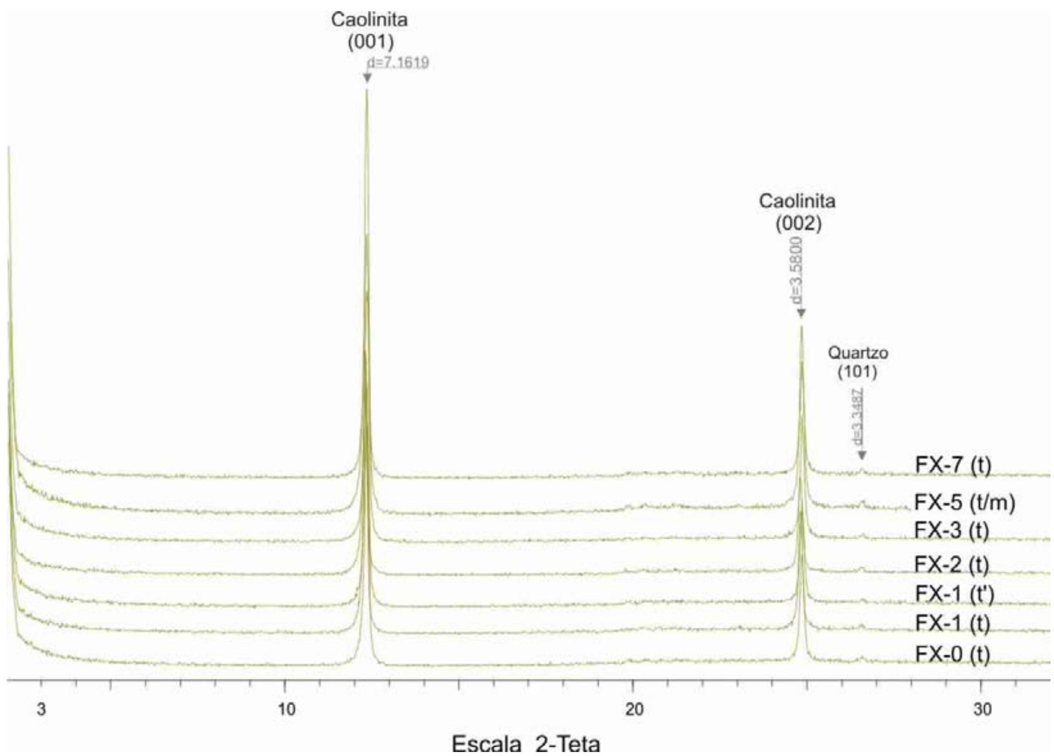

Figura 8 – Padrões de difração de raios-X de amostra orientada natural do topo da camada de tonstein mostrando um único argilomineral presente, a caolinita muito bem cristalizada.

1.5.2.2 – Palinofácies

As análises de palinofácies foram efetuadas nos diferentes níveis (**b, m, t**) de cinco amostras integrais (cada uma dividido em **b, m, t**) do leito de tonstein. O material foi primeiramente tratado com ácidos clorídrico HCL e fluorídrico HF, seguindo pelo líquido denso cloreto de zinco ($ZnCl_2$), a fim de concentrar a matéria orgânica. A matéria orgânica isolada foi então montada de forma dispersa na lâmina. A técnica de preparação empregada foi o procedimento palinológico padrão, não-oxidativo.

A caracterização palinofaciológica foi baseada em análises quantitativas da matéria orgânica particulada de acordo com procedimentos descritos por Tyson (1995) e foram contadas um total de 300 partículas para cada amostra, observada em microscópio óptico de luz transmitida em luz branca e ultravioleta (Mendonça Filho, 1999).

1.6 - Análise Integradora

O tonstein da jazida do Faxinal (RS) constitui-se em um conspícuo marco estratigráfico correlacionado ao Permiano Inferior da Formação Rio Bonito, sul da Bacia do Paraná. Esta unidade litológica com aproximadamente 10 cm de espessura, estende-se por dezenas de quilômetros e possui limites abruptos (Ribeiro et al., 1987) (Fig. 5b,c). Análises petrográficas, mineralógicas e de palinofácies na camada de argilito intercalada à camada de carvão **S** na jazida do Faxinal, forneceram argumentos importantes para confirmar uma origem vulcânica para essa rocha.

A caracterização petrográfica do tonstein evidencia uma rocha texturalmente fina, síltico-argilosa, com laminação irregular e com orientação sub-paralela de minerais piroclásticos alongados ou suas pseudomorfoses (Huff e Spears, 1989) (Fig, 9a,b,c). O tonstein é uma rocha constituída predominantemente por caolinita autigênica (Fig. 7, 8, 10a,b,c). Dispersos na massa caolinítica ocorrem os minerais primários piroclásticos: paramorfos de quartzo-beta bipiramidal euédrico e *splinters* de quartzo transparente, zircão idiomórfico, apatita euédrica, alanita e pseudomorfos de sanidina (Fig. 9d,e,f,g,h,i,j,k,l). Estes minerais piroclásticos são considerados como uma suíte restrita de minerais vulcânicos de tonsteins distais, cujas características foram preservadas durante os processos diagenéticos (Bohor e Triplehorn, 1993).

A presença dos minerais piroclásticos e suas texturas reliquiares, assim como as características de campo desta camada, constituem-se nos principais diagnósticos para atribuir-se a proveniência vulcânica ao tonstein. Tais minerais primários são típicos de magmas silicosos, o que confirmam estudos geoquímicos a partir de elementos menores e traços menos móveis (razões Zr/Ti *versus* Nb/Y), conferindo ao tonstein uma fonte vulcânica de cinzas riodacíticas a riolíticas (em preparação).

Nesta camada foram observados três níveis textural e mineralogicamente distintos, caracterizados como níveis microestratigráficos, (medindo c.a. 3 cm cada) divididos em: base (b), intermediário (m) e topo (t) (Fig. 6). Nos níveis intermediário e de base, houve variações nas condições de Eh e pH, as quais produziram sequencialmente as seguintes fases eodiagenéticas: caolinita, pirita, siderita e calcita (Fig. 7). Na porção média do tonstein, a caolinita é substituída por siderita associada à pirita (Fig. 10g,h,i,j)e, no nível de base, a caolinita sofre uma pronunciada substituição por calcita (Fig. 10b,c,k).

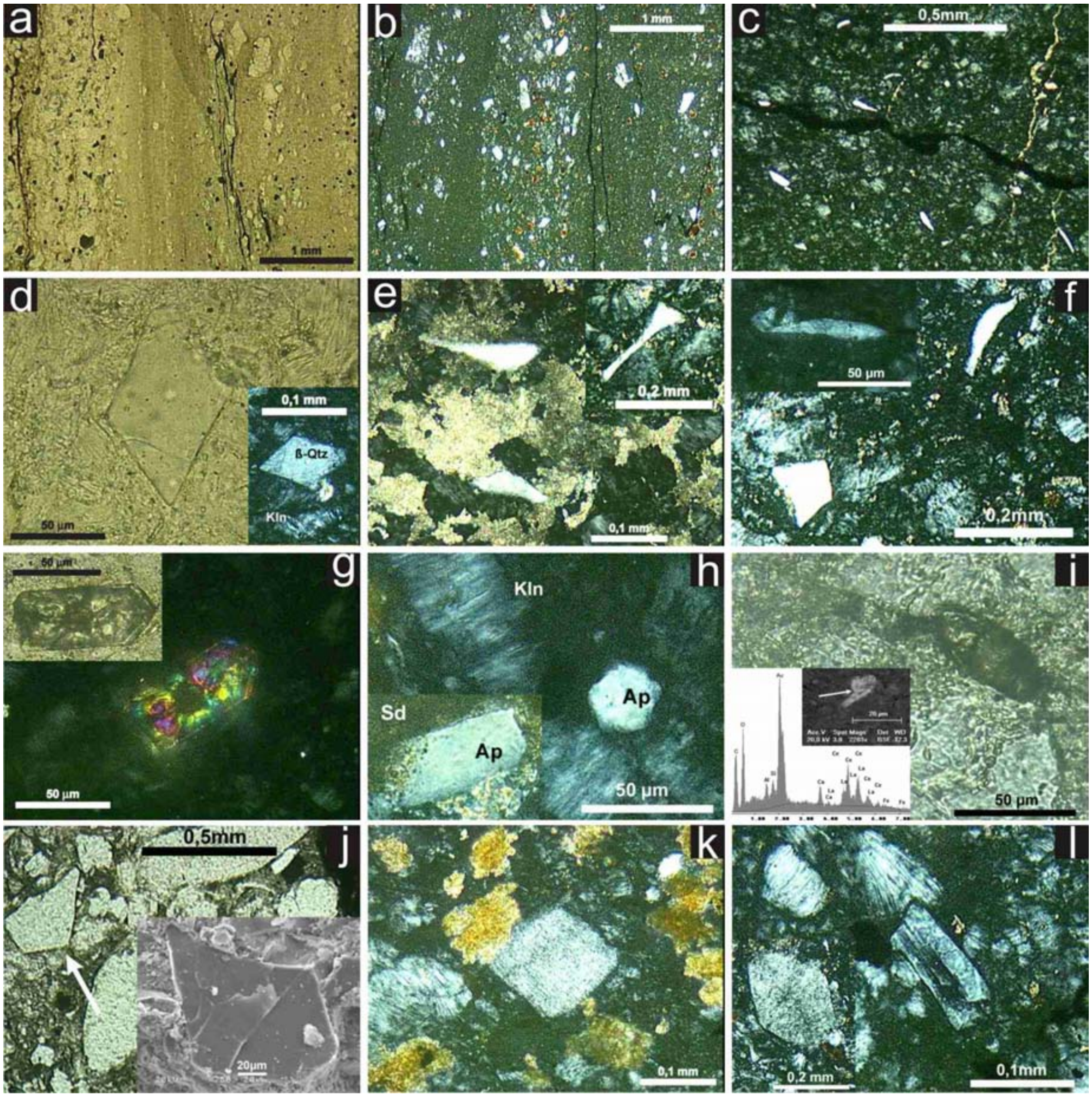

Figura 9 - Fotomicrografias de lâminas delgadas mostrando feições texturais e minerais piroclásticos do tonstein do Faxinal: **a, b)** laminação irregular devido à variação granulométrica; **b, c)** orientação sub-paralela marcada por partículas alongados de “splinters” de quartzo e pseudomorfos de feldspatos; **d)** paramorfo de quartz-ß bipiramidal euédrico; **e)** “splinters” de quartzo transparente; **f)** “splinters” de quartzo mostrando feições de embaimento (superior esquerdo), em forma curva (superior direito); **g)** zircão idiomórfico zonado e com inclusão em matriz caolinítica; **h)** apatita euédrica, face basal em matriz caolinítica e prismática com substituição parcial por siderita (inferior esquerdo); **i)** alanita em forma elíptica, imagem de MEV e análise química por EDS; **j, k, l)** pseudomorfos de feldspatos substituídos por caolinita, formas rômbicas; l) seção primática de feldspato pseudomorfo. Legenda: **Ap** - apatite, **ß-qtz** - quartzo-ß, **Kln** – kaolinite, **Sd** - siderite.

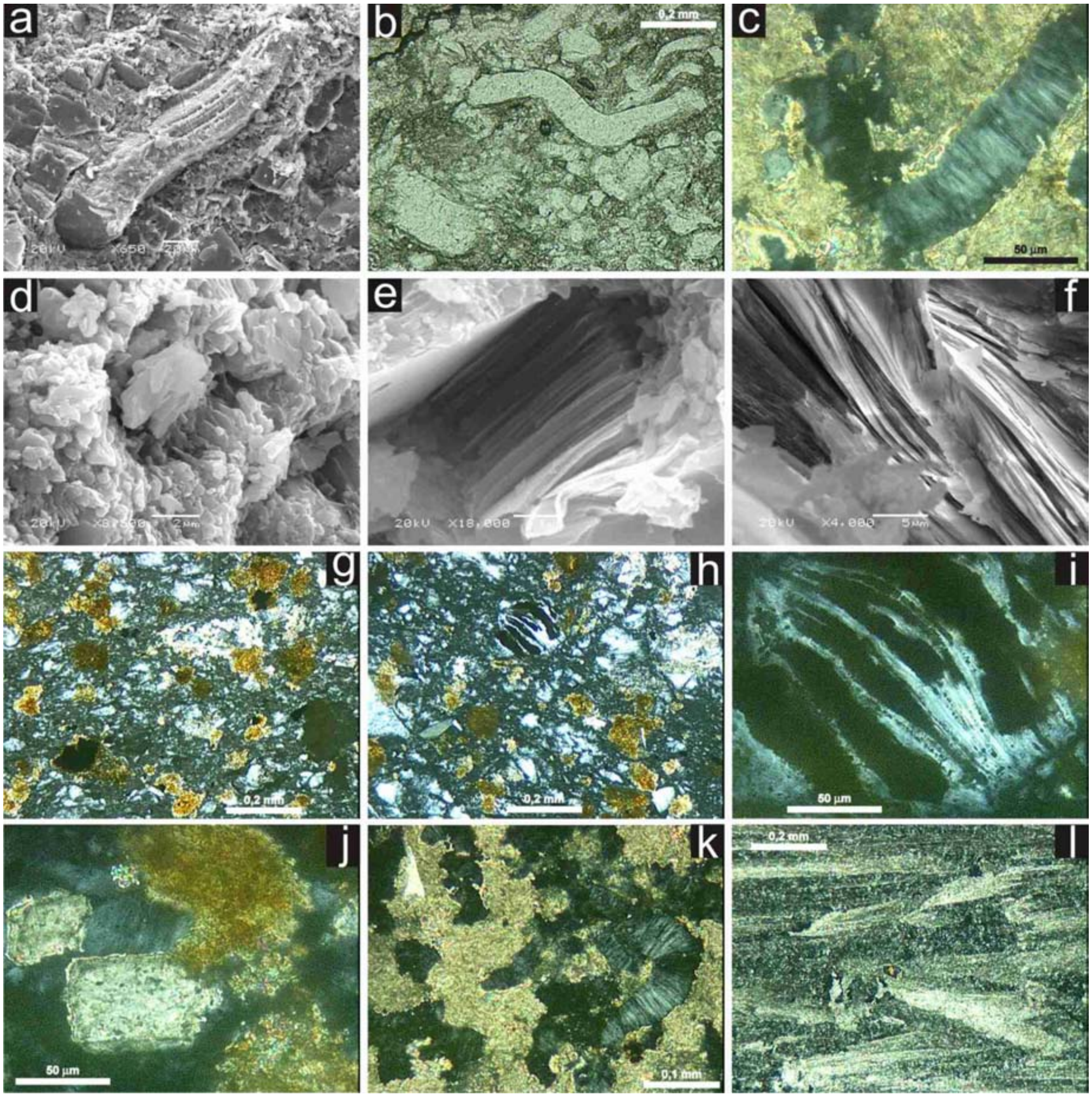

Figure 10 - Fotomicrografias de lâminas delgadas mostrando minerais autigênicos do tonstein do Faxinal: **a, b, c)** caolinita em vermículos; **c)** caolinita engolfada por calcita (nível de base); **d)** caolinita fina em agregados granulares constituindo a matriz microcristalina; **e,f)** acordeons de caolinita; **a, d, e, f)** são imagens de MEV; **g, h)** siderita marrom amarelada como agregados granulares dispersos em matriz caolinítica; **g)** siderita engolfando pirita; **h)** pirita entre lamelas de caolinita (centro); **i)** feição em detalhe mostra pirita substituindo parcialmente a caolinita; **j)** calcita substitui alguns minerais prismáticos euédricos preservando formas reliquiares; k) caolinita vermicular e *splinter* de quartzo engolfados e substituídos por grandes cristais de calcita poiquilotópica (nível de base); **l)** calcita com textura "cone-em-cone" engolfando zircão primário (centro), deslocando e substituindo toda caolinita na concreção calcítica lenticular da base do tonstein.

A composição mineralógica do nível de topo constituí-se de até 95 % de caolinita autigênica muito bem cristalizada (Fig. 8, 10a,b,e,f) formada a partir de intensa lixiviação e alterações produzidas pelos ácidos orgânicos presentes no ambiente paludal, bem como por transformações diagenéticas dos depósitos de cinzas vitroclásticas de queda. No nível de topo são encontrados todos os minerais piroclásticos reliquiares observados na camada de tonstein, que juntos perfazem cerca de 2%.

O estudo de palinofácies, inédito para este tipo de rocha, evidenciou uma composição diferenciada da matéria orgânica estruturada, ao longo do perfil. Análises estatísticas indicaram altas percentagens de fitoclastos (xilema e epiderme) associados à baixa representatividade de palinomorfos (Tabela 1). Alguns fragmentos de epiderme (cutículas) evidenciam, por sua coloração, acentuada alteração termal. O nível basal caracteriza-se por densos aglomerados de esporos e polens, enquanto o topo é marcado pela ocorrência de fragmentos de colônias de algas *Botryococcus*. Esses dados possibilitaram vincular as peculiaridades do mecanismo de deposição e preservação da matéria orgânica com o processo de formação do tonstein relacionado à rápida precipitação das cinzas vulcânicas.

Peculiaridades do mecanismo de formação do tonstein relacionadas a uma rápida deposição de cinzas vulcânicas de queda foram consideradas para interpretação de dados de palinofácies.

A presença de maciças associações amalgamadas de esporomorfos (pólens monossacados e bissacados) (Fig. 11a,b,c) no nível basal do tonstein, atestado pela utilização de luz ultravioleta, pode ser explicada através da atuação do processo que gerou a precipitação e deposição de forma muito rápida dos esporomorfos desde as estruturas produtoras de esporomorfos na planta mãe. Em ambiente detrítico, após a dispersão aérea aleatória, as fases de saturação, precipitação e sedimentação dos esporomorfos ocorrem em processos mais lentos (Traverse, 1994). As condições particulares encontradas neste material podem ser explicadas pela rápida incorporação dos grãos de pólen concomitantes à precipitação das cinzas.

A excelente preservação das colônias de Botryococcus, que correspondem a algas coloniais microscópicas do fitoplancton (Tyson, 1995) (Fig.11d), evidenciada no topo da camada de tonstein, em diferentes amostragens, usando luz ultravioleta, enfatiza sua deposição subaquática. Essa interpretação foi apresentada também por Creech (2002) para tonsteins do Newcastle Coal Measures, Permiano Superior do norte da Bacia de Sydney, Austrália. A presença de lâmina d'água protegeria o depósito de cinza de redistribuição subseqüente por ação da chuva e escoamento superficial (Creech, 2002).

No grupo dos fitoclastos as cutículas estão bem representadas ao longo de todo o perfil microestratigráfico (Fig. 11f,g,h,i,j). Alguns exemplares apresentam estruturas epidérmicas compatíveis com o grupo das glossopteridales (Fig. 11f,h,i). Por outro lado, a coloração marrom de alguns fragmentos cuticulares é atribuída à alteração térmica, considerando que a cinza ainda estava quente quando tomou contato com a superfície da folha.

Os elementos do xilema (traqueídeos) são representados por fragmentos opacos grandes, alongados, equidimensionais, angulosos, com pontoações preservadas, indicando a ausência de transporte extensivo, de outra forma, fitoclastos bioestruturados, não opacos, listrados, estriados, bandeados ou perfurados representam séries de traqueídeos gimnospérmicos com espessamento helicoidal, escalariforme e com pontoações areoladas (Fig. 11e). A presença de membranas que envolvem a pontoação (*torus*) em alguns fitoclastos, constitui evidência muito forte de sepultamento rápido (Tyson, 1995). Alguns fitoclastos de lenho opacos, de coloração marrom (Fig. 11g,h,i), sugerem um grau de alteração termal diferenciado, provavelmente relacionado à temperatura da cinza.

Fragmentos de carvão, não opacos, não bioestruturados, são comuns no nível basal do tonstein (Fig. 11k,l). Sua presença pode ser explicada pelas estruturas de escape de fluidos, formados pela expulsão vertical de água ou pelo escapamento de gás produzido pela decomposição da matéria orgânica na camada de turfa subjacente (Reineck e Singh, 1986) (Fig. 6b,c). No nível basal do tonstein também são observadas estruturas de deformação como falhas de pequena escala e distorções da laminação, resultantes da movimentação e deslizamento de camadas, penecontemporâneas, associadas à rápida sedimentação, e que ocorrem principalmente sob a ação da gravidade, e neste caso estão relacionadas à queda de troncos, ramos ou tufos foliares no sedimento fino subaquoso (Reineck e Singh, 1986) (Fig. 6e,g,h).

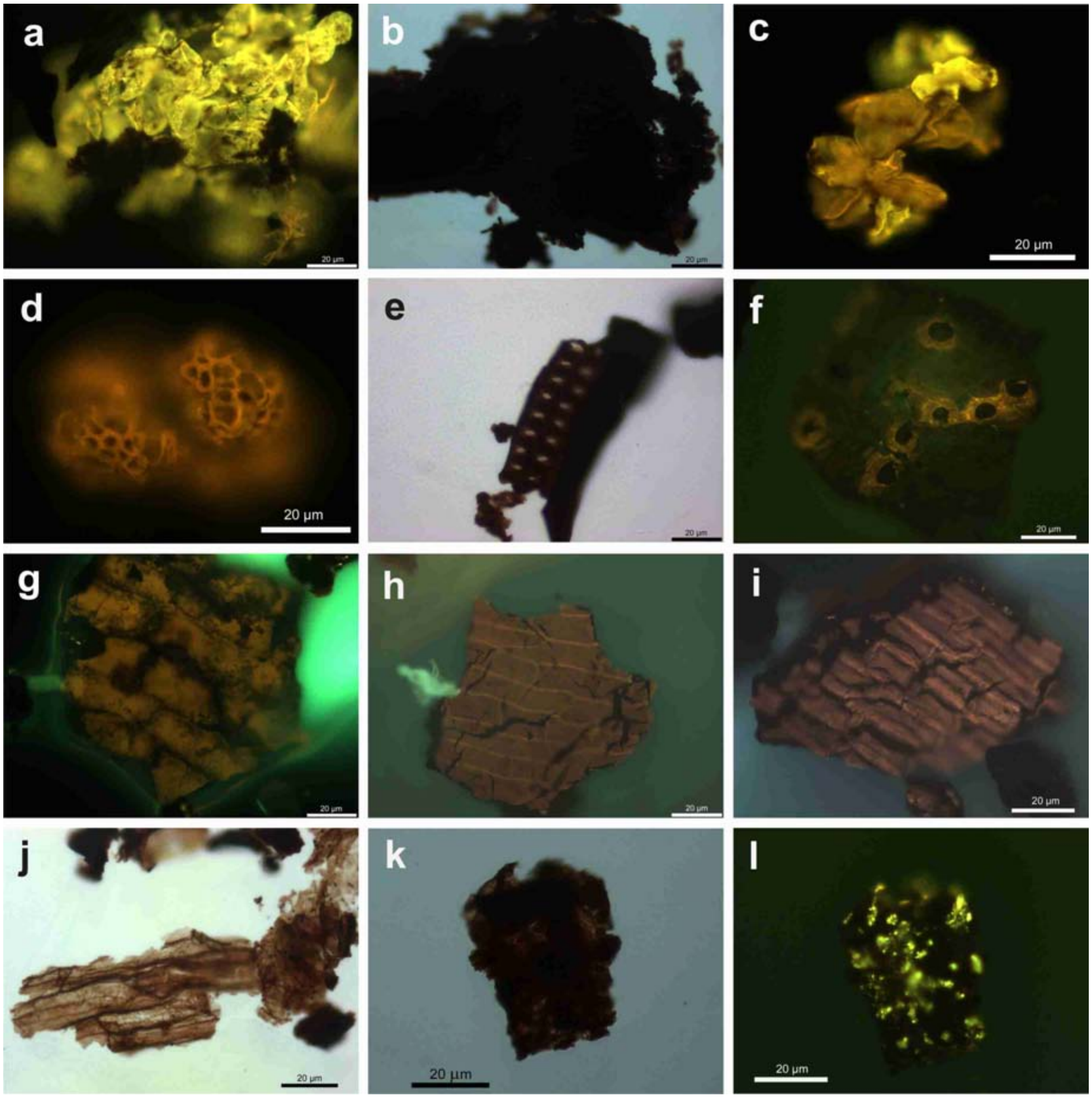

Figura 11 - **a, b, c**) Esporomorfos amalgamados; **d**) Colonias de *Botryococcus*; **e**) Traqueídeo de gimnosperma com pontoações e toros preservados; **f**) Esculturações epidérmicas de cutícula superior de Glossopteris; **g, h, i**) cutícula inferior de epidermes de Glossopteris **h, i**) Cutícula termicamente alterada; **j**) Cutícula fina; **k, l**) Fragmentos de carvão. **a, c, d, f, g, h, i, l**) Obtidas por fluorescência; **b, e, j, k**) Obtidas por microscopia por luz transmitida (luz branca).

Amostra	Nível	Fitoclastos (%)												Palinomorfos (%)				MOA (%)	Fitoclasto (%)	Palinomorfo (%)
		Opaco			Não Opaco															
					Bioestruturado					Não Bioestruturado				Espor.	Pólen	Indet.	*Botry*			
		Along.	Equid.	Corr.	Listr.	Estr.	Band.	Perf.	Cut.	N. Degr.	Degr.	Memb.	Coal							
FX-0	**T**	2,9	1,1	9,3	4,5	0,3	1,9	0,5	0,5	2,1	59,6	0	0,8	**0,3**	4	11,2	**1,1**	0	83,5	16,5
FX-1	**O**	4,3	9,2	2	0	0,3	8,6	0	0	28,3	41,4	0	0	**1,3**	4,3	0	**0,3**	0	94,1	5,9
FX-2	**P**	4,5	5,1	3,5	5,1	0,3	8,7	0	0	10,3	61,7	0	0	0	0,3	0,3	0	0	99,4	0,6
FX-3	**O**	1	1,2	1	0,7	0,5	2,2	0,2	4,8	6,9	79,4	0,2	0,2	**0,2**	0,2	0,2	1	0	98,3	1,7
FX-5		5,3	3	12,1	4,1	0,9	4,1	0	0,6	53,3	16	0	0	0	0	0,6	0	0	99,4	0,6
FX-0	**M**	1,9	0,9	4,9	4,3	3,1	1,9	0	0	0,3	81,5	0	0,6	0	0,6	0	0	0	99,4	0,6
FX-1	**E**	0,3	0,6	0,9	0,3	0,3	2,7	0	0	2,4	90,3	0	0	0	2,4	0	0	0	97,6	2,4
FX-2	**I**	16,4	2,4	15,2	0,6	0	0	5,1	0	2,7	57	0	0	0	0,3	0,3	0	0	99,4	0,6
FX-3	**O**	2,6	2	6	3,4	0	2,3	0	0,3	12,6	65,5	0	0	0	2,3	2,9	0	0	94,8	5,2
FX-5		0,9	0,6	8,6	3,2	2,3	0,6	0	10	60,5	5,7	0	7,2	0	0,6	0	0	0	99,4	0,6
FX-0	**B**	3,6	1,2	4,5	2,7	0	3	0,3	2,4	2,1	66,9	0,3	0,3	0	2,1	10,5	0	0	87,3	12,7
FX-1	**A**	1,8	0	0,9	2,5	0,3	0,3	0	0,9	2,1	49,4	0	0	0	6,4	35,3	0	0	58,3	41,7
FX-2	**S**	10,3	2,3	22,5	0	0	6,1	5,8	0	11,9	32,8	0	0	0	2,6	5,8	0	0	91,6	8,4
FX-3	**E**	0,8	0,8	4,1	1,4	0,5	2,2	0	14,6	6	52,7	0	5,5	0	2,2	9,1	0	0	88,7	11,3
FX-5		1,7	0,3	13,7	2,3	0,3	1,5	0,3	0,6	53,9	0	0	2,6	0	4,1	18,7	0	0	77,3	22,7

Tabela 1 - Análises de Palinofácies do Tonstein da Jazida do Faxinal - de cinco amostras, cada qual dividida em três níveis de topo, meio e base. Legenda: **Along**.: Alongado; **Equid**.: Equidimensional; **Corr.**: Corroído; **Listr**.: Listrado; **Estr.**: Estriado; **Band**.: Bandado; **Perf.**: Perfurado; **Cut.**: Cutícula; **N.Degr**.: Não degradado; **Degr**.: Degradado; **Memb**.: membrana; **Spor.**: Esporos; **Indet.**: Indeterminado; **Botry**.: Botryococcus; **MOA**: Matéria Orgânica Amorfa.

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2 ARTIGO SUBMETIDO

"Mineralogy and Palynofacies analyses of the Tonstein of Faxinal coalfield, an altered volcanic-ash layer from the Lower Permian of Paraná Basin, Brazil"

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Mineralogy and Palynofacies analyses of the Tonstein of Faxinal Coalfield, an altered volcanic-ash layer from the Lower Permian of Paraná Basin, Brazil.

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Abstract

Mineralogical and palynofacies analyses are reported from a tonstein layer interbedded with coal seams in the Faxinal coalfield, Rio Grande do Sul, Brazil. Integration of data has far reaching significance for attributing a volcanic origin for this kaolinitic claystone bed. The tonstein is almost monomineralic rock, composed mainly by authigenic kaolinite. Scattered in the kaolinitic mass primary pyroclastic minerals occur: euhedral beta-quartz paramorphs and water-clear quartz splinters, idiomorphic zircons, apatite, allanite and sanidine pseudomorphs; considered as a restricted suite of silicic volcanic minerals of the distal tonsteins which preserved during diagenesis. The primary minerals and their textural features, as well as the field relations, indicate a volcanic air-fall origin. Analyses of the kerogens from different levels of tonstein layer indicate high percentages of phytoclasts combined with very low palynomorph percentages. Microstratigraphic analyses of the tonstein profile demonstrated that saturation and precipitation of palynomorphs were highly influenced by the intense ash-fall process. The preservation of *Botryococcus* colonies at the top of the tonstein evidenced the subaqueous deposition of this bed. The brown color of several cuticle fragments and tracheids was linked to thermal alteration. The tonstein interbedded in a coal seam indicates an episode of tephra sedimentation during the deposition of the coal-bearing sequence of the Lower Permian in the southern Paraná Basin.

Keywords: Tonstein, volcanic air-fall origin, mineralogy, palynofacies, Lower Permian, Paraná Basin

1. Introduction

Tonsteins are claystone beds, synchronous with the sedimentary rocks in which they are interbedded. Tonstein beds extend over large distances and usually contain minerals that can be dated by isotopic analyses. Their geographical distribution is limited to sites with favorable preservation potential, such as lacustrine environments. Their limitation to coal measure sequences reflect the higher depositional energy that operates outside of the topographic peat-accumulating depression.

Evidence of volcanic activity is widespread in different coal successions in the southern Brazil, which are historically assigned to the Rio Bonito Formation (Fig. 1), a fluvial-marine sandstone and shale prone lithostratigraphic unit. These rocks are recorded by discrete and continuous horizons of clay beds identified as tonsteins interbedded within coal seams in Candiota and Faxinal coalfields (Formoso et al., 1999, Guerra-Sommer et al., 2006).

Corrêa da Silva (1973) suggested, on the basis of field relationships and some mineralogical and chemical analyses, that the clay beds in the Candiota Coalfields can be classified as *stratotonstein* (according to Bouroz's scheme) or *dichtertonstein* (apropos the Schüller nomenclature). Furthermore Della Favera et al. (1992) agrees with a detrital origin for those tonsteins.

Formoso et al. (1999) studied three of these clay beds, two in the upper Candiota coal seam (8-10 and 1-3 cm thick) and one in the lower coal seam (1-2 cm thick). The samples, both oriented and unoriented, were analyzed by XRD (Siemens D500-CoK, 40 mA – 30 kV). Advanced kaolinization suggests an *in situ* diagenetic alteration to nearly pure kaolinite (ca. 90%): preservation of primary minerals is poor. The presence of euhedral beta-quartz is a reliable indicator of volcanic origin. The higher content of U and Th, negative Eu anomalies, and high La/Yb signal that source rock was acidic. Geochemical diagrams support the view that the tonsteins are of acidic volcanic origin, in agreement with a volcanic ash origin accepted for these beds (Bohor and Triplehorn, 1993).

On the other hand, field relationships of these tonsteins, particularly their extensive distribution, relative thinness, and continuity, indicate not to be a detrital, but also an ash-fall volcanic origin (Formoso et al., 1999).

Radiometric data in clay beds characterized as tonsteins in different coalfields in the southern Brazilian coal succession were made by several authors (Matos et al., 2000, 2001; Guerra-Sommer et al., in press-a,b) using IDTIMS U-Pb method to date zircons.

Ion microprobe (SHRIMP II) dating of zircons from tonsteins interbedded with coal seams from the Candiota and Faxinal coalfields (Early Permian, Rio Bonito Formation, Paraná Basin, Brazil) are presented by Guerra-Sommer et al. (in press-c). The mean ages obtained (290.6 ± 1.5 Ma) are more precise than previously published intervals. Calibrations of chronostratigraphic data with radiometric ages show that the main coal succession from the southern Basin is constrained to the Middle Sakmarian. The ± 2 Ma time interval of deposition supports the hypothesis that the coal-generating process was quite rapid in terms of geological time. The new results have far-reaching significance for correlations of the Basin with sequences of the Argentinian Paganzo Basin (302 ± 6 Ma and 288 ± 7 Ma) and also with the Karoo Basin, with the lowermost Ecca Group (288 ± 3 Ma and 289.6 ± 3.8 Ma). This new evidence supports the presence of an active and widespread Lower Permian explosive volcanic event in western Gondwana, which is interpreted as the same volcanism which produced the Choiyoi Group in western Argentina.

Previous petrographic studies developed by Guerra-Sommer et al. (in press-a) from the tonstein layer interbedded on the Upper Coal Seam (S) in the Faxinal coal field confirmed that the claybed is composed of authigenic and probably pyroclastic, ash-derived minerals.

The Faxinal tonstein bed, in particular, is the focus of this work for several reasons. Firstly, it is a unique, highly recognizable, laterally persistent claybed on the coal field profile. Secondly, SHRIMP zircon dating of the tonstein bed allowed for absolute ages for its deposition (290.6 ± 1.5 Ma). Thirdly, this kaolinitic claybed contains a high proportion of fossil plants, represented mainly by leaves, in excellent stage of preservation. Fourthly, the presence of a continuous carbonatic band (microstratigraphic level) at the base of this altered ash-fall deposit represents a conspicuous feature, absent in other tonstein layers of the basin.

Taking into account the available geological data and its effect on the tonstein formation process for the southern Paraná Basin, in Brazil, the aim of the present contribution is to make accurate previous petrographic studies with the purpose of: to document petrographic analyses in different levels of this tonstein layer; calibrate the petrographic and mineralogical results with palynofacies analyses; integrate results from different methodologies in order to confirm the volcanic origin for this claystone bed, designed as tonstein sensu Bohor and Triplehorn (1993).

2. Geological and stratigraphic setting

The Paraná Basins is a large (1,400,000 km2) intracratonic sag basin covering part of southern Brazil, Paraguay, Uruguay and Argentina. Basin floor subsidence, in addition to Paleozoic sea-level changes, created six second-order sequences deposited from the Ordovician to Late Cretaceous, separated by regional unconformities (Milani, 2003). The coal-bearing Rio Bonito Formation, which is the object of this study, occurs at the base of the second-order Carboniferous–Early Triassic sequence. The study area comprises the Candiota and Faxinal coal fields, which is part of the southeastern outcrop belt of the Rio Bonito Formation of the Paraná Basin, southern Brazil (Fig. 1).

Detailed sedimentological and stratigraphic work demonstrated that coal deposits of the Rio Bonito Formation in the Candiota and Faxinal coal fields occur adjacent to paralic, i.e., estuarine, deltaic, backshore, foreshore and shoreface siliciclastic deposits, and that coal was deposited in back-barrier environments (Holz, 1998). Tissue preservation and gelification index corroborate with deposition in a coastal swamp environment (Alves and Ade, 1996). Deposition occurred at the cool temperate climatic belt (Scotese, 2002) or, according to the criteria of Rees et al. (1999), in the cool temperate bioma, at a palaeolatitude of 50° approximately (Scotese, 2002). The Permian in the Paraná Basin was a period of overall transgression of the shoreline, punctuated by short regressive episodes (Zalán et al., 1990). The Rio Bonito Formation integrates part of two third-order depositional sequences of the Carboniferous Early Triassic second-order sequence, named S2 and S3 (Holz et al., 2002).

The Faxinal coalfield, mined by the Companhia de Pesquisas e Lavras Minerais (UTMN6651.5/E432.7) (COPELMI), is located near the town of Arroio dos Ratos, about 120 km southwest of Porto Alegre and close to Água Boa and Sul do Leão coalfields (Fig. 2). These coalfields are situated in a graben, referred to previously as the Leão/Mariana

Pimentel paleovalley (Ribeiro et al, 1987). It is an elongate structure trending SE-NW in its eastern portion and E-W to the west. The graben, inserted in the basement, is 60 km long and up to 5 km wide. The three coalfields are downthrown structural blocks, mainly controlled by a N40°E fault system, and their extent is limited by subsequent erosion. The Faxinal coalfield (producing 18 × 106 ton coal/tons of rock by open pit) is situated in the eastern part of the graben.

The Faxinal succession includes five coal seams, named, from base to top: **I, IM, M, MS,** and **S**. the seams are interbedded with siltstones, mudstones, sandstones, and paleosols (Fig. 3). The present study focuses on a light gray clay-bed, approximately 10 cm thick that is laminated to massive and fossiliferous and interbedded with the upper coal seam (**S**). The bed is exposed along the cutbanks of the open pit and displays mostly sharp lower and upper boundaries (Fig. 3 and 4a,b).

The bed present on its base, a continuous carbonatic level for all crop out section, with 3 to 6 cm of thickness, and a claystone upper level, from which it was described a palaeoflora mostly composed by *Glossopteris* leaves, also occurring *Cordaites* and filicopsids leaves, conifers and fronds of undetermined botanical affinity (Guerra-Sommer, 1988).

3. Petrography and Mineralogy

Methodology

- **Sampling techniques**

Tonstein samples were collected from the different cutbanks of the open pit areas (Fig. 4a,b). In each sample three different levels were analyzed independently, taking into account their secondary mineralogical characteristics. The base level (**b**) is calcitic carbonate composition with kaolinite; the intermediate level (**m**) besides kaolinite contains often siderite and secondarily pyrite and calcite; at the top level (**t**) the kaolinite is always dominant (Fig. 4c,d,e,f).

- **Analytical techniques**

The samples were analyzed using the following methodologies: 1) conventional optical microscopy analyses on 13 thin sections (*Leitz* - Laborlux 12 POL S).; 2) Scattered electronic microscopy (SEM) analyses of semi-quantitative chemical analyses by Energy-dispersive X-ray spectrometer (EDS) and images acquisitions by Backscattered electrons (BSE) and Secondary electron images (SE) in thin section and rock mount in stub, at the Electronic Microscopy Centers of the Pontifícia Universidade Católica do Rio Grande do Sul and Universidade Federal do Rio Grande do Sul; 3) X-ray diffraction (XRD) analyses (Siemens-Bruker AXS D5000 - CuKα - 25 mA - 40 kV) using powder diffraction technique to whole rock to identify the mineralogical composition qualitatively and semi-quantitative of 21 samples (seven of each levels) (Fig.5a,b,c), and natural oriented preparation to identify the clay minerals (7 samples of the top level) (Fig.5d), the XRD analyses were made in the laboratory of IG-UFRGS).

Petrography

The tonstein at the Faxinal Coalfield is a continuous bed with constant thickness (about 10 cm), showing sharply bounded upper and lower contacts, widespread for kilometers (Ribeiro et al., 1987).

Texturally is a claystone to mudstone, silty clay with medium sand particles, light gray colors. Irregular lamination is observed that was characterized by granulometric variation (Fig. 6a,b) and marked by thin black lenses of organic matter (coalfield leaves) (Fig. 4c,d,e,f). Some Tuffaceous character are observed in thin sections of the original ash preserved as sub-parallel orientation of the elongate quartz splinters and pseudomorphs feldspars (Fig. 6b,c) (Huff and Spears, 1989).

The tonstein is composed by primary minerals derived from volcanic ash-fall and dust, and by secondary minerals were formed during the diagenetic processes. This rock is constituted mainly by authigenic kaolinite, make up around 90% of its mineralogical composition.

Relict pyroclastic minerals occur into the kaolinitic mass and correspond to: euhedral bipyramidal beta-quartz paramorph and water-clear quartz splinters, idiomorphic zircon, apatite, allanite and sanidine pseudomorph, which characterize distal tonsteins. The presence of other diagenetic minerals that formed after the kaolinization of pyroclastic ash fall was also observed. These early diagenetic mineral phases were established in the following sequence: kaolinite→pyrite→siderite→calcite.

Small differences in the colors of the hand samples are observed, that due to the variations in the mineralogical composition (kaolinite, siderite, calcite), which characterizing microstratigraphic levels (Fig. 4c,d,e,f). Thus the tonstein bed is here divided in three levels that denominate: base level (**b**), intermediate level (**m**) and top level (**t**). The microstratigraphic levels are observed in the XRD patterns of the sequential analysis of samples to the each level (Fig. 5a,b,c).

In the base microstratigraphic level calcite predominates, replace almost all kaolinite and the primary minerals such as quartz, zircon, apatite and others (Fig. 7c,j,k,l). The base level display a continuous carbonatic band (3 cm thick), as well as some carbonate concretion lenses (6 cm thick in its center) (Fig. 4c,d,f). The secondary phases such as pyrite and siderite are formed mainly into the intermediate level (Fig. 5a,d). Kaolinite is the mainly secondary phase present on the top level, making up 95 % of this level and all the pyroclastic mineral suite of this claystone, showing an irregular laminations by variation of grain size (clay, silt up to fine sand particles), that could suggest a wind variations during an eruption or, possibly, pyroclastic pulses, by alterning ash and dust, with more or less glass particles or crystals. Therefore, the characteristics of the top level develop the more typical tonstein composition, structures and textures.

Mineralogy

The minerals were divided in two groups: pyroclastic minerals, which preserved their characteristics during the action of weathering and diagenetic processes over the tephra, and the authigenic minerals, that were post-depositional formed in the peat swamp environment.

- **Pyroclastic minerals**:

Quartz is the most abundant volcanic mineral. There are many euhedral grains of beta-quartz paramorph, with bipyramidal habit, without prism development (Fig. 6d).

Quartz, generally is the most common and abundant primary mineral present in tonsteins. It crystallizes as phenocrysts from silicic magmas in the high-temperature phase (beta) form, inverting to the low-temperature phase (alpha paramorph) when temperatures fall bellow 573ºC (Bohor and Triplehorn, 1993).

The characteristically clear-water volcanic quartz occurs as splinters, showing elongated and almost always deformed, wedged, but delicate forms (Fig. 6c,e,f). Also subhedral crystals or fragments were identified with sharply angular, triangular to cuspate forms, probably representing broken bipyramids (Bohor and Triplehorn, 1993). Few anhedral crystals of elongated, with embayment or curved forms are observed (Fig. 6f). The elongate quartz particle grain size varies between 38 µm to 230 µm, with average around of 123 µm. The bipyramidal crystals displaying an average grain size of 68 µm. In the powder X-ray diffraction (XRD) analyses of the whole rock, the quartz was detected in low quantities, presenting intensities (counts) relatively lower in the base level when compared with intermediate and top levels. (Fig. 5a,b,c,d)

Zircon occurs as prismatic, idiomorphic elongate crystals with grain size average of 80 µm (Fig. 6g). Most crystals display bipyramidal termination, straight walls. This zircon morphology is characteristic of volcanic rocks, and therefore, may be useful for correlation of pyroclastic rocks (Kowallis and Christiansen, 1989; Guerra-Sommer et al, 2007b,c). A second zircon population is equant, rounded, with grain size ranging from 10 to 100 µm, but those detrital grains are rare.

Apatite show clear crystals with euhedral hexagonal and prismatic forms. Grain sizes vary from 25 to 70 µm, mostly around 50 µm (Fig. 6h). Apatite is found in most fresh volcanic ashes of silicic composition; however, this mineral is not present in most tonsteins because of its susceptibility to acid dissolution (Bohor and Triplehorn, 1993). The apatite of the Faxinal tonstein seems to be pyroclastic, and its dimensions are similar to the volcanic zircon dimensions. An accurate study in the apatite is necessary to verify this question. Zircon and apatite represent less than 0.1% and with quartz make up around 2 % of the rock.

Feldspar pseudomorphs replaced by kaolinite show euhedral equant habit (almost square to elongated pseudohexagonal or rhombic shape) and rare prismatic forms (Fig. 6j,k,l). The pseudohexagonal forms vary between 140 and 400 µm whereas prismatic are from to 80 µm on average. Relict feldspar, with irregular form and 50 µm in diameter, display intense dissolution along the cleavage planes and present K-feldspar composition by EDS-SEM analyses Baveno-like gemination is observed in euhedral rhombohedral grain of pseudomorph potassium feldspar (see Fig. 5f in Guerra-Sommer, in press-a).

Some evidences suggest that the pseudomorph feldspars were sanidine, as the potassium feldspar composition, abundant pseudo-hexagonal to rhombic or elongate squares forms, probably (010) faces, and these minerals are replaced by fine kaolinite which preserves the forms of the crystals and rare features similar to twins. There are indications of very subordinate presence of plagioclase pseudomorphs, presenting prismatic forms replaced by kaolinite and with features similar to albite twinning (Fig. 6l). The relative amounts of plagioclase and sanidine pseudomorphs are possibly modified in relation to the parent ash, because plagioclase is commonly found altered or dissolved during weathering, rarely as sanidine (Bandfield and Eggleton, 1990).

Allanite was observed by optical microscopy and also detected and confirmed by electron microscopy (SEM) at the same sample, FX-0 on the base and the top levels. It presented elongated forms with rounded edges and apex, as an ellipse, with dark brown color, high birefringence, but it seems in metamict state, and measuring from 55 µm to 18 µm (Fig. 6i – right upper). The SEM-EDS analyses show the Ce, La and Y (REE) and Fe, Ca, Si and Al as elemental composition (Fig. 6i – left lower).

Allanite is a component of the restrict suite of primary volcanic minerals of the most distal tonsteins (Bohor and Triplehorn, 1993). It was reported in tonsteins from Eoceno coal beds in Wyoming (Bohor et al., 1979). Nevertheless, it is easily altered, and only rarely found in tonsteins in trace amounts, characteristically as corroded crystals (Bohor and Triplehorn, 1993). Taking into account these allanite characteristics and the considerations pointed out in this paper, this mineral is has probably a pyroclastic nature, but further investigations will be able to verify its origin.

The presence of bipyramidal beta-quartz paramorphs, elongate idiomorphic zircons, as well as, sanidine pseudomorphs, allanite and apatite with compatible forms and dimensions, suggest that the tonstein was derived from an silicic volcanic tuff. Based on geochemical studies of less mobile element (in preparation), the ratios Nb/Y against Zr/TiO_2 which discriminate between volcanic magma series and rock types (Winchester and Floyd, 1977) are confirming the mineralogical observations and suggest a rhyodacitic to rhyolitic for the volcanic source to the altered ashes.

- **Authigenic minerals**

Kaolinite is the most common and abundant mineral in the coal-tonstein bed. X-ray diffraction analyses of the tonstein showed very well-crystallized kaolinite as the sole component of the clay fraction (Fig. 5a,b,c,d). It constitutes around 90% of the tonstein bed, and is formed by the alterations, eodiagenetic transformations by replacement of many primary pyroclastic minerals and particles, such as glass, biotite, feldspars, and possibly other minerals.

The kaolinite comprise since very fine flakes and granular aggregates that is the tonstein matrix (Fig. 7d), until large aggregates such as vermicular forms and booklets with size up to 1000 μm (Fig. 7a,b,c,e,f). Exceptionally kaolinite vermicular aggregates with up to 700 μm are found from the base until the top of the tonstein bed (Fig. 7b). In thin section and X-ray diffraction patterns, kaolinite constitutes more than 90% of the top level of the tonstein layer (Fig. 5a and 7a). On the intermediate (m) and base (b) levels, there is a reduction in the amount of kaolinite due to the replacement by siderite and calcite (Fig. 5b,c and 7c,g,k).

Pyrite is the most common sulphide in the tonstein, appearing notably on the intermediate level, especially as nucleus within siderite masses (Fig. 7g). It displays tiny euhedral crystals with cubic habit, small spherical framboids, infilling kaolinite {001} cleavages and some other cavities displaying replacement of organic materials (Fig. 7h,i).

In the tonstein sample FX-3, the pyrite shows lenses (0,7 x 6 cm) on the boundary of intermediate and base level, that marks the separation of calcitic rich level (base) to the siderite rich level (intermediate). Some rounded pyritic concretions (like balls) are observed near the lower limit of the tonstein (Fig. 4f). The pyrite was formed in the early diagenesis, on the bacterial sulphate reduction zone, where there was Fe^{2+} availability in reducing conditions.

Siderite occur mainly on the intermediate level, in some samples (FX-0, FX-2, FX-3 and FX-4) comprise 10 to 20% of the rocks. Siderite is also present at the top level of the FX-0 sample ranging from 1% on the upper part, up to 20% on the lower part of this level, displaying the bedding distribution (Fig. 4c,f). The siderite is yellowish brown in thin section, forming irregular massive aggregates up to 200 μm, as well as disseminated crystals smaller than 5 μm (Fig. 7g,h,j,k and 6k). In the most of siderite aggregates there is a pyritic nucleus, i.e. the siderite engulfing pyrite (Fig. 7g). Siderite precipitates when a solution containing abundant Fe2+ and HCO3- evaporates or the pH increases. Under unusual conditions, where either the supply of ferrous iron is large or a reducing environment is maintained by abundant organic matter, siderite can precipitate in large quantities (Krauskopf, 1967).

Calcite is common mineral in the basal level of the tonstein and small amounts are observed in the lower part of the intermediate level (mainly in the FX-1). The calcite was the latter diagenetic mineral phase, that occurs as irregular aggregates and like large poikilotopic crystals, and therefore, it includes and replaces other minerals of the tonstein (Fig. 7c,j,k).

At the bottom of the tonstein layer (sample FX-1), a white lenticular concretion occurs with up to 6 cm thickness to almost 1 m length. This concretion is formed predominately by calcite, that in some places make up to 98%, and present cone-in-cone texture, with displacive precipitation that dislocated and replaced all other minerals (Fig. 4d and 7l).

Organic matter is black, brown to yellow colored in thin section, occurring as small fragments, visible as thin laminated lenses, mainly produced by coalified leaf fragmentation process, making up to 1 to 5 % of the rock (Fig. 4c,d,e,f).

The reflectivity of the vitrinite – Ro (%) of the coalified tracheids in the tonstein (0,45) corresponds to around 60ºC to the Permian temperature curves, in other words, these temperature, as well as, the authigenic minerals formed in the tonstein are compatible with eodiagenetic conditions.

4. Palynofacies

Methodology

- **Kerogen classification**

The organic matter (POM: Palynological Organic Matter) was divided according Lorente and Ran (1991) into for major groups: palynomorphs, structured debris, amorphous matter and indeterminate matter. At the present paper the scheme use to classify dispersed organic matter in transmitted light microscopy is derived and simplified from the classification of Tyson (1995). The palynofacies characterization was based on quantitative analyses of the particulate organic matter and a total of 300 particles were counted for each sample according to the criteria of Mendonça Filho (1999).

- **Sampling techniques**

They followed the same criteria used for petrographic analyses. Tonstein samples were collected from the different cutbanks of the open pit areas aiming to compare the distribution of the POM along the ash fall deposition profile. In each sample three different levels were analyzed independently. The base level (**b**) is calcitic carbonate composition with kaolinite; the intermediate level (**m**) besides claystone contains siderite and calcite; at the top level (**t**) the kaolinitic claystone is dominant (Fig. 4).

- **Analytical techniques**

For palynofacies studies the samples were first treated with HCl and HF acids followed by heavy liquid ($ZnCl_2$), in order to concentrate the organic matter. The isolated organic matter was then mounted on strewn slides. The preparation technique employed was the standard non-oxidative palynological procedure.

Results

Statistical analyses of the kerogens for the three different levels of five tonsteins samples indicated high percentages of phytoclasts combined low palynomorph percentages (Table 1).

Qualitative observation of phytoclasts in sedimentary basins is determined by several factors (Cole, 1987); rapidly deposited proximal sediments (e.g. flood deposits) commonly have poorly sorted phytoclast assemblage. On the other hand, proximal energy sediments (e.g. delta tops swamps, lagoons) are also generally poorly sorted. Generally, large amounts of phytoclasts particles are related to proximal depositional conditions. Otherwise, distal low energy facies have better sorted assemblage; small percentages of palynomorph would indicate distance of terrestrial source (Tyson, 1995).

Nevertheless, at the present case study, peculiarities of the mechanism of the tonstein formation, related to rapid volcanic ash-fall deposition, must be taking into account for palynofacies analyses interpretations. This process is considered as geologically instantaneous events, according Prothero (1990). During eruptions, the pyroclastic material was ejected to high altitudes and transported by tropospheric air flows over significant distances and deposited over a peat-surface.

Palynofacies analyses established in the tonstein layer challenges palynological results obtained by Guerra-Sommer et al. (2007a) for the Faxinal tonstein. Those analyses characterized well-preserved cuticles showing affinity with Glossopteridophyta and Cordaitophyta and very rare spores and pollen grains, frequently poorly preserved and undetermined. Palynofacies analyses, using blue light excitation or ultraviolet irradiation, identified massive associations of hundreds well preserved amalgamated sporomorphs (bissacate and monossacate pollen grains) in the basal level (b) composed of calcitic claystone (Fig. 8a,b,c). Ash fall might have played an important role in the anomalous kind of preservation of the continuous band of those clusters at the base of the tonstein. These aggregates, judging by their excellent preservation, seem to be deposited directly from the atmosphere, with a short transport from their place of origin.

The random dispersion of pollen in the atmosphere using wind currents, typical from Permian gymnosperms, discharged a great quantity of pollen grains, which were dispersed the bulk of it is lost in lakes and bogs (Traverse, 1994). Thus, the presence of amalgamated clusters of sporomorphs is a feature that would be explained by special environmental conditions. Such conditions would be supplied if large amounts of mature pollen grains, tapped directly from male inflorescences, were buried rapidly and readily incorporated in ash-fall deposits. Consequently the saturation and precipitation of those grains in clusters were intensely influenced by the intense ash-fall process.

The dominance of pollen grains over spores reflects the composition of the megaflora preserved within the tonstein layer, characterized by the dominance of *Glossopteris* and *Cordaites* leaves (Guerra-Sommer, 1988).

The magnific preservation of *Botryococcus* colonies (Chlorococcales), evidenced at the top level (t) of the tonstein layer in different samples by blue light excitation or ultraviolet irradiation, emphasize the subaqueous deposition of the tonstein layer (Fig. 8d). These forms encompass microscopic phytoplankton colonial algae, from freshwater lacustrine, fluvial, lagoonal and deltaic facies (Traverse, 1955; Pocock, 1972; Claret et al., 1981; Batten and Lister, 1988; Cole, 1987; Riding et al., 1991; Williams, 1992), but also occur in unstable salinity regimes (Naggapa, 1957; Hunt, 1987). A subaqueous intraseam tonstein deposition was also inferred by Creech (2002) for Late Permian Newcastle Coal Measures of the northern Sydney Basin (Australia), based in organic coal petrography, sedimentology and paleobotany. In that study the presence of *Botryococcus* was considered as an important marker of subaqueous deposition. Thus, the palynological composition of the sporomorph group is consistent with a protection of volcanic ash deposit from subsequent redistribution by rain fall and surface runoff.

At the phytoclast group, cuticles are well represented in the three mycrostratigraphic levels (b, m, t). However, as it was emphasized by Tyson (1995), size data from sediments rich in macroscopic plant fragments, such as in the present case study (Fig. 9a) should be interpreted with great care, as the breakdown of large leaf fragments during maceration may completely distort the nature and size characteristics of the palynofacies assemblage.

The segregation of a cuticle of a leaf may occur either by biochemical activity, physical disintegration, or a combination of process. Complete degradation of parenchymatous tissues within a plant organ can result in the isolation of the protective cuticle (Traverse, 1994). The well preserved leaf fragments with upper and lower cuticles stuck together represented in figure 8f,g,h,i,j and figure 9b,c,d are rare phytoclasts in the palynofacies assemblage.

These thick fragments of cuticles correspond, actually, to fragmented leaf laminae, still composed by parenchyma, epidermis and cuticle layers, not yet "softened" by bacterial attack (Garden & Davies, 1988) (Fig. 8f,g,h.i). This kind of preservation can be explained by the fast ash-fall deposition process. Large canopy leaves, sometimes arranged in whorls, are particularly sensitive to ash coating, which predisposes them to abscission (Fig. 9a). Subsequent falls of the ash and dust dislodge such leaves, which become incorporated in the air-fall deposits, remaining not degraded (Spicer, 1991). Otherwise, the brown color of several cuticle fragments could be the results of the thermal alteration (Fig. 8h,i). Nevertheless, the excellent preservation of some isolated cuticles permits the identification of diagnostic epidermic sculptures typical of *Glossopteris* specie (Fig. 8f and 9d) described from the same tonstein level (Guerra Sommer, 1988).

The most conspicuous lignified phytoclast are fragments of "xylem elements" comprising tracheids; large, opaque elongate (lath shape), equidimensional (equant shape) and corroded wood phytoclasts with internal mycrostructural grain suggest absence of extensive transportation. On the other hand, translucent biostructured phytoclasts striped, striated, banded and pitted represents series of gymnosperm tracheids with helical, scalariform thickening and with bordered pits. The preservation of the pit-closing membrane in some phytoclasts constitutes a strong evidence of rapid burial process; otherwise, this organic structure would be easily degraded by bacteria (Eaton and Hale,

1993) (Fig 8e). The xylem phytoclasts might be originated by branches and shoots from the falling tree canopy, commonly observed with the naked eye in the tonstein layer (Fig. 4d,e). Some opaque biostructurated brown color wood phytoclast suggest a different thermal degree (Figs 8h,i).

Translucent not biostructurated coal fragments are frequent, mainly close to the lower boundary of the base (b) level (Fig. 8k,l). Their occurrence into de tonstein layer can be explained by sedimentary structures locally observed, similar to pit and mound structure, and slump structures, such as distorted bedding and small-scale faulting. The pit and mound or mud volcanoes are structures related to vertical water expulsion, or possibly the escaping gas formed by decomposition of organic matter in underlying sediments (Reineck and Singh, 1973; p. 48). The structures similar to slump structure, such as distorted bedding and small-scale faulting, are penecontemporaneous deformation structure resulting from movement and displacement of already deposited sediment layer, generally associated with rapid sedimentation (Reineck and Singh, 1973, p. 79). In the present case study, this process probably occurs due to fall of branches, trunks and foliar tufts, that is a common feature on the base level of the tonstein (Fig. 4d,e,f).

5- Final Remarks

The tonstein bed of Faxinal Coalfield corresponds to a conspicuous stratigraphic marker for the Rio Bonito Formation to the Paraná Basin. Integration of petrographic, mineralogical and palynofacies analyses confirm a volcanic air-fall origin for this claystone bed.

Taking into account the presence of a restricted suite of primary volcanic minerals such as euhedral bipyramidal beta-quartz paramorph and water-clear quartz splinters, idiomorphic zircon, euhedral apatite, allanite and euhedral sanidine pseudomorph phenocrystals, this claystone bed can be characterized as a distal tonstein. On the other hand, the constitution of this rock composed mainly by *in situ* kaolinite, exclude a detrital origin hypothesis and points out to a typical volcanic-ash alteration.

The texture of the primary minerals, the irregular laminations evidenced by granulometric variation and sub-parallel orientation of primary minerals reflects pyroclastic ash and dust deposition characteristics. Small color differences are consequence of weathering alterations and diagenetic transformation in the mineralogical composition (kaolinite, siderite, calcite), characterizing three different microstratigraphic levels.

The authigenic kaolinite was formed by intense leaching of the organic acids generated from the abundant organic matter in the paludal environment over the pyroclastic glass particles, feldspars, micas and other minerals. The sulphide and carbonate authigenic phases such as pyrite, siderite and calcite are formed respectively after kaolinite, due to changes in the pH conditions, and distributing preferentially in the three distinct microstratigraphic levels.

Palynofacies analyses of the kerogens from different levels indicated high percentages of phytoclasts, combined with low palynomorph content. Microstratigraphic analyses reflected the presence of hundreds of amalgamated sporomorphs at the base level (b) and the presence of algal *Botryococcus* colonies at the top level (t). Special environmental conditions can be inferred by this kind of preservation, linked to a rapid saturation and precipitation of palynomorphs associated to a subaqueous deposition of the bed, supported by the presence of algal colonies. These evidences challenge hypotheses of a detrital input for the structured organic matter and points to a rapid burial process. Thus, a volcanic air-fall deposition hypothesis fits well with palynofacies analyses interpretations.

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Figure Captions

Figure 1 - Simplified geological map of the Paraná Basin in Brazil with major tectonic elements and geographic references (after Milani, 2003).

Figure 2 - Location map of the Faxinal Coalfield.

Figure 3 - Lithological log, facies, parasequence, geochronology and radiometric data of the Faxinal Coalfield (after Guerra-Sommer in press-a,c).

Figure 4 - Profiles from the Faxinal tonstein in the outcrop **a)** showing field relations with coal seams and **b)** interbedded in the coal seam S. Hand samples profile: **c)** FX-0 sample, **d)** FX-1 (with a calcitic concretion lense into the base level), **e)** FX-5, **f)** FX-4. Arrows in a) and b) points to the Faxinal tonstein bed; in c) aim the boundaries of the sideritic intermediate level; in d) the left arrow aim to the organic matter (fallen branches) disturbing bedding, and the right arrow points to the fluid escaping structure; in e) aim to the branches showing disturbance in the lamination; f) arrows point to small-scale faulting; in pictures c), d), e) and f) the general aspects showing lamination marked organic matter (black lines) and microstratigraphic levels: base (b), intermediate (m) and top level (t).

Figure 5 – X-ray diffraction patterns of whole rock (by the powder method - 2º to 72º 2-Theta) from the Faxinal tonstein samples separated in **a)** top level, **b)** intermediate level, **c)** base level, displaying diagenetic phase minerals as: kaolinite, calcite, siderite, pyrite and one pyroclastic mineral: quartz; **d)** XRD pattern of oriented preparations (natural – air dry state - 2º to 32º 2-Theta) of the top level samples displaying only the very well crystallized kaolinite (001) and (002) basal planes. Legend: Kln – kaolinite, Cal – calcite, Qtz – quartz, Sd – siderite.

Figure 6 - Photomicrographs of thin sections showing pyroclastic features and minerals from the Faxinal tonstein. **a, b)** irregular lamination by granulometric variation; **b, c)** sub-parallel orientation

the elongated pseudomorphs feldspar and quartz splinters; **d)** euhedral bipyramidal crystals of beta-quartz paramorph; **e**) delicate elongated shapes of water-clear quartz splinters; **f)** water-clear quartz splinters showing particles with embayment (upper left side), and curved shape (upper right); **g)** idiomorphic zircon with bipyramidal terminations, within kaolinite matrix, displaying straight walls, is zoning crystal with rounded inclusion at the center **h)** apatite showing euhedral hexagonal basal face within kaolinite matrix and prismatic face with replacement by siderite on the left end; **i)** allanite elliptical forms with rounded edges, are presenting SEM image and EDS chemical analyses; **j, k, l)** feldspar pseudomorphs replaced by kaolinite, with rhombic forms (pseudohexagonal to square elongated), in **l)** a prismatic section of feldspar pseudomorph with relict features similar to albite twins (center of the picture). Legend: ap – apatite, ß-qtz – beta-quartz, kln – kaolinite, sd - siderite.

Figure 7 - Photomicrographs of thin sections showing authigenic minerals: **a, b, c)** kaolinite in elongate vermicular stacks, with well-developed hexagonal outline **(a)**; **c)** kaolinite are engulfing by calcite (base level); in **d)** fine kaolinite like granular aggregates as a microcrystalline matrix; **e,f)** showing "booklets" of kaolinite; **a, d, e, f**) are SEM images; **g, h)** yellowish brown siderite as granular aggregates dispersed in a kaolinitic matrix; in g) siderite engulfing pyrite aggregates; **h)** pyrite infilling kaolinite cleavages (center top) and partially replacing kaolinite, detailed feature in **i); j)** calcite replace some euhedral prismatic minerals preserving relict forms into the kaolinitic matrix and with siderite aggregates in right side of the picture; **k)** kaolinite vermículos and quartz splinter are engulfing and replaced by large poikilotopic calcite (base level); **l)** calcite with "cone-in-cone" texture engulfing zircon remnant (center), dislocate and replace all kaolinite on the bottom calcitic concretion lense.

Figure 8 - **a,b,c)** are amalgamated sporomorphs; **d)** is Botryococcus colonies; **e)** is a tracheid of gimnosperm with bordered pits and toros preserved.; **f)** is epidermis sculpture of upper cuticle of Glossopteris; **g,h,i)** are lower epidermis cuticles, and **h,i)** are thermally altered; **j)** is a thiny cuticle; **k,l)** are coal fragments. The **a, c, d, f, g, h, i** and **l**) obtained by fluorescent light; **b, e, j** and **k**) are obtained by transmitted light microscopy (white light).

Figure 9 - **a)** foliar tuft of *Glossopteris papillosa sp.*; **b** and **c)** epidermic tissue of lower laminar face; **d)** epidermic sculpturations in upper laminar face of *Glossopteris papillosa sp.*

Table 1 - Palynofacies analyses of the tonstein of Faxinal Mine - five samples with three levels each (top, middle and base). Lath.: elongate (lath shape); Eq.: equidimensional (equant shape); Corr.: Corroded; Listr.: striped; Estr.: striated; Band.: banded; Perf.: pitted; Cut.: Cuticle; N.Degr.: not degrated; Degr.: degrated; Memb.: membrane; Spor.: spors; Indet.: Indeterminate; Botry.: Botryococcus; AOM: amorph organic matter.

Fig. 1

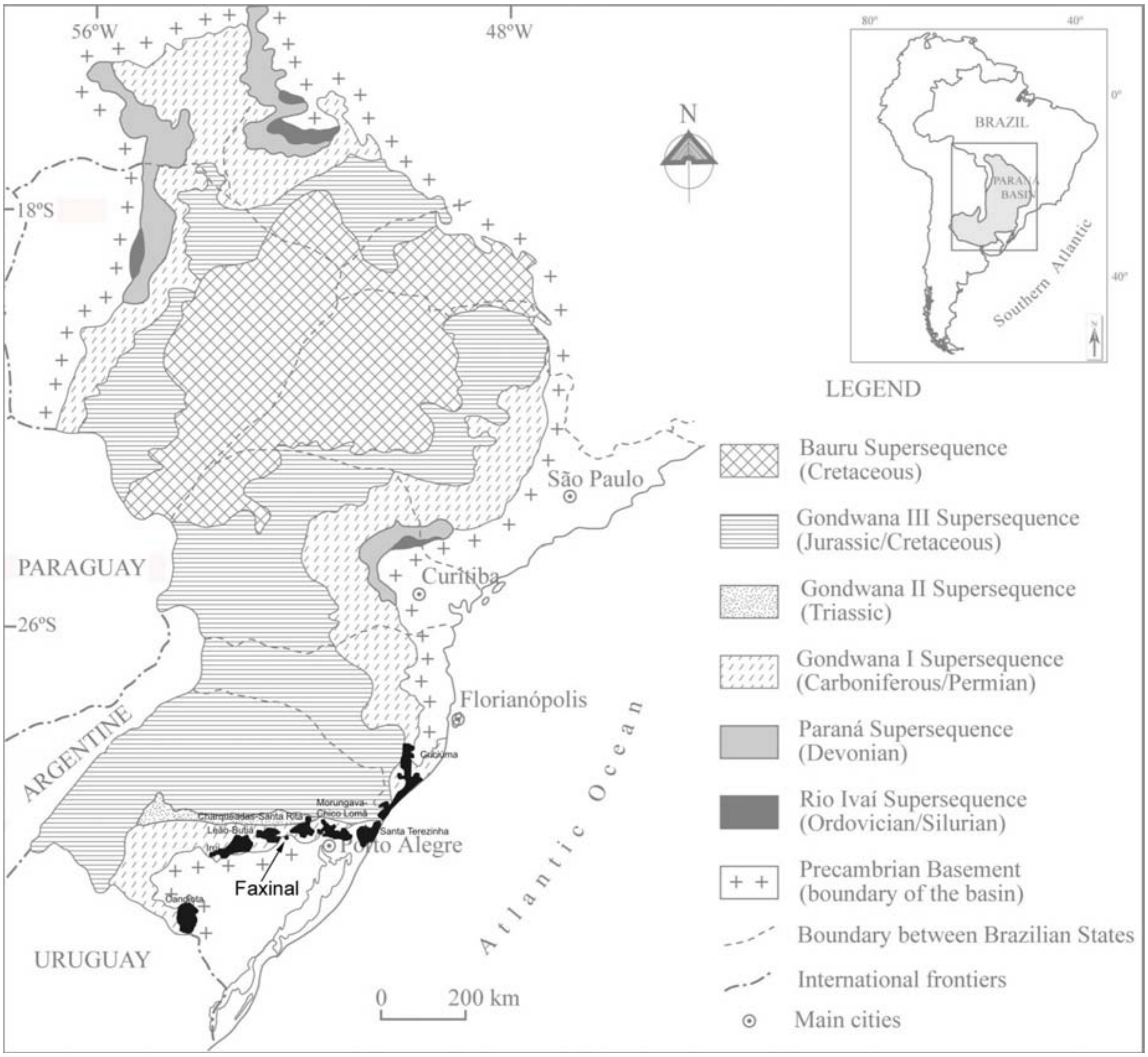

56ºW
48ºW
18ºS
26ºS
N
PARAGUAY
ARGENTINE
URUGUAY
São Paulo
Curitiba
Florianópolis
Porto Alegre
Faxinal
Morungava-
Chico Lomã
Santa Terezinha
Leão-Butiá
Irui
Atlantic Ocean
0
200 km
80º
40º
0º
BRAZIL
PARANÁ
BASIN
Southern Atlantic
LEGEND
Bauru Supersequence
(Cretaceous)
Gondwana III Supersequence
(Jurassic/Cretaceous)
Gondwana II Supersequence
(Triassic)
Gondwana I Supersequence
(Carboniferous/Permian)
Paraná Supersequence
(Devonian)
Rio Ivaí Supersequence
(Ordovician/Silurian)
Precambrian Basement
(boundary of the basin)
Boundary between Brazilian States
International frontiers
Main cities

Fig. 2

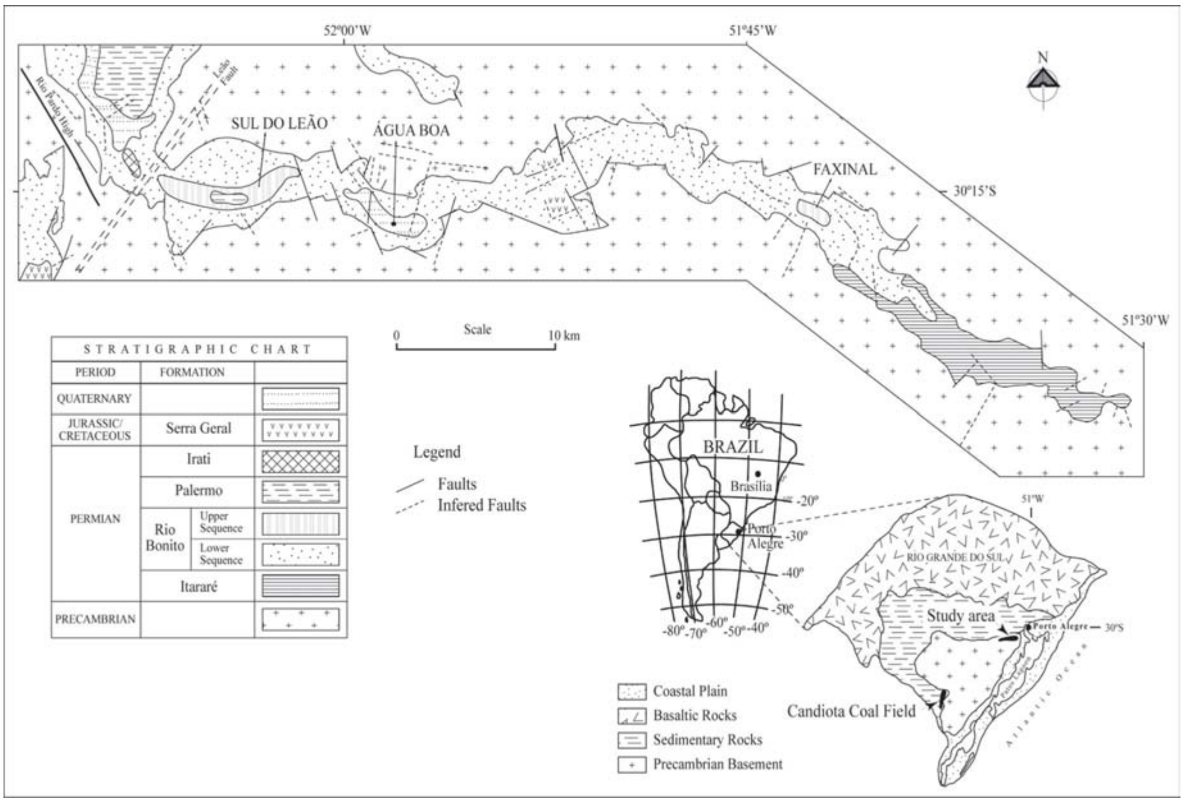
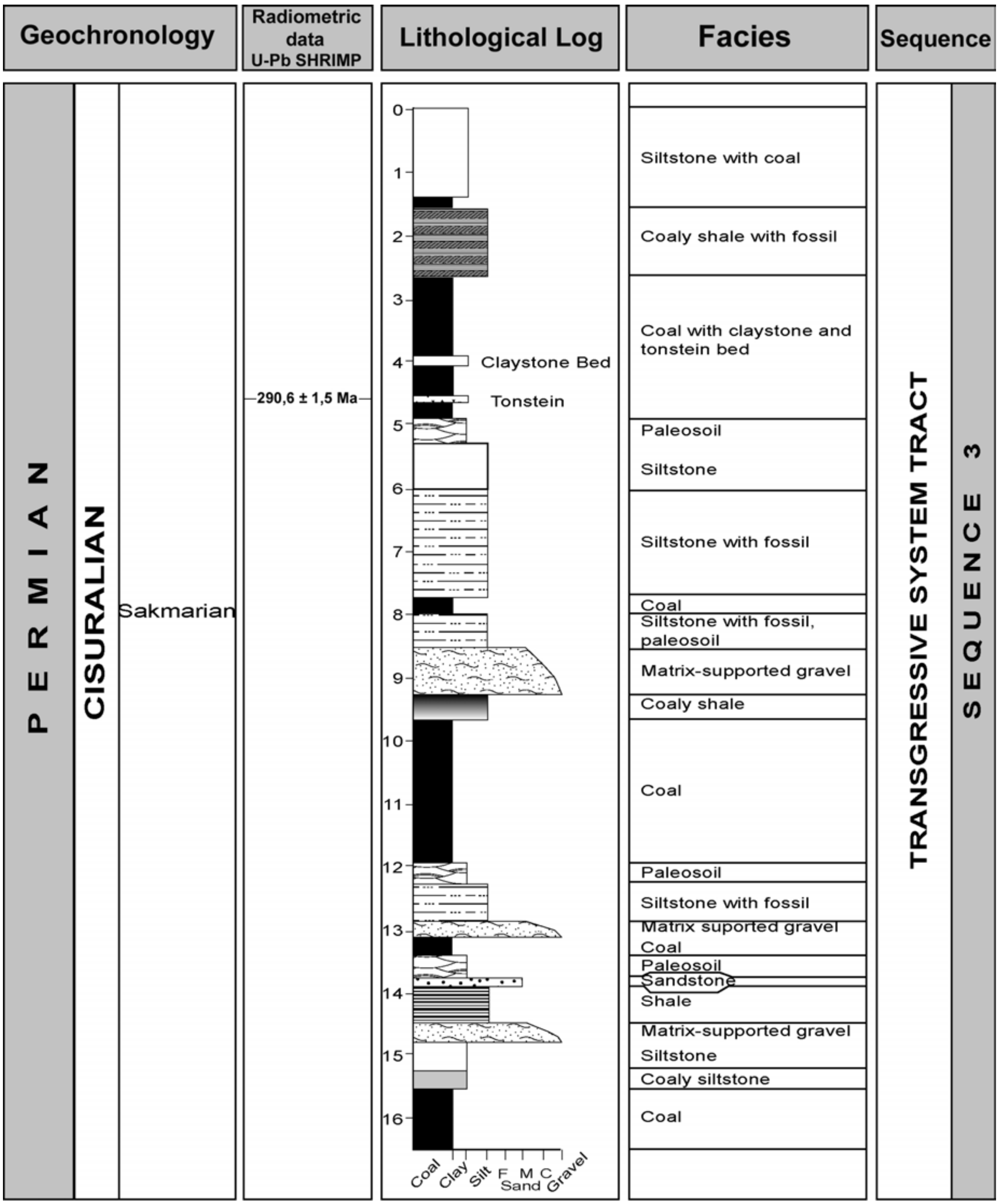

52°00'W
51°45'W
30°15'S
51°30'W
N
Rio Pardo High
Leão Fault
SUL DO LEÃO
ÁGUA BOA
FAXINAL
Scale
0
10 km
STRATIGRAPHIC CHART
PERIOD
FORMATION
QUATERNARY
JURASSIC/ CRETACEOUS
Serra Geral
PERMIAN
Irati
Palermo
Rio Bonito
Upper Sequence
Lower Sequence
Itararé
PRECAMBRIAN
Legend
Faults
Infered Faults
BRAZIL
Brasília
Porto Alegre
-20°
-30°
-40°
-50°
-80°
-70°
-60°
-50°
-40°
51°W
RIO GRANDE DO SUL
Study area
Porto Alegre
30°S
Candiota Coal Field
Atlantic Ocean
Coastal Plain
Basaltic Rocks
Sedimentary Rocks
Precambrian Basement

Fig. 3



Geochronology
Radiometric data U-Pb SHRIMP
Lithological Log
Facies
Sequence
PERMIAN
CISURALIAN
Sakmarian
290,6 ± 1,5 Ma
Claystone Bed
Tonstein
Siltstone with coal
Coaly shale with fossil
Coal with claystone and tonstein bed
Paleosoil
Siltstone
Siltstone with fossil
Coal
Siltstone with fossil, paleosoil
Matrix-supported gravel
Coaly shale
Coal
Paleosoil
Siltstone with fossil
Matrix suported gravel
Coal
Paleosoil
Sandstone
Shale
Matrix-supported gravel
Siltstone
Coaly siltstone
Coal
Coal
Clay
Silt
F
M
C
Sand
Gravel
TRANSGRESSIVE SYSTEM TRACT
SEQUENCE 3

Fig. 4

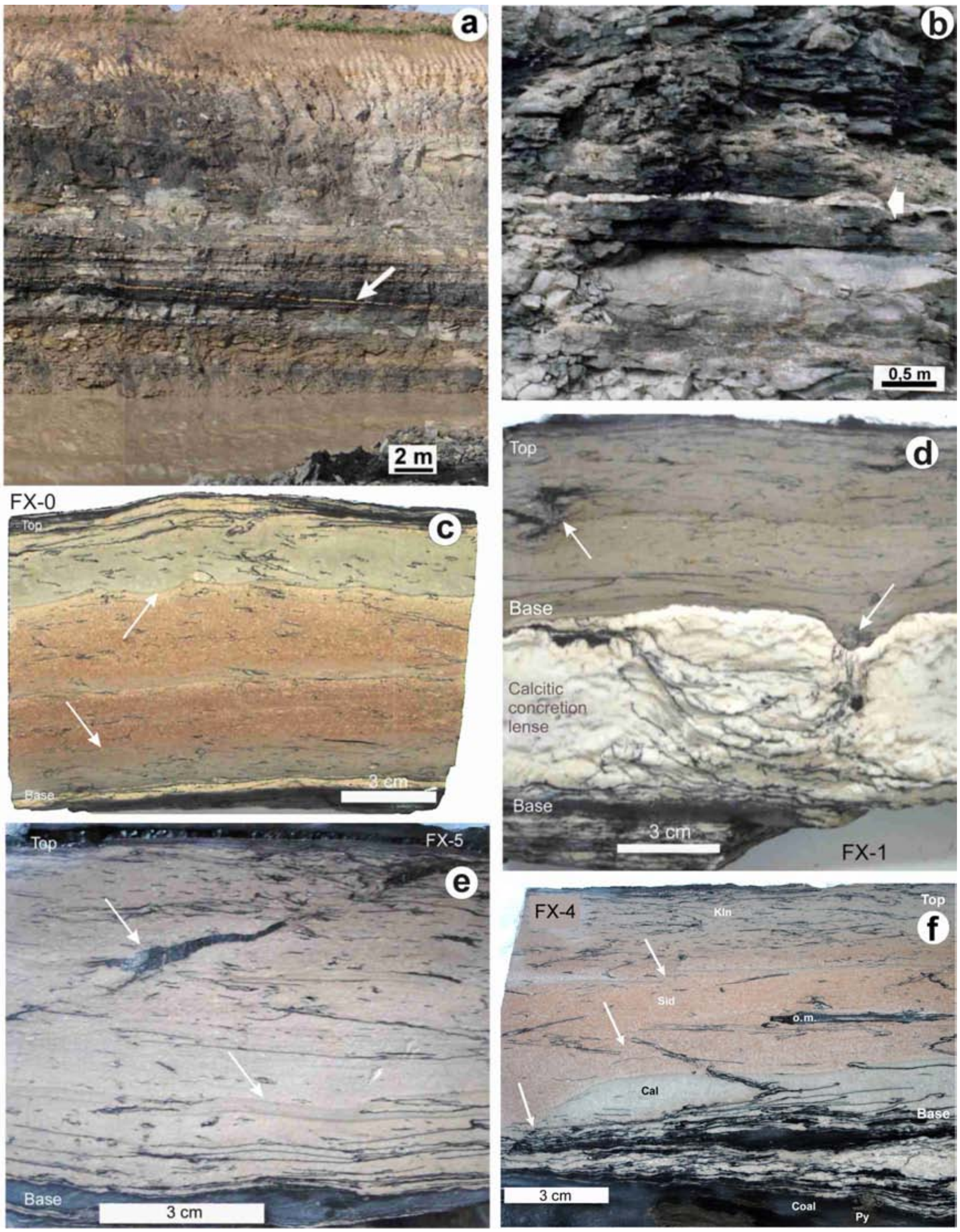

a
2 m
b
0,5 m
FX-0
Top
c
Base
3 cm
Top
d
Base
Calcitic
concretion
lense
Base
3 cm
FX-1
Top
FX-5
e
Base
3 cm
FX-4
Kln
Top
f
Sid
o.m.
Cal
Base
3 cm
Coal
Py

Fig. 5

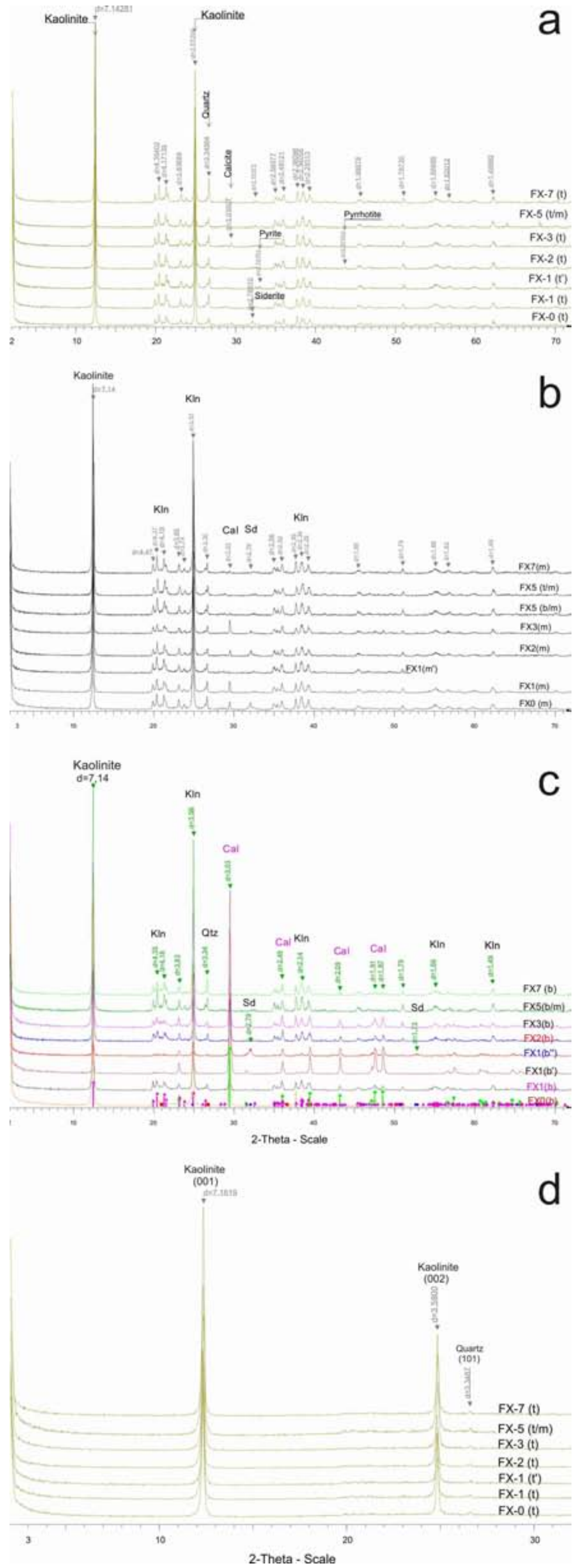

a
Kaolinite
Quartz
Calcite
Pyrrhotite
Pyrite
Siderite
FX-7 (t)
FX-5 (t/m)
FX-3 (t)
FX-2 (t)
FX-1 (t')
FX-1 (t)
FX-0 (t)
b
Kln
Cal
Sd
FX7(m)
FX5 (t/m)
FX5 (b/m)
FX3(m)
FX2(m)
FX1(m')
FX1(m)
FX0 (m)
c
Kaolinite
d=7.14
Qtz
FX7 (b)
FX5(b/m)
FX3(b)
FX2(b)
FX1(b'')
FX1(b')
FX1(b)
FX0(b)
2-Theta - Scale
d
Kaolinite
(001)
Kaolinite
(002)
Quartz
(101)
2-Theta - Scale

Fig.6

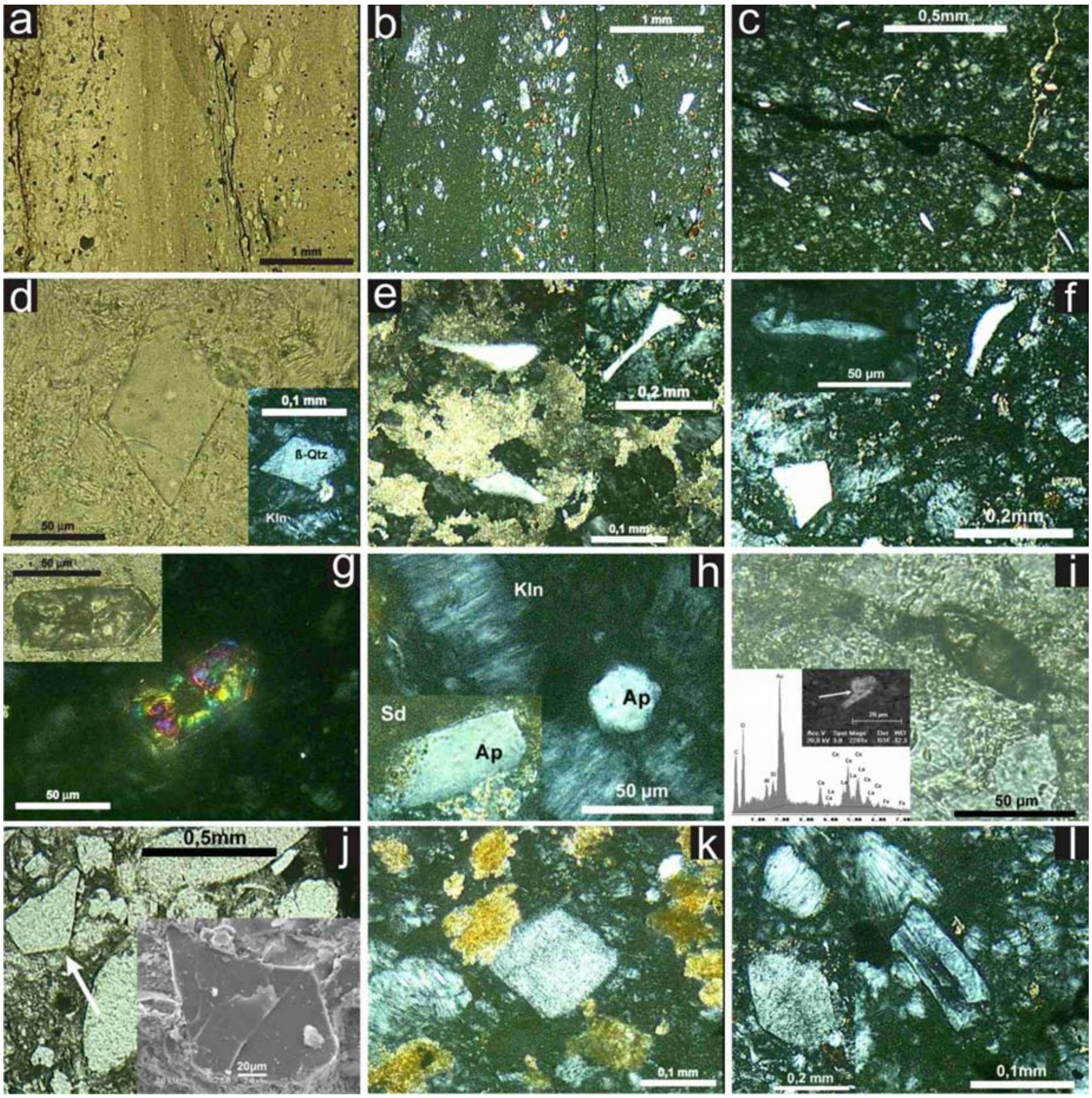

a
1 mm
b
1 mm
c
0,5mm
d
0,1 mm
ß-Qtz
Kln
50 µm
e
0,2 mm
0,1 mm
f
50 µm
0,2mm
g
50 µm
50 µm
h
Kln
Sd
Ap
Ap
50 µm
i
50 µm
j
0,5mm
20µm
k
0,1 mm
l
0,2 mm
0,1mm

Fig. 7

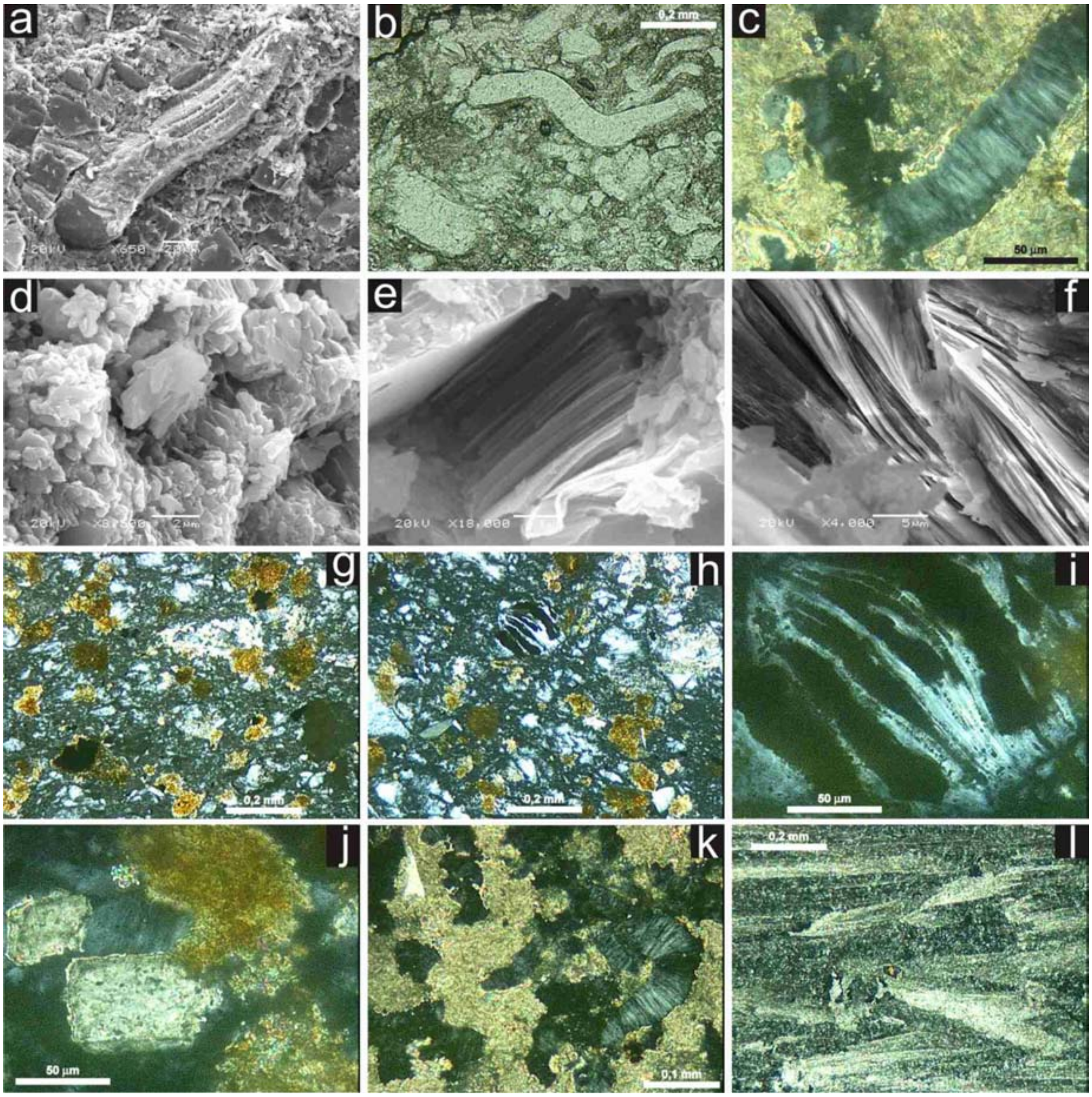

a
b
0,2 mm
c
50 µm
d
20kU
e
20kU X18,000
f
20kU X4,000 5µm
g
0,2 mm
h
0,2 mm
i
50 µm
j
50 µm
k
0,1 mm
l
0,2 mm

Fig. 8

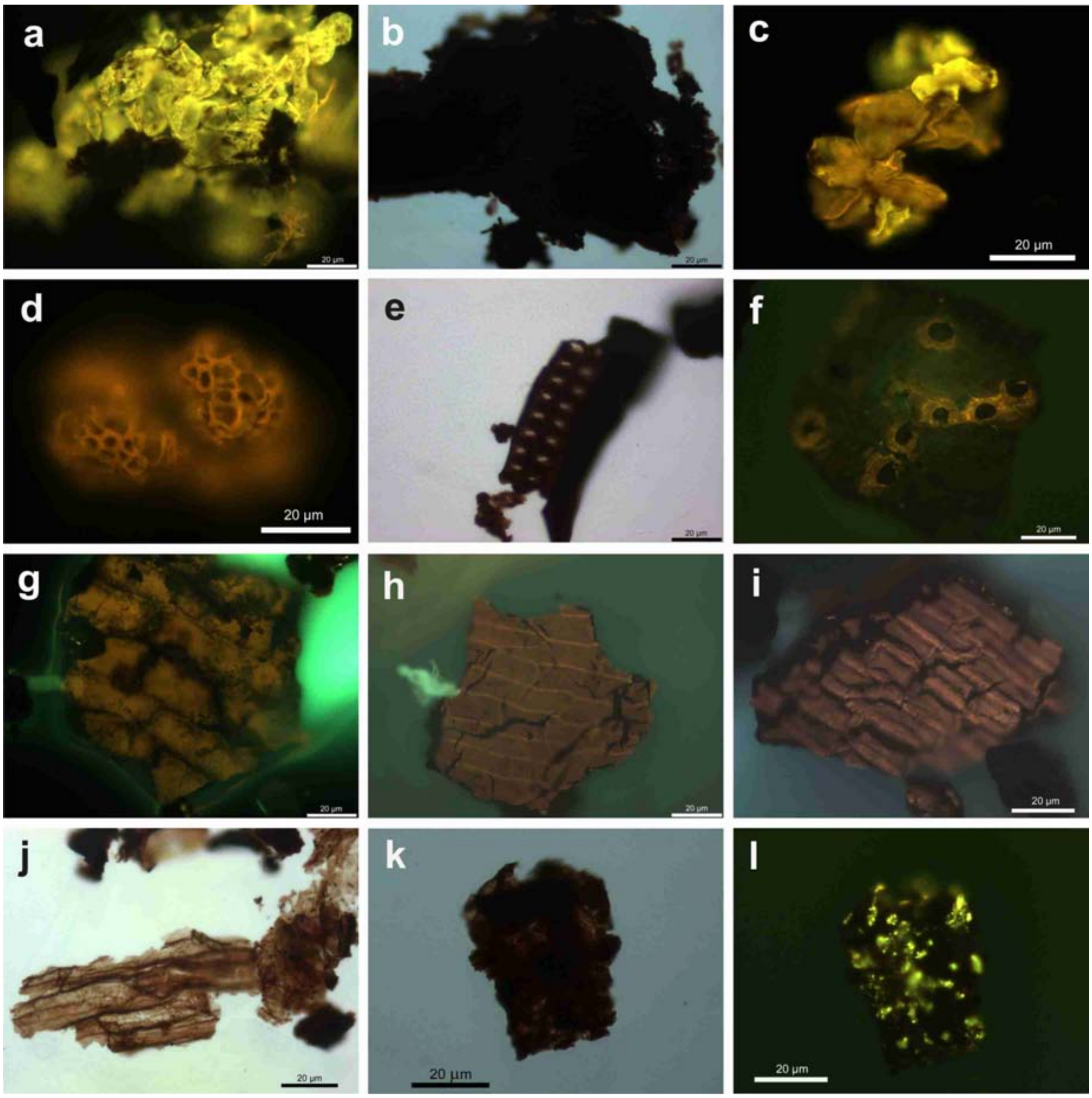


Fig. 9

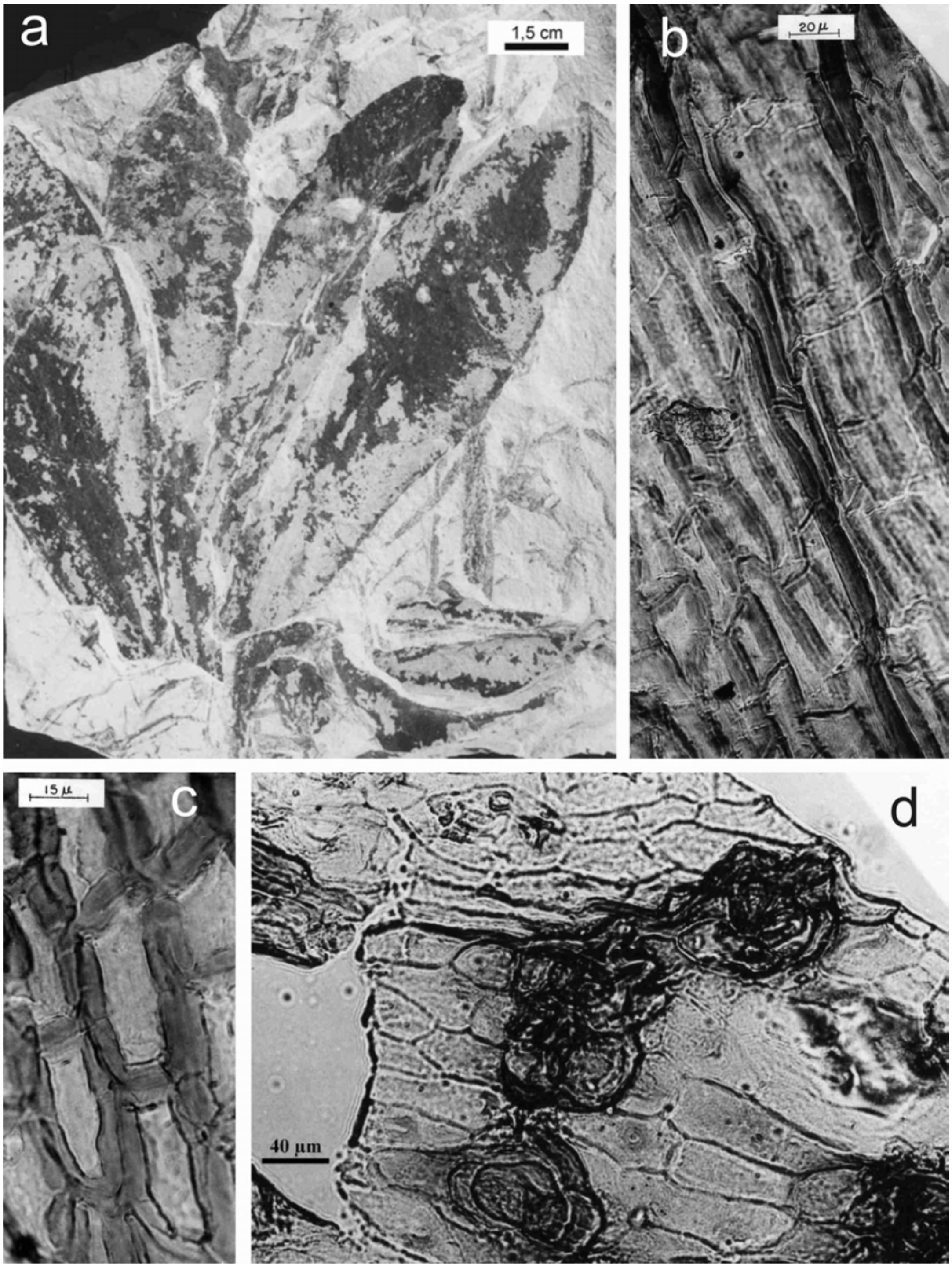


Table 1

		Phytoclast (%)												Palynomorph (%)						
		Opaque			Not Opaque									Spor.	Polen	Indet.	*Botry*			
					Biostructurate					Non-Biostructurate										
Sample	Level	Along.	Equid.	Corr.	Listr.	Estr.	Band.	Perf.	Cut.	N. Degr.	Degr.	Memb.	Coal					MOA (%)	Phytoclast (%)	Palynomorph (%)
FX-0	T	2,9	1,1	9,3	4,5	0,3	1,9	0,5	0,5	2,1	59,6	0	0,8	0,3	4	11,2	1,1	0	83,5	16,5
FX-1	O	4,3	9,2	2	0	0,3	8,6	0	0	28,3	41,4	0	0	1,3	4,3	0	0,3	0	94,1	5,9
FX-2	P	4,5	5,1	3,5	5,1	0,3	8,7	0	0	10,3	61,7	0	0	0	0,3	0,3	0	0	99,4	0,6
FX-3		1	1,2	1	0,7	0,5	2,2	0,2	4,8	6,9	79,4	0,2	0,2	0,2	0,2	0,2	1	0	98,3	1,7
FX-5		5,3	3	12,1	4,1	0,9	4,1	0	0,6	53,3	16	0	0	0	0	0,6	0	0	99,4	0,6
FX-0	MI	1,9	0,9	4,9	4,3	3,1	1,9	0	0	0,3	81,5	0	0,6	0	0,6	0	0	0	99,4	0,6
FX-1	D	0,3	0,6	0,9	0,3	0,3	2,7	0	0	2,4	90,3	0	0	0	2,4	0	0	0	97,6	2,4
FX-2	D	16,4	2,4	15,2	0,6	0	0	5,1	0	2,7	57	0	0	0	0,3	0,3	0	0	99,4	0,6
FX-3	L	2,6	2	6	3,4	0	2,3	0	0,3	12,6	65,5	0	0	0	2,3	2,9	0	0	94,8	5,2
FX-5	E	0,9	0,6	8,6	3,2	2,3	0,6	0	10	60,5	5,7	0	7,2	0	0,6	0	0	0	99,4	0,6
FX-0	B	3,6	1,2	4,5	2,7	0	3	0,3	2,4	2,1	66,9	0,3	0,3	0	2,1	10,5	0	0	87,3	12,7
FX-1	A	1,8	0	0,9	2,5	0,3	0,3	0	0,9	2,1	49,4	0	0	0	6,4	35,3	0	0	58,3	41,7
FX-2	S	10,3	2,3	22,5	0	0	6,1	5,8	0	11,9	32,8	0	0	0	2,6	5,8	0	0	91,6	8,4
FX-3	E	0,8	0,8	4,1	1,4	0,5	2,2	0	14,6	6	52,7	0	5,5	0	2,2	9,1	0	0	88,7	11,3
FX-5		1,7	0,3	13,7	2,3	0,3	1,5	0,3	0,6	53,9	0	0	2,6	0	4,1	18,7	0	0	77,3	22,7

3 ANEXOS

ANEXO A - Carta de aceitação do manuscrito submetido

De: International Journal of Coal Geology
Para: margaws@terra.com.br
margaws@yahoo.com.br
Data: 11/02/08 19:51
Assunto: Submission Confirmation

Texto:

Dear Margaws,

Your submission entitled "Mineralogy and Palynofacies analyses of the Tonstein of Faxinal Coalfield, an altered volcanic-ash layer from the Lower Permian of Paraná Basin, Brazil" has been received by International Journal of Coal Geology

You may check on the progress of your paper by logging on to the Elsevier Editorial System a an author. The URL is http://ees.elsevier.com/cogel/.

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Your manuscript will be given a reference number once an Editor has been assigned.

Thank you for submitting your work to this journal.

Kind regards,

Elsevier Editorial System
International Journal of Coal Geology

Anexos:

ANEXO B - Cópias de resumos e artigos publicados em coautoria

Resumo

"*A Roof Shale Flora da Mina do Faxinal (Sakmariano do Rio Grande do Sul): Uma nova concepção sobre o processo tafonômico*"

XX Congresso Brasileiro de Paleontologia

XX CONGRESSO BRASILEIRO DE PALEONTOLOGIA
A PALEONTOLOGIA CELEBRANDO A VIDA
www.xxcongressobrasileirodepaleontologia.com

A Roof Shale Flora da Mina do Faxinal (Sakmariano do Rio Grande do Sul): Uma nova concepção sobre o processo tafonômico.

A Roof Shale Flora of Faxinal Mine (Sakmarian of Rio Grande do Sul State): A new conception about the taphonomic process.

Margarete Wagner Simas[a], Margot Guerra-Sommer[b] & Miriam Cazzulo-Klepzig[b]
[a]Programa de Pós-Graduação em Geociências-UFRGS
[b]Instituto de Geociências-UFRGS

margaws@terra.com.br margot.sommer@ufrgs.br miriam.klepzig@ufrgs.br

Uma origem hipoautóctone associada à lenta sedimentação em ambiente límnico, tem sido proposta para a deposição de Roof Shale Flora intercalada a uma camada de carvão na Mina do Faxinal, RS (Sakmariano da Bacia do Paraná).

Essa paleoflora procedente de um nível de argilito, até então caracterizado como tonstein de origem detrítica, é composta majoritariamente por folhas de glossopterídeas identificadas como as espécies *Glossopteris brasiliensis* sp. n., *Glossopteris similis-intermittens* n. sp., *Glossopteris papillosa* n. sp., *Glossopteris rio-grandensis* sp. n.; estruturas reprodutivas correspondentes à *Plumsteadia sennes* Rigby e sementes, caracterizadas como *Platicardia* sp.; folhas de Cordaitanthales, relacionadas a uma só espécie, *Rufloria gondwanensis* sp. n.; fragmentos de frondes estéreis, caracterizadas como Pteridophylla (sensu Boureau & Doubinger, 1975) correspondentes exclusivamente a sphenopterídeas (S*phenopteris* cf. S. *ischanovensis*, S*phenopteris* sp.) ocorrem em baixíssima representatividade.

Estudos recentes comprovaram uma origem vulcânica para esse tonstein, modificando radicalmente a concepção sobre o processo tafonômico responsável pela preservação da paleoflora. Dessa forma, a excelente preservação da paleoflora, seu espectro composicional e a paleossucessão passam a ser explicadas por processo autóctone ocorrido em um estreito (diminuto) intervalo de tempo em ambiente relacionado a deposição de cinza vulcânica.

Artigo A

"Geochronological data from the Faxinal coal succession, southern Paraná Basin, Brazil: a preliminary approach combining radiometric U-Pb dating and palynostratigraphy."

Journal of South American Earth Sciences

Accepted Manuscript

Geochronological data from the Faxinal coal succession, southern Paraná Basin, Brazil: a preliminary approach combining radiometric U-Pb dating and palynostratigraphy

Margot Guerra-Sommer, Miriam Cazzulo-Klepzig, Rualdo Menegat, Milton Luiz Laquintinie Formoso, Miguel Ângelo Stipp Basei, Eduardo Guimarães Barboza, Margarete Wagner Simas

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Reference: SAMES 705

To appear in: *Journal of South American Earth Sciences*

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Geochronological data from the Faxinal coal succession, southern Paraná Basin, Brazil: a preliminary approach combining radiometric U-Pb dating and palynostratigraphy

Margot Guerra-Sommer[1]*, Miriam Cazzulo-Klepzig[1], Rualdo Menegat[1], Milton Luiz Laquintinie Formoso[1], Miguel Ângelo Stipp Basei[2], Eduardo Guimarães Barboza[1], and Margarete Wagner Simas[1]

[1]Instituto de Geociências, UFRGS, Av. Bento Gonçalves, 9500 -91501.970, Porto Alegre, RS, Brazil;
[2]Centro de Pesquisas Geocronológicas, USP, Rua da Reitoria, 109 - 05508-9000 Butantã, São Paulo, SP, Brazil
*Contact author.

E-mail address: margot.sommer@ufrgs.br (M. Guerra-Sommer)

Abstract

A radiometric zircon age of 285.4 ± 8.6 Ma (IDTIMS U-Pb) is reported from a tonstein layer interbedded with coal seams in the Faxinal coalfield, Rio Grande do Sul, Brazil. Calibration of palynostratigraphic data with the absolute age show that the coal depositional interval in the southern Paraná Basin is constrained to the Sakmarian. Consequently, the basal Gondwana sequence in the southern part of the basin should lie at the Carboniferous–Permian boundary, not within the Sakmarian as previously considered. The new results are significant for correlations between the Paraná Basin and the Argentinian Paganzo Basin (302 ± 6 Ma and 288 ± 7 Ma) and with the Karoo Basin, specifically with the top of the Dwyka Tillite (302 ± 3 Ma and 299.2 ± 3.2 Ma) and the lowermost Ecca Group (288 ± 3 Ma and 289.6 ± 3.8 Ma). The evidence signifies widespread latest Carboniferous volcanic activity in western Gondwana.

Keywords: U-Pb zircon dating, Coal succession, Paraná Basin, Palynostratigraphy, Sakmarian

1. Introduction

The Paraná Basin occupies some 1,700,000 km^2 in southeastern South America and comprises six depositional supersequences (cf. Milani, 2003) that resulted from second-order eustatic and tectonic events. These supersequences are, from base to top, (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), and (6) Bauru (Late Cretaceous) (Fig. 1).

The Gondwana I Supersequence is a second-order transgressive–regressive cycle consisting of a basal transgressive package and an overlying regressive package. The transgressive interval corresponds to lithostratigraphic units known as the Itararé Group and the Rio Bonito and Palermo formations. The regressive package comprises the Irati, Serra Alta, Teresina, Rio do Rasto, and Sanga do Cabral formations.

Palynology has been used to establish formal biostratigraphic zonations (Daemon and Quadros, 1970; Marques-Toigo, 1991; Souza and Marques-Toigo, 2003) that facilitate regional and interregional correlations. However, some correlation problems arise from the extension of the basin, the endemism of the Gondwana flora, and the poor resolution of facies correlations in contiguous areas of the same basin. These issues emphasize the need for reliable chronostratigraphic markers.

Evidence of volcanic activity is recorded in the coal succession within the Rio Bonito Formation of the southern Paraná Basin as tonsteins and discrete and continuous horizons of clay beds, coeval with the interbedded coal seams of the Faxinal, Sul do Leão, and Água Boa coalfields (Ribeiro et al., 1987) (Fig. 2).

Tonsteins are excellent time markers for stratigraphic and basin analysis, because they were evidently deposited during a limited time interval (Huddle and Englund, 1996). Combining biostratigraphic data from the coal seams with biostratigraphic and radiometric data from the tonsteins provides a useful tool for stratigraphic correlation and dating.

The purposes of this article are to (1) document the petrographic components of the clay bed interbedded with the upper coal seam of the Faxinal, confirming its identity as a tonstein; (2) obtain a radiometric age determination through conventional U-Pb analysis of zircons isolated from that rock; (3) calibrate the palynostratigraphic zonation through radiometric dating, thus offering additional criteria for the construction of a geochronologic depositional model for the coal succession in the southern Paraná Basin, and (4) propose a preliminary correlation with the International Stratigraphic Chart of the International Commission on Stratigraphy [ICS], (2004).

2. Geologic and stratigraphic setting

Tectonic and eustatic events in the southern Paraná Basin of southern Brazil induced several third-order sea level cycles during the long duration embodied by the Gondwana I Supersequence. This supersequence comprises four third-order sequences termed, from base to top, S1, S2, S3, and S4 (Holz, 1998; Holz et al., 2000). The studied interval focuses on the Rio Bonito Formation that includes the coal-bearing strata and comprises sequence S2 and the lower part of S3. The S2 sequence corresponds to a Lowstand System Tract (LST), at its base, followed by a Transgressive System Tract (TST) and, at the top, to a Highstand System Tract (HST). The lower part of S3 represents again a Lowstand System Tract. The top interval of S3 belongs to the Palermo Formation and represents a Transgressive and a Highstand System Tract

The Lowstand System Tract of S2 is composed of two parasequences (Holz et al., 2000) that contain prograding fluvio-deltaic beds and a few coal beds. The LST is overlain by a Transgressive System Tract (TST) of four parasequences (swamp associated to barrier/lagoon). The coal beds in the three basal parasequences are thick and continuous while in the uppermost parasequence they are thin and discontinuous. The Highstand System Tract (HST) comprises a single parasequence of marine facies (Fig.8 a).

The Faxinal coalfield, mined by the Companhia de Pesquisas e Lavras Minerais (UTM-N6651.5/E432.7) (COPELMI), is located near the town of Arroio dos Ratos, about 120 km southwest of Porto Alegre and close to Água Boa and Sul do Leão coalfields (Fig. 2). These coalfields are situated in a graben, referred to previously as the Leão/Mariana Pimentel paleovalley (Ribeiro et al, 1987). It is an elongate structure trending SE-NW in its eastern portion and E-W to the west. The graben, inserted in the basement, is 60 km long and up to 5 km wide. The three coalfields are downthrown structural blocks, mainly controlled by a N40°E fault system, and their extent is limited by subsequent erosion. The Faxinal coalfield (producing 18×10^6 ton coal/tons of rock by open cut) is situated in the eastern part of the graben.

The Faxinal succession includes five coal seams, named, from base to top: I, IM, M, MS, and S. The seams are interbedded with siltstones, mudstones, sandstones, and paleosols (Fig. 8b). The present study focuses on a light gray clay bed, approximately 7 cm thick that is massive and fossiliferous and interbedded with the upper coal seam (S). The bed is exposed along the cutbanks of the open pit and displays mostly sharp lower and upper boundaries.

3. Paleobotanical and palynological data

The rich compression taphoflora hosted by the Faxinal tonstein is predominantly gymnospermous (Guerra-Sommer, 1992). Fragments of glossopterids (leaves, branches, and reproductive organs) constitute 70% of the entire association; taxa identified include *Glossopteris brasiliensis*, *G. papillosa*, *G. similis-intermittens*, *Plumsteadia sennes*, and *Platycardia* sp. Cordaitean leaves (*Rufloria gondwanensis*) are subordinate; very delicate filicoid fronds (*Sphenopteris* cf. *ischanovensis*), often cross-cutting the lamination, represent understory herbaceous forms. The integration of paleobotanical and coal petrographic studies of the tonstein indicate a forest swamp flora. An Artinskian–Kungurian age was inferred mainly from the evolutionary characteristics of the glossopterid foliar morphology represented mainly by the *Glossopteris*-type of venation (Fig. 3).

Ash fall should have played an important role in the plant preservation. Spicer (1991), studying the effects of ash fall from recent volcanism, pointed out that delicate groundcover plants tend to be buried rapidly and are thus readily preservable. Moreover, large amounts of canopy leaves may be incorporated in ash-fall deposits because they are particularly sensitive to ash coating, which predisposes them to abscission.

Palynological studies of the Faxinal coalfield (Guerra-Sommer et al, 1984; Dias and Guerra-Sommer, 1994; Cazzulo-Klepzig, 2001) have shown some differences in relation to other Brazilian Gondwana coals, such as quantitative dominance of gymnosperm pollen grains over pteridophytic spores.

The basal portion of the coal seam (S), subjacent to the tonstein, carries a palynoflora dominated by well-preserved fragments of gymnosperm cuticles and woody material. Monosaccate pollen grains, produced by gymnosperm vegetation (including Cordaitophyta), comprise *Cannanoropollis diffusus* (Tiwari) Dias-Fabrício 1981, *Plicatipollenites malabarensis* (Potonié and Sah) Foster 1975, and *P. gondwanensis* (Balme and Hennelly) Lele 1964. Glossopteridophyta is represented by such bisaccate pollen grains as *Limitisporites rectus* Leschik 1956, *L. delasauccei* (Potonié and Klaus) Schaarschmidt 1963, *Scheuringipollenites medius* (Burjack) Dias-Fabrício 1981, and *Vesicaspora wilsonii* Schemel emend. Wilson and Venkatachala 1963. This palynoflora thus reflects the important contribution of gymnosperms to the peat-forming plant community. However, spores produced by lycopsids and ferns are unrepresented. The presence of algae-like elements such as *Maculatasporites minimus, M. gondwanenssi,* and *Portalites gondwanensis* Nauhys, Alpern & Ybert 1969 was confirmed by the present study. Similar palyno-assemblages were identified in the tonstein, with abundant well-preserved cuticles showing affinity with Glossopteridophyta and Cordaitophyta. Spores are poorly preserved and undetermined.

Palynofloras at the top of the coal seam (S), overlying the tonstein, are different. They are strongly dominated by pteridophytic spores derived mainly from lycopsids and ferns (*Lundbladispora braziliensis* (Pant & Srivastava) Marques-Toigo & Picarelli 1984*, Punctatisporites gretensis* forma *minor* Hart 1965 and *Kraeuselisporites apiculatu s*Jansonius 1962), associated with presumed algal cysts such as *Maculatasporites gondwanensi Tiwari 1964, M. minimus* Segroves 1967 and *Portalites gondwanensis* Nahuys,Alpern & Ybert 1969.

The composition similarity between palynofloras in the basal portion of the upper coal seam and those in the tonstein indicates that the paleoecological conditions in which coal formed persisted during tonstein accumulation. These data support the hypothesis of rapid deposition, probably spanning days or weeks, as in recent ash falls (Huddle and Englund, 1996). Accordingly, the change in palynofloras of the coal beds that overlie the tonstein horizon in Faxinal's upper coal seam may be attributed to the chemical effects of ash-fall deposition.

In a regional context, the Faxinal palynoflora has been assigned to Interval J of Daemon and Quadros (1970) or the uppermost portion of the *Caheniasaccites ovatus*/base of the *Hamiapollenittes karooensis* subzones of Marques-Toigo *(1991).* This assignment is based mainly on the presence of *Maculatasporites minimus* Segroves 1967 and *M. gondwanensi* Tiwari 1964s according to Dias and Guerra-Sommer, 1994.

In the present study, the Faxinal coal-bearing strata are assigned to the *Hamiapollenittes karooensis* subzone, in accordance with the framework proposed by Souza and Marques Toigo (2003) for the Paraná Basin.

4. Petrography of tonsteins

The tonstein beds of the Faxinal coalfield are light gray, very fine-grained rocks with thin, black lenses of coal or organic matter (Fig. 8b). They are composed of authigenic and probably pyroclastic, ash-derived minerals.

In the authigenic minerals, the bulk of the matrix consists of very fine (1–10 µm) or prismatic kaolinite, the latter packed in "booklets" (approximately 100 µm). The prismatic kaolinite is probably the alteration (authigenetic) product of preexisting feldspars (Fig. 4a, b, d). Kaolinite constitutes nearly 85–90% of the rock, which verifies an ash-fall derivation.

Siderite and calcite comprise 8–12% of the rock. Siderite is yellowish brown in thin section, forming irregular, 100–150 μm aggregates, as well as individual crystals (<5 μm) (Fig. 4d, e). Calcite also forms irregular aggregates up to 100 μm (Fig. 4c).

Organic matter is brown to yellow in thin section. It constitutes 2–4% of the rock, occurring as small fragments and lenses or as fracture infillings (Fig. 4a, b).

Some sulfide grains were identified by SEM. Pyrite is the most common sulfide, 1–50 μm in grain size. It displays euhedral to anhedral cubic habit or skeletal texture, especially within siderite masses (Fig. 4d, e). Galena also occurs as cubic, subhedral crystals about 2 μm in size (Fig. 4f).

Of the pyroclastic minerals, zircon occurs as prismatic, euhedral to subhedral crystals (50 μm by 20–30 μm). Most crystals display pinacoidal or bipyramidal terminations and straight walls, though a few may show corrosion features (Fig. 5a, b). A second zircon population consists of equidimensional, rounded, clearly detrital grains with a size range of 30 to <10 μm.

Apatite forms euhedral to subhedral, hexagonal to subhexagonal (rarely prismatic) crystals. Grain sizes are 5–90 μm, mostly around 50 μm. Some crystals display corroded rims (Fig. 5c, d).

Quartz is anhedral to subhedral, commonly fragmented or splintery, but in many grains, the bipyramidal habit is still recognizable. Grain size varies between 3 and 55 μm, and the bipyramidal crystals display an average grain size of 20–30 μm (Fig. 5e). Zircon and apatite represent less than 0.3%. Added to quartz, they make up approximately 2% of the rock.

Feldspar pseudomorphs and relics are also present. Kaolinite-replaced feldspar pseudomorphs show subhedral, prismatic, and sometimes rhombohedral shapes, with Baveno-like gemination (Fig. 5f). Prismatic shapes average 100 μm, whereas rhombs vary between 100 and 360 μm. Relics of K-feldspar are 50 μm in diameter; their irregular shapes indicate intense corrosion along cleavage planes (Fig. 5f). Some of these features suggest the presence of sanidine among the feldspars from the original volcanic rock. The presence of quartz with pyroclastic characteristics suggests that the tonsteins derived from an acidic volcanic tuff.

5. Radiometric dating

Radiometric analyses were conducted at the Geochronological Research Center (CPGeo-Igc) of the University of São Paulo (USP). Zircon dating was achieved with conventional Isotope Dilution

Thermal Ionization Mass Spectrometry (IDTIMS) and plotting on the Tera-Wassenburg diagram (Ludwig, 1993, 2001) (Fig. 7). The methodology is detailed in Basei et al. (1995).

Zircon crystals were split into four fractions for radiometric dating. The M(-3)1 fraction was not considered for age computation because of the probable recent loss of Pb, which would explain the younger radiometric age in relation to the other three fractions.

Two different populations were analyzed. Zircon population type 1 (M(-3) fraction) are prismatic, with well-defined bipyramidal terminations. They are highly crystalline, transparent, colorless, commonly with inclusions and micro-fractures. Pyramidal faces are well developed and not abraded. The length-to-width ratio is 2:1 (Fig. 6a).

Zircon population type 2 (M(-4) fraction) are prismatic with well-defined bipyramidal terminations. They are highly crystalline, transparent, and colorless, sometimes with inclusions and micro-fractures. Pyramidal faces are not well developed. The length-to-width ratio is 5:1 (Fig. 6b).

Despite morphological differences observed in zircon populations 1 and 2, they are considered to be coeval. Zircon crystallization is interpreted as having occurred at 285.4 ± 8.6 Ma. This age represents the average of U^{238}/Pb^{206} ages of the five fractions analyzed (Table 1). The typology of zircon crystals supports an origin from ash falls produced by explosive volcanic activity.

6. Stratigraphic implications of the zircon dating

The zircon age of 285.4 ± 8.6 Ma, obtained from the tonstein layer in the Faxinal coalfield, is clearly significant for the integration of absolute time and stratigraphy. As summarized in Fig. 8a, the isotopic dating facilitates geochronological calibration of the coal succession in the southern Paraná Basin.

Correlation with the International Stratigraphic Chart (Gradstein and Ogg, 2004) enhances constraints on the age of the coal-bearing strata. It is assumed that the Faxinal coal seams were deposited during the Sakmarian (285.4 ± 8.6 Ma), which predates the Artinskian–Kungurian age proposed for the coal deposits (Milani, 2003). The present study reveals that, according to the stratigraphic framework of the coal succession in the basin, based on high-resolution sequence stratigraphy (Holz, 1998; Holz et al., 2000; Holz and Kalkreuth, 2004), the Faxinal coal seams occur within the TST of the S3 third-order Sequence 2 (Fig. 8a).

Palynostratigraphic data assign the main Faxinal coal succession to the *Hamiapollenites karooensis* subzone, now dated as Sakmarian. Considering that coal-forming floras in the southern Paraná Basin are significantly different (Cazzulo-Klepzig, 2001), the particular paleoecological character of the coal-forming flora at Faxinal, dominated by gymnosperms, may represent not only local paleoenvironmental conditions but also a stratigraphic signature.

In the western Gondwana realm, similar radiometric ages obtained from ash-fall rocks in Argentina and South Africa provide additional significance to the new data reported herein.

The *Fusacolpites fusus-Vittatina subsaccata* Interval Zone was defined by Césari and Gutiérrez (2001) in the Bajo de Veliz Formation (Paganzo Basin, Argentina). Geochronologic data from basaltic intrusions intercalated with the lower part of the La Colina Formation (equivalent to the Bajo de Veliz Formation) yield ages of 302 ± 6 Ma and 288 ± 7 Ma (Thompson and Mitchell, 1972) for the palynofloras. This zone is distinct from the overlying *Lueckisporites virkkiae/Weylandites lucifer* Assemblage Zone, which was correlated by Souza and Marques-Toigo (2003) with the *Lueckisporites virkkiae* Interval Zone of the Paraná Basin. The latter zone is typical of the Palermo and Irati formations, succeeding the coal-bearing Rio Bonito Formation. Santos et al. (2006) obtained SHRIMP zircon age data from bentonitic ash-fall layers intercalated with the Irati sedimentary rocks, assigned to the *Lueckisporites virkkiae* zone, and reveal an age of approximately 278.4 ± 2.2 Ma. This new dating confirms the biostratigraphic data from Souza and Marques-Toigo (2005).

In the Karoo Basin, South Africa, Bangert et al. (1999) report U-Pb ages of 288.1 ± 3 Ma in tuff beds of the lowermost Prince Albert Formation (Ecca Group), just above the Dwyka boundary in the southernmost part of the main Karoo Basin (Sakmarian; cf. Gradstein and Ogg, 2004). These tuff beds are interbedded with shales genetically related to the upper part of the deep-water deglaciation sequence IV (Visser, 1997). Bangert et al. (1999) do not calibrate biostratigraphic zonal schemes with radiometric data, which hinders stratigraphic correlations between the Paraná and Karoo basins.

Because glacial deposits in the Paraná Basin differ lithostratigraphically from those in the Karoo Basin, radiometric data could be important for establishing the timing of depositional processes during glacial and the subsequent coal-generating systems in different basins of western Gondwana.

The source of the ash falls in the Karoo Basin, as well as in Argentina and southern Brazil, has been envisaged as located in Patagonia and West Antarctica, forming an extensive volcanic arc situated to the south and west in the pre-breakup Gondwana configuration (López Gamundi, 1994, Limarino et al., 1996, Stollhofen et al., 2000).

Although determination of the ash source was not the goal of this study, petrographic evidence indicates that the volcanic ash of the Faxinal Coalfield was generated nearby.

7. Conclusions

The integrated studies in the Faxinal Coalfield of southern Paraná Basin (Brazil) yield the following conclusions:

- Petrographic study of the clay layer interbedded with the upper coal seam (S) reveals a volcanic ash-fall origin for this sediment, thus identifying it as a tonstein.
- The Faxinal coal occurs within the TST of the S3 third-order Sequence 3 in the sequence stratigraphy framework proposed for the coal succession in the southern Paraná Basin.
- The coal-bearing strata are assigned to the *Hamiapollenites karooensis* subzone according to the palynostratigraphic framework for the southern Paraná Basin.
- The radiometric age of 285.4 ± 8.6 Ma, obtained through U-Pb zircon dating of the tonstein and the calibration of biostratigraphic data, preliminarily places the regional stratigraphy of Brazilian Gondwana sequences in an international context. The southern Brazilian coal succession is dated as the base of the Sakmarian (i.e., older than the Artinskian–Kungurian assignment proposed previously).
- An indirect conclusion is that the oldest rocks of the basal Gondwana sequence in the southern Paraná Basin, presently considered Sakmarian, are constrained to the Carboniferous–Permian boundary.
- Correspondence between radiometric data from the Faxinal tonstein and those from the lowermost Ecca Group (288.1 ± 3 Ma and 289.6 ± 3.8 Ma) in the Karoo Basin implies widespread, end-Carboniferous volcanism in Western Gondwana.

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Figure captions

Fig. 1. Simplified geological map of the Paraná Basin in Brazil with major tectonic elements and geographic references (after Milani, 1997).

Fig. 2. Location map of the Faxinal coalfield.

Fig. 3. *Glossopteris* from the tonstein: (a, d) details of the venation pattern; (b) epidermal pattern; (c) foliar tuft.

Fig. 4. Petrography of the Faxinal tonstein, showing authigenic minerals. (a, b) Large kaolinite "booklets," lenses of siderite, and organic matter within fine kaolinite crystals; (c) large calcite aggregate with siderite and kaolinite; (d, e) thin section and SEM images, respectively, of pyrite within siderite aggregates, surrounded by kaolinite; (f) small galena crystals under SEM. Legend: kaolinite, kaol; organic matter, o.m.; calcite, ca; siderite, si; pyrite, py; galena, ga.

Fig. 5. Photomicrographs and SEM images, including features of possible volcanic minerals from the Faxinal tonstein. (a, b) Euhedral zircon, with straight walls and one corroded end, within kaolinite matrix; (c, d) euhedral and subhedral apatite, hexagonal to subhexagonal, within kaolinite matrix; (e) quartz splinters and fragmented, corroded bipyramidal crystals; (f) K-feldspar relic displaying corrosion features along cleavage plane (upper left); feldspar pseudomorph replaced by kaolinite (center); arrow points at feature resembling Baveno twinning. Legend: zircon, zir; apatite, ap; quartz, qz; K-feldspar, Kfelds; kaolinite, kaol; siderite, si.

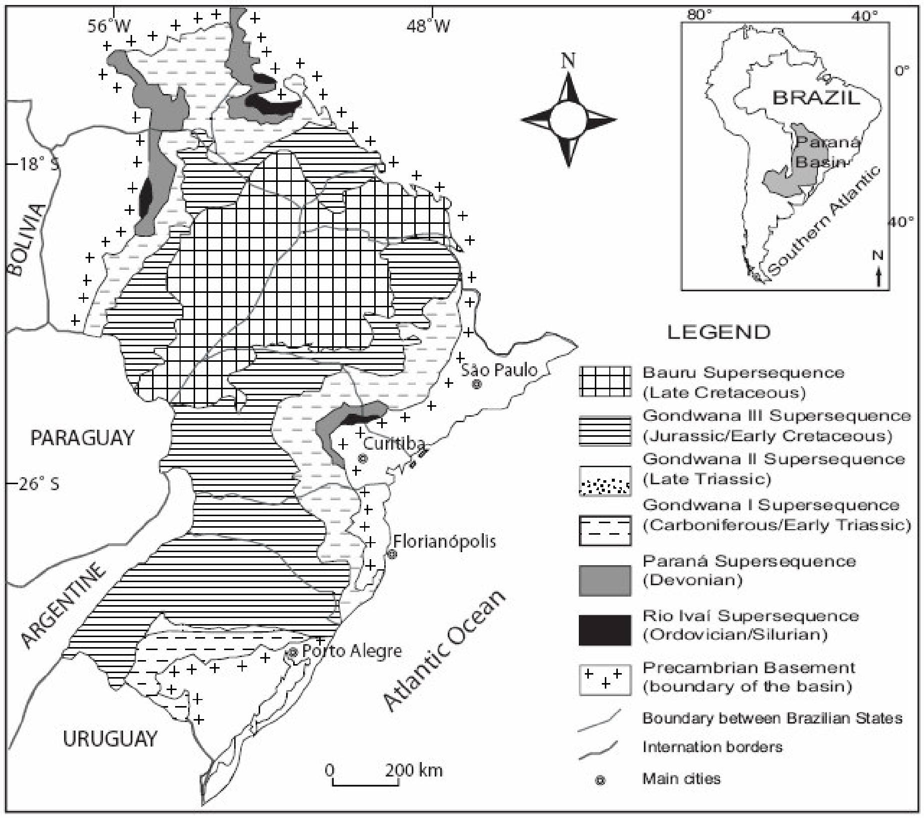
Fig. 6. (a) Sample MS-1, population type 1 magnetic fraction M (-3); (b) Sample MS-1 population type 2, magnetic fraction M(-4).

Fig. 7. Tera-Wasserburg diagram for zircon crystals from the Faxinal tonstein.

Fig. 8. (a) Geochronology, lithostratigraphy, biostratigraphy, sequence stratigraphy, and radiometric data of Carboniferous-Permian succession of the southern Paraná Basin. Biostratigraphy *sensu* Souza and Marques-Toigo (2003); sequence stratigraphy *sensu* Milani (2003); third-order sequence *sensu* Holz et al. (2000). The position of the lithological log of Faxinal coalfield is identified by the rectangle in the right-hand column. The black star indicates the radiometric data from the present study (285.4 ± 8.6 Ma); the white star indicates the radiometric data (278.4 ± 2.2 Ma) from Santos et al (2006). (b) Lithological log, facies, parasequence, geochronology and radiometric data of the Faxinal Coalfield.

Table 1. Statistical data from zircons of the tonstein in the upper coal seam of the Faxinal coalfield. ZIRCON TYPOLOGY–SHAPE: P(x/y)–prismatic crystal (length/width); Dt–prismatic crystal with double termination well developed; Py–prismatic crystal with pyramidal faces well developed; COLOR/TRANSPARENCY: T, transparency crystal; C, colorless crystal; INTERNAL PATTERNS: I, crystal with common inclusions; F, crystal with common fractures.

Fig.1


56°W
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80°
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0°
BRAZIL
Paraná Basin
Southern Atlantic
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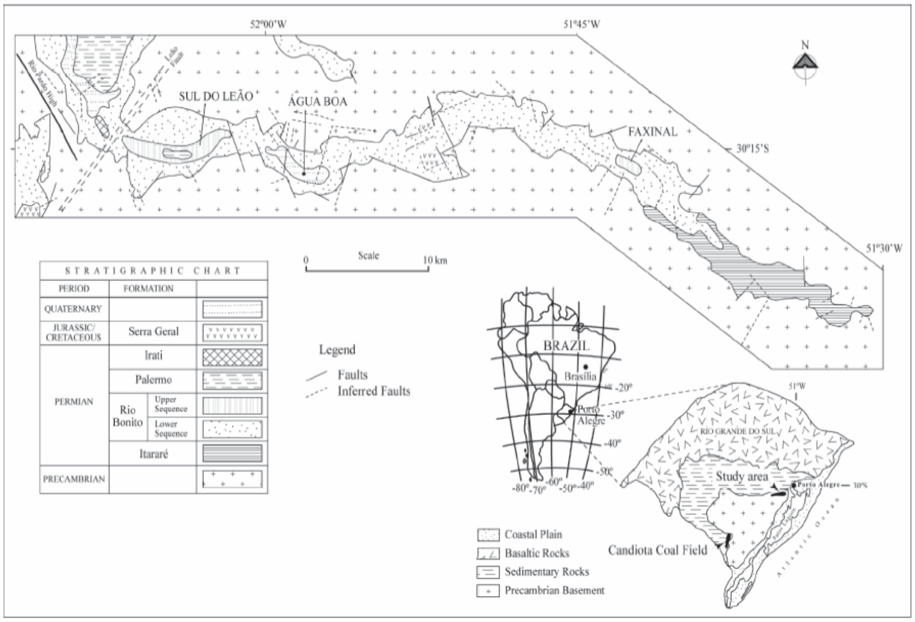
PARAGUAY
26° S
ARGENTINE
URUGUAY
São Paulo
Curitiba
Florianópolis
Porto Alegre
Atlantic Ocean
0 200 km
LEGEND
Bauru Supersequence (Late Cretaceous)
Gondwana III Supersequence (Jurassic/Early Cretaceous)
Gondwana II Supersequence (Late Triassic)
Gondwana I Supersequence (Carboniferous/Early Triassic)
Paraná Supersequence (Devonian)
Rio Ivaí Supersequence (Ordovician/Silurian)
Precambrian Basement (boundary of the basin)
Boundary between Brazilian States
Internation borders
Main cities

Fig.2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PERIOD
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QUATERNARY
JURASSIC/ CRETACEOUS
Serra Geral
Irati
Palermo
PERMIAN
Rio Bonito
Upper Sequence
Lower Sequence
Itararé
PRECAMBRIAN
Legend
Faults
Inferred Faults
BRAZIL
Brasília
Porto Alegre
-20º
-30º
-40º
-50º
-80º -70º -60º -50º -40º
RIO GRANDE DO SUL
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Candiota Coal Field
Coastal Plain
Basaltic Rocks
Sedimentary Rocks
Precambrian Basement

Fig.3

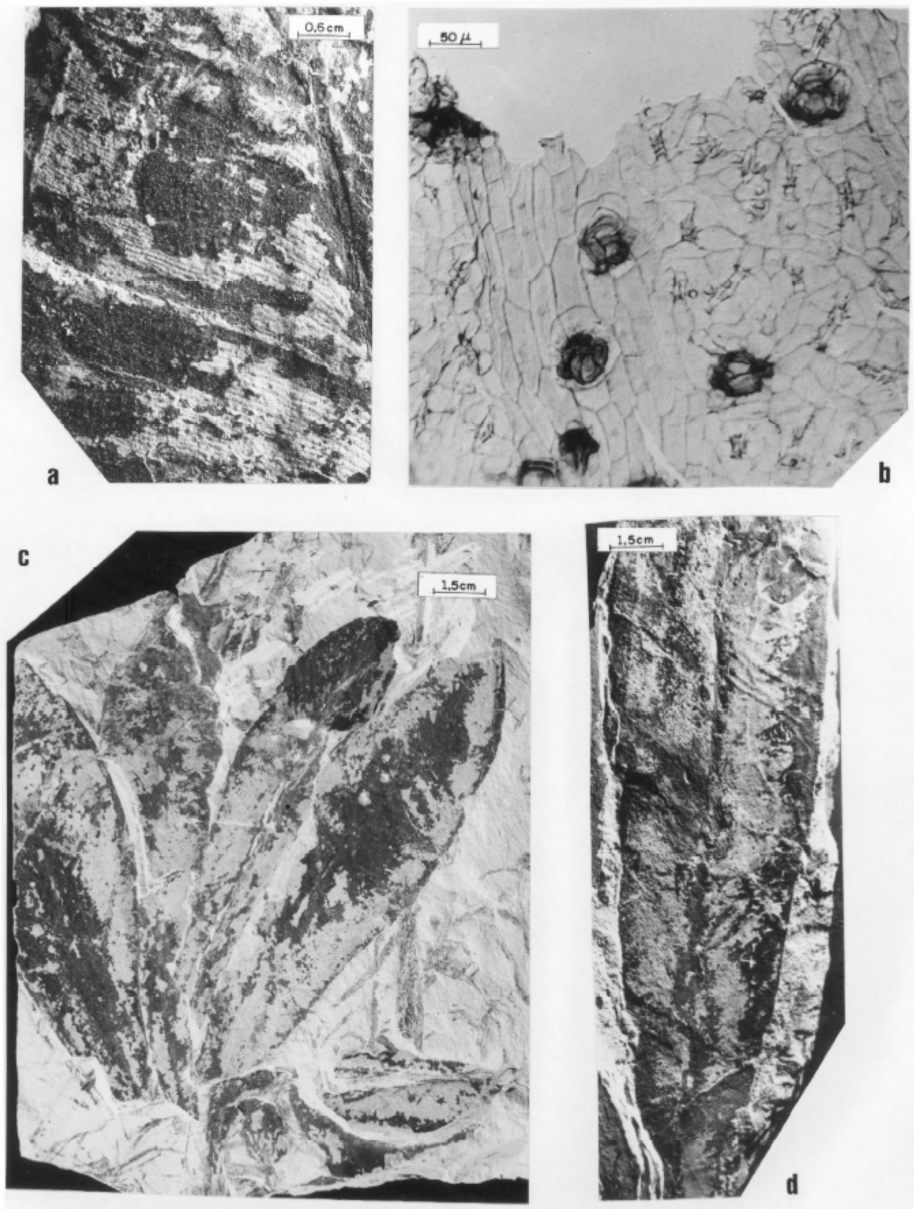

Fig.4

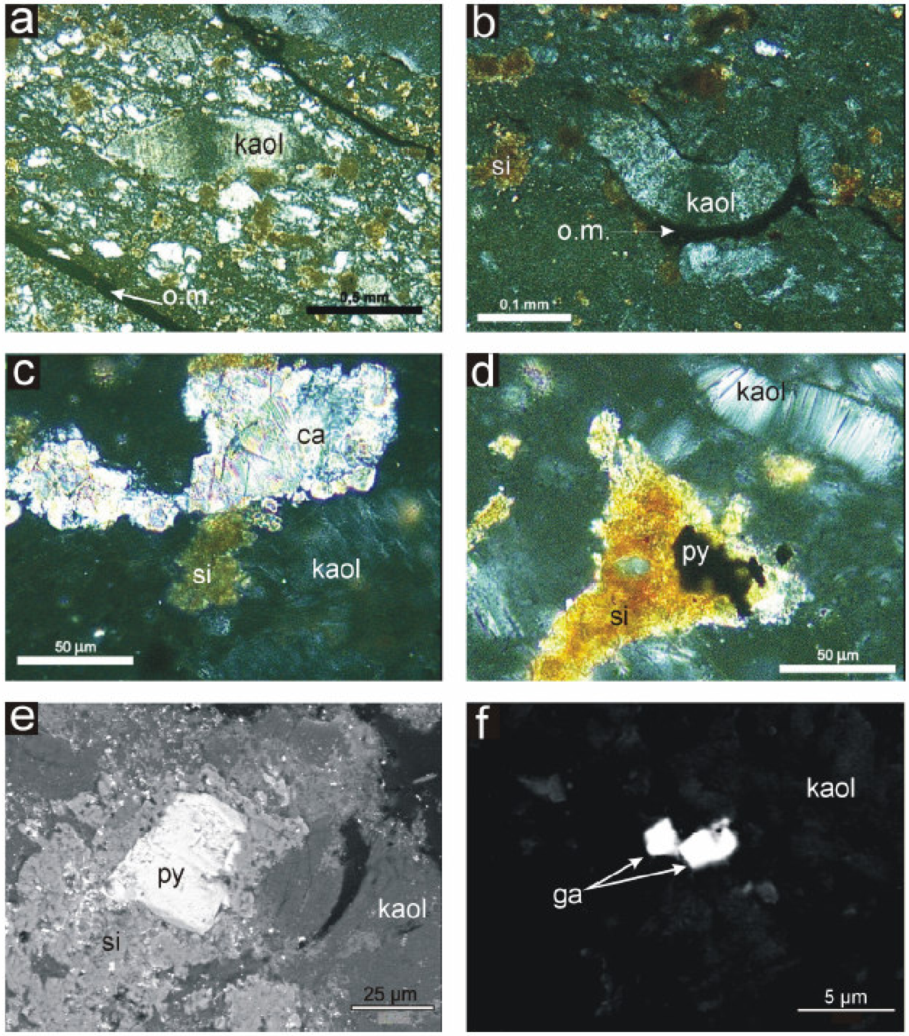
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Fig.5

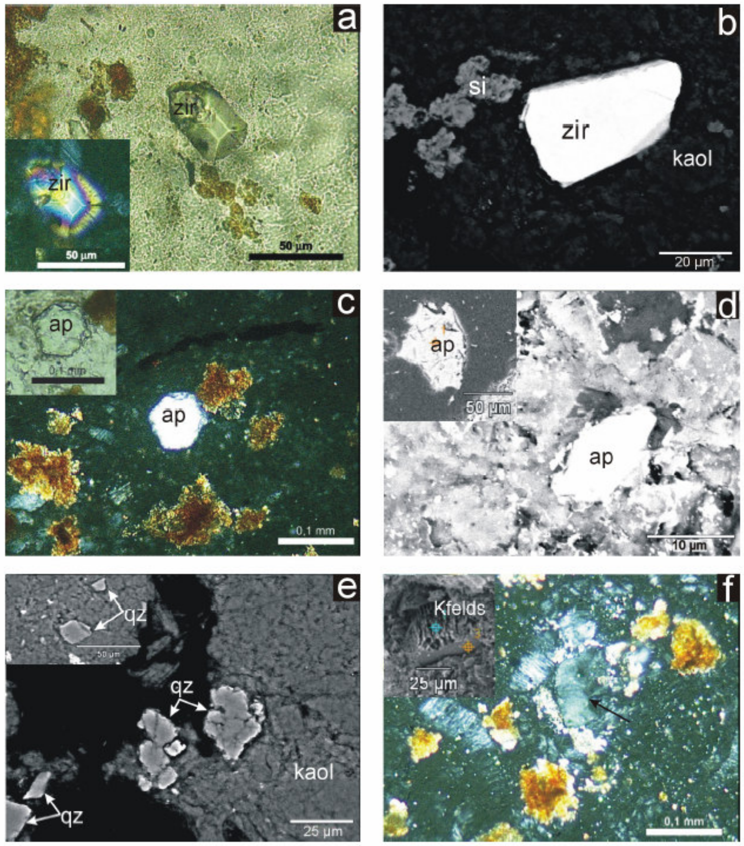
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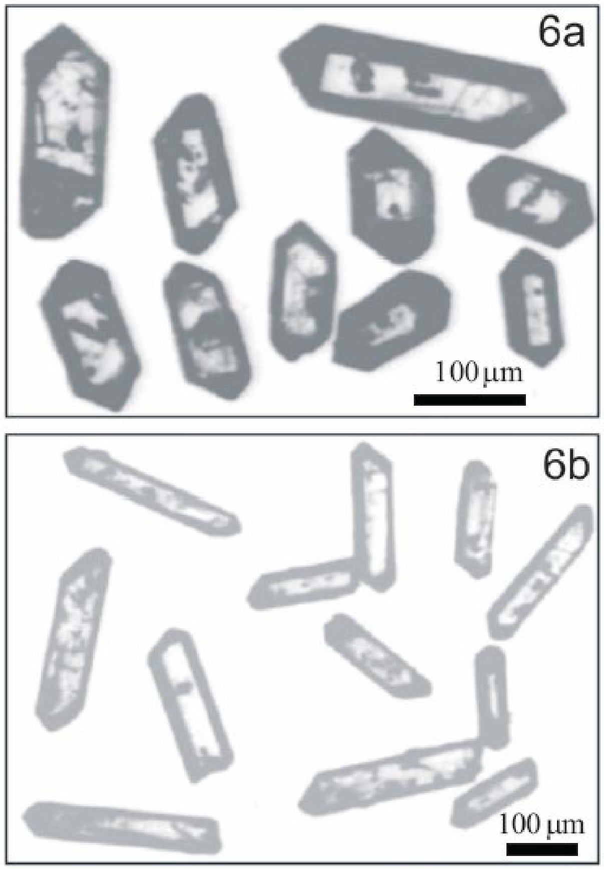
Fig.6



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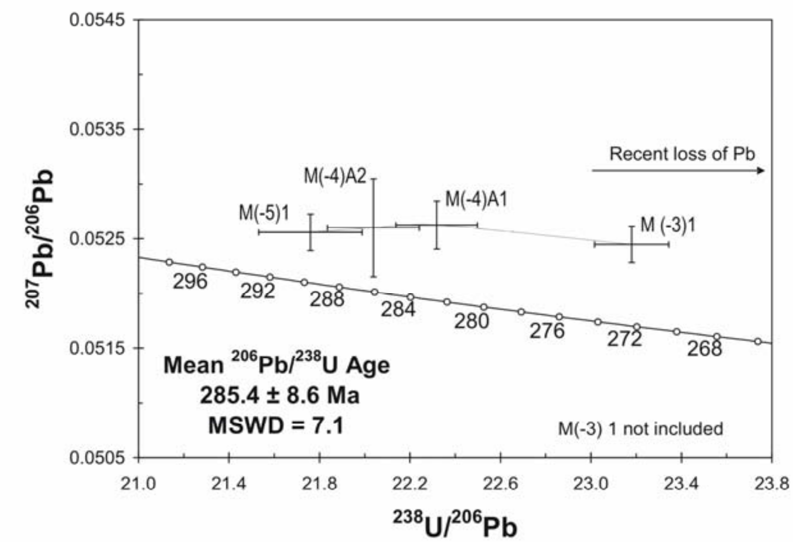
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21.0
21.4
21.8
22.2
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23.0
23.4
23.8
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$
Recent loss of Pb
M(-4)A2
M(-4)A1
M(-5)1
M (-3)1
296
292
288
284
280
276
272
268
Mean $^{206}Pb/^{238}U$ Age
285.4 ± 8.6 Ma
MSWD = 7.1
M(-3) 1 not included

Fig.8

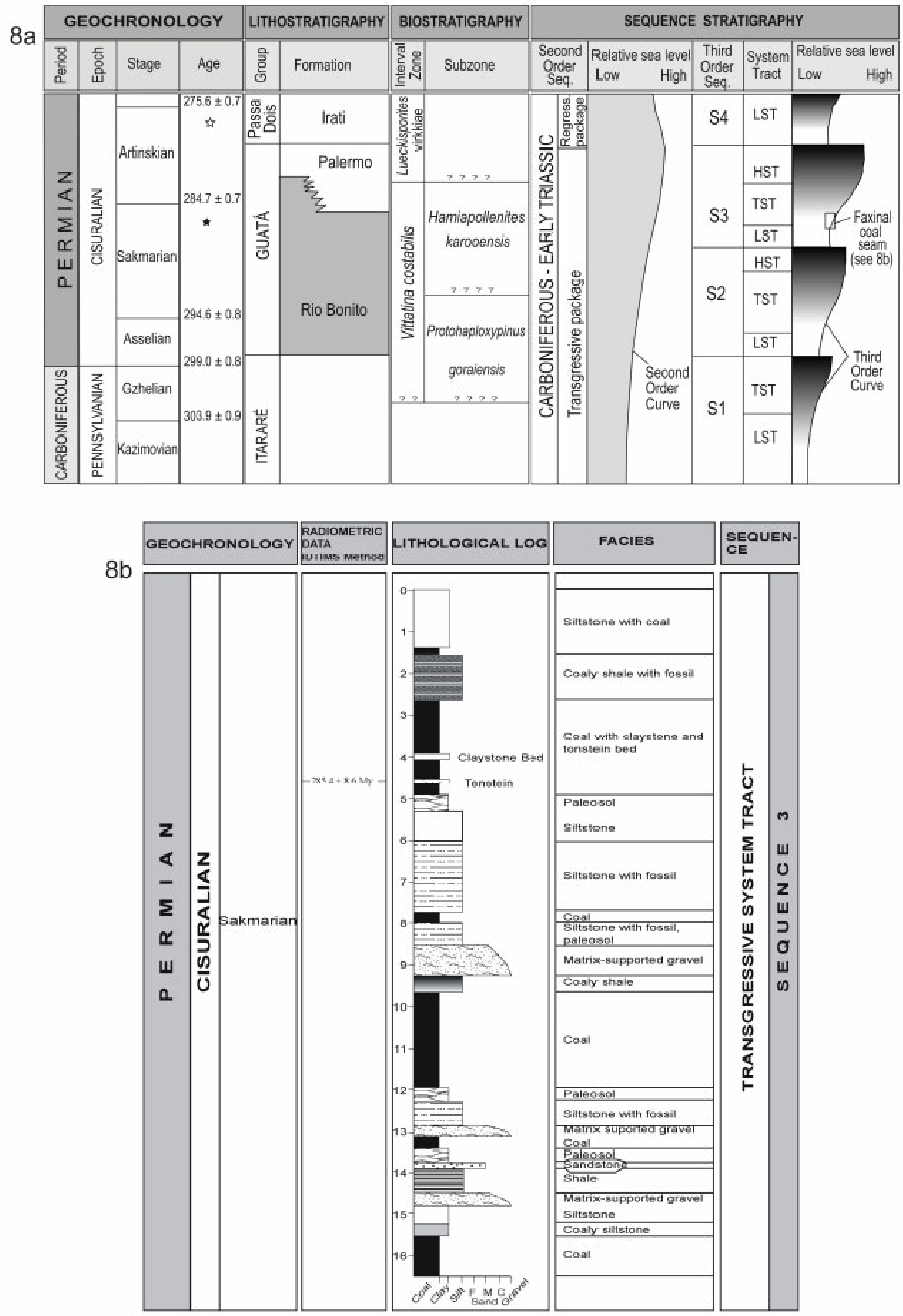
8a
GEOCHRONOLOGY
LITHOSTRATIGRAPHY
BIOSTRATIGRAPHY
SEQUENCE STRATIGRAPHY
Period
Epoch
Stage
Age
Group
Formation
Interval Zone
Subzone
Second Order Seq.
Relative sea level
Low
High
Third Order Seq.
System Tract
Relative sea level
Low
High
PERMIAN
CARBONIFEROUS
CISURALIAN
PENNSYLVANIAN
Artinskian
Sakmarian
Asselian
Gzhelian
Kazimovian
275.6 ± 0.7
284.7 ± 0.7
294.6 ± 0.8
299.0 ± 0.8
303.9 ± 0.9
Passa Dois
GUATÁ
ITARARÉ
Irati
Palermo
Rio Bonito
Lueckisporites virkkiae
Vittatina costabilis
Hamiapollenites karooensis
Protohaploxypinus goraiensis
CARBONIFEROUS - EARLY TRIASSIC
Regress. package
Transgressive package
Second Order Curve
S4
S3
S2
S1
LST
HST
TST
LST
HST
TST
LST
TST
LST
Faxinal coal seam (see 8b)
Third Order Curve
8b
GEOCHRONOLOGY
RADIOMETRIC DATA
LITHOLOGICAL LOG
FACIES
SEQUENCE
PERMIAN
CISURALIAN
Sakmarian
Claystone Bed
Tonstein
Siltstone with coal
Coaly shale with fossil
Coal with claystone and tonstein bed
Paleosol
Siltstone
Siltstone with fossil
Coal
Siltstone with fossil, paleosol
Matrix-supported gravel
Coaly shale
Coal
Paleosol
Siltstone with fossil
Matrix suported gravel
Coal
Paleosol
Sandstone
Shale
Matrix-supported gravel
Siltstone
Coaly siltstone
Coal
Coal
Clay
Silt
F
M
C
Sand
Gravel
TRANSGRESSIVE SYSTEM TRACT
SEQUENCE 3

Table 1

TONSTEIN FAXINAL

Sample	Fraction	ZIRCON TYPOLOGY	$^{207}Pb/^{235}U$	error	$^{206}Pb/^{238}U$	error %	COEF	$^{206}Pb/^{204}Pb$	Pb ppm	U ppm	Weight mg	$^{206}Pb/^{238}U$	error	$^{207}Pb/^{206}Pb$	error %	$^{206}Pb/^{238}U$ Ma	error Ma	$^{207}Pb/^{235}U$ Ma	$^{207}Pb/^{206}Pb$ Ma
1747	M (-3)1	P(2.1).Dt.Py.T.C.I.F	0.311975	0.777	0.0431406	0.709	0.91496	860.29	26.65	564.34	0.05826	23.180021	0.709	0.0524484	0.314	272.27	1.93	275.71	305.02
1748	M(-4)A1	P(2.1).Dt.Py.T.C.I.F	0.325125	0.914	0.0448075	0.808	0.88997	296.06	19.49	353.31	0.06828	22.317692	0.808	0.0526257	0.417	282.56	2.28	285.84	312.70
1749	M(-4)A2	P(5.1).Dt.T.C.I.F	0.329093	1.250	0.0453768	0.921	0.73707	454.92	18.61	358.80	0.05606	22.037693	0.921	0.0525997	0.848	286.08	2.63	288.87	311.58
1751	M(-5)1	P(2.1).Dt.Py.T.C.I.F	0.333032	1.100	0.0459558	1.050	0.95757	561.05	12.21	243.69	0.0687	21.760039	1.050	0.0525587	0.318	289.64	3.04	291.88	309.80

Artigo B

"Peat-forming environment of Permian coal seams from the Faxinal coalfield (Paraná Basin) in southern Brazil, based on Palynology and Palaeobotany."

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PEAT-FORMING ENVIRONMENT OF PERMIAN COAL SEAMS FROM THE FAXINAL COALFIELD (PARANÁ BASIN) IN SOUTHERN BRAZIL, BASED ON PALYNOLOGY AND PALAEOBOTANY

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ABSTRACT – Coal seams from the Faxinal coalfield (Rio Bonito Formation, Lower Permian of Paraná Basin) are compositionally distinct from other South Brazilian coal palynofloras. The dominance of bisaccate and striate pollen grains such as *Alisporites*, *Scheuringipollenites*, *Limitisporites*, *Vesicaspora* and *Protohaploxypinus* in the palynofloras reflect a peat-forming plant community composed namely of glossopterids, cordaites and conifers. Subordinate trilete spores derived from lycopsids, sphenopsids and filicopsids (e.g. *Lundbladispora*, *Punctatisporites*, *Granulatisporites*, *Leiotriletes*, *Deltoidospora*, *Calamospora*) are less abundant, occurring in variable proportions. Algae-like elements, commonly found in south Brazilian coal palynofloras (*Portalites*, *Tetraporina*, *Brazilea* and *Quadrisporites*), are scarce and *Botryococcus* was not recorded. This palynological feature as well as the record of abundant woody tissues, cuticles and other phyterals is quite different from palynoassemblages identified in other southernmost Brazilian coal seams. The dominance of woody seed plants in the Faxinal peat-forming vegetation, low proportion of pteridophytic plants and scarcity of algal elements suggest a different peat-forming environment for the Faxinal coal seams compared to other coals from Brazil that have been studied. By integration of palynological and macrofossil data with available sequence stratigraphical studies on the coal-bearing strata in south Brazilian Paraná Basin, a landscape unit has been outlined, that is different from that proposed for the Candiota coalfield. Faxinal coals were interpreted to have accumulated in inland coastal plain mires, linked to delta fluvial settings, at relatively high sea-level, but under low marine influence.

Key words: Coal palynofloras, peat-forming flora, palaeoecology, Faxinal coalfield, landscape unit, Paraná Basin, Brazil.

RESUMO – A palinoflora dos carvões da Jazida do Faxinal (Formação Rio Bonito, Permiano Inferior, Bacia do Paraná) caracteriza-se por uma composição palinológica distinta daquelas reconhecidas para outros carvões do sul do Brasil. O predomínio de grãos de pólen bissacados e estriados, como *Alisporites*, *Limitisporites*, *Scheuringipollenites*, *Vesicaspora* e *Protohaploxypinus* reflete a presença de uma vegetação formadora das turfeiras constituída principalmente por glossopterídeas, cordaites e coníferas. Esporos triletes derivados de licófitas, esfenófitas e filicófitas, abundantes na maioria das palinofloras dos carvões sul-brasileiros, como *Lundbladispora*, *Punctatisporites*, *Granulatisporites*, *Leiotriletes*, *Calamospora*, *Deltoidospora*, *Cristatisporites* e *Vallatisporites*, ocorrem em baixa proporção. Representantes do grupo das algas (*Botryococcus*) e elementos incertae sedis ou acritarcas, comumente identificados nos carvões da Bacia do Paraná (*Portalites*, *Tetraporina*, *Brazilea* e *Quadrisporites*), ocorrem em baixíssima frequência. Estas características palinológicas, associadas à identificação de abundantes fragmentos de lenho, cutículas e outros fiterais relacionados a glossopterídeas e cordaites, evidenciam significativa diferença na composição da vegetação formadora das turfeiras, provavelmente originada por mudanças nas condições do paleoambiente. Através da integração dos dados microflorísticos, megaflorísticos e paleoecológicos com modelos deposicionais já definidos para sucessões de carvão no sul da Bacia do Paraná com base em estratigrafia de seqüências, foi reconstruída, de modo tentativo, a unidade de paisagem condicionadora da acumulação da turfa geradora dos carvões de Faxinal. A unidade de paisagem proposta, diferente daquela indicada para a jazida de Candiota, é relacionada a áreas mais internas de planície costeira, vinculada à sistema fluvio-deltaico, em nível relativo de mar alto, porém com influência marinha menos marcada.

Palavras-chave: Palinologia de carvões, megafloras, Jazida de Faxinal, paleoecologia, unidade de paisagem, bacia do Paraná, Brazil.

INTRODUCTION

Many depositional models of coal formation have been described in the literature (Stach *et al*., 1982; McCabe, 1987; Diessel, 1992; DiMichele & Phillips, 1994; Nowak & Górecka-Nowak, 1999) often using different kinds of data for the reconstruction of the original environment. Coal petrography, palynology, palaeobotany, organic geochemistry, and sequence stratigraphy are usually the main methods used to define the features of coal depositional environments. The palynological composition of coals has been widely applied to characterize the peat-forming environment, considering that pollen and spores overwhelmingly derive from the peat-forming flora and thus reflect the compositional changes that occurred during peat accumulation.

Considering that vegetation is very sensitive to slight environmental changes, reflected in palaeofloristic composition, the association of palynological studies with palaeofloristic data can provide important information on the ecological preferences of different plant groups, original edaphic conditions, and mire hydrology, as well as changes in these variables during the interval of peat formation (Smith, 1962). On the other hand, the interpretation of miospore succession within coals is based on the assumption that the miospore-forming plants are autocthonous or hypoautocthonous and represent a local population of parent plants.

The most important studies on the peat-forming vegetation of the South Brazilian coals (Figure 1) were those of Marques-Toigo & Corrêa da Silva (1984), Guerra-Sommer *et al*. (1991) and Corrêa da Silva (1991) which integrated palynology, palaeobotany and coal petrography in an attempt to define the main organic constituents of the coals. Their results demonstrated that these coals have characteristics that are indicative of an origin in limno-telmatic moors, where pteridophytic herbaceous and arborescent plant material accumulated after some transport, promoting hypoautochthonous coal seams.

On the other hand, sequence stratigraphical studies applied to the main coal-bearing strata in southernmost Brazil (Paraná Basin) demonstrated that whereas some coal seams were predominantly originated in fluvial settings, the most important coal beds derived from a lagoon-barrier system linked with a third-order transgressive systems tract, subdivided into four parasequences sets, each set representing a major transgressive pulse in the sedimentary history of the basin (Holz, 1998; Holz & Vieira, 2001; Holz & Kalkreuth, 2004).

Palynological studies conducted on the most important coal-bearing strata in the southern Paraná Basin, mainly those

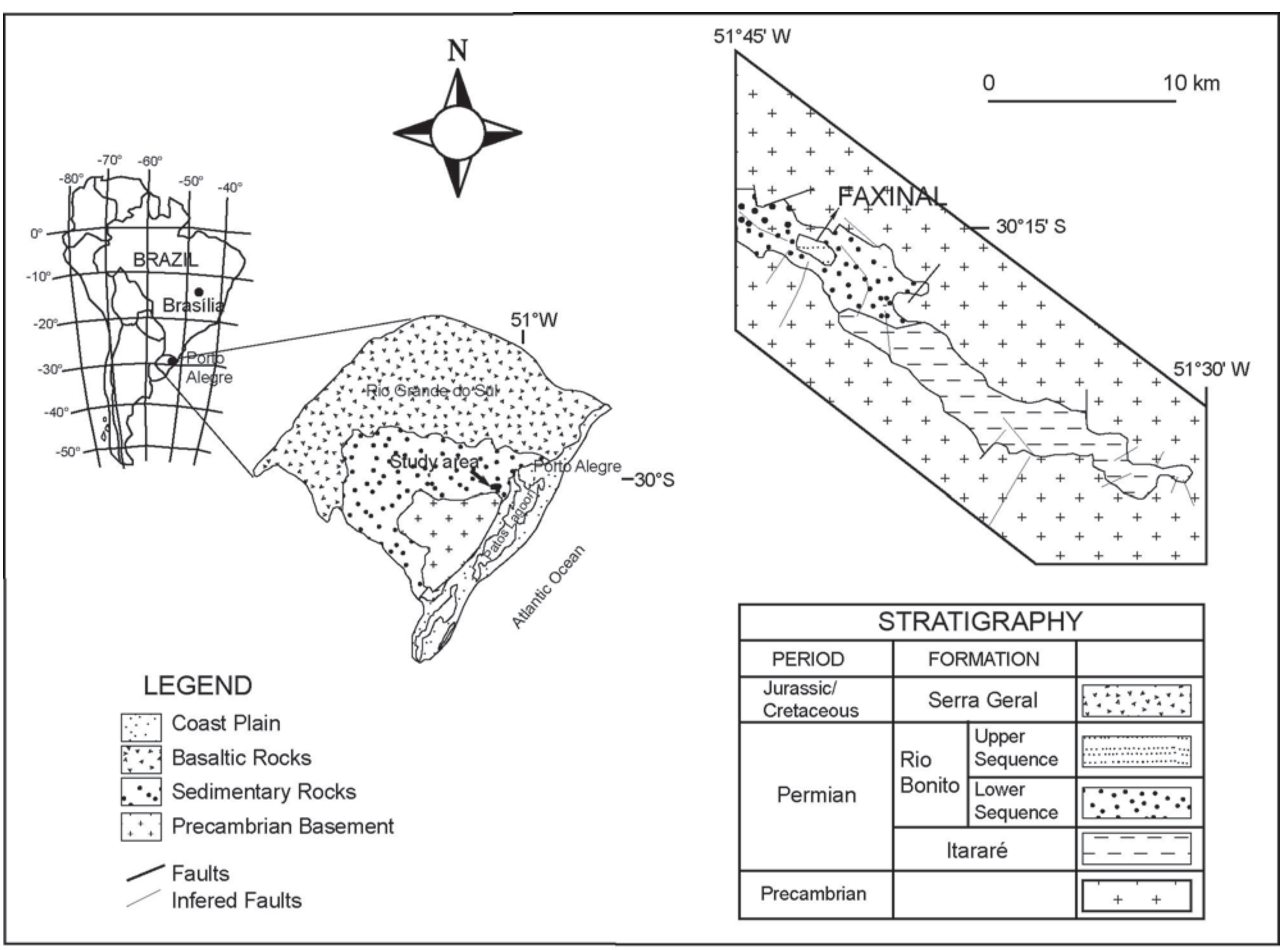

Figure 1. Location map of the Faxinal coalfield and stratigraphic chart of the Paraná Basin.

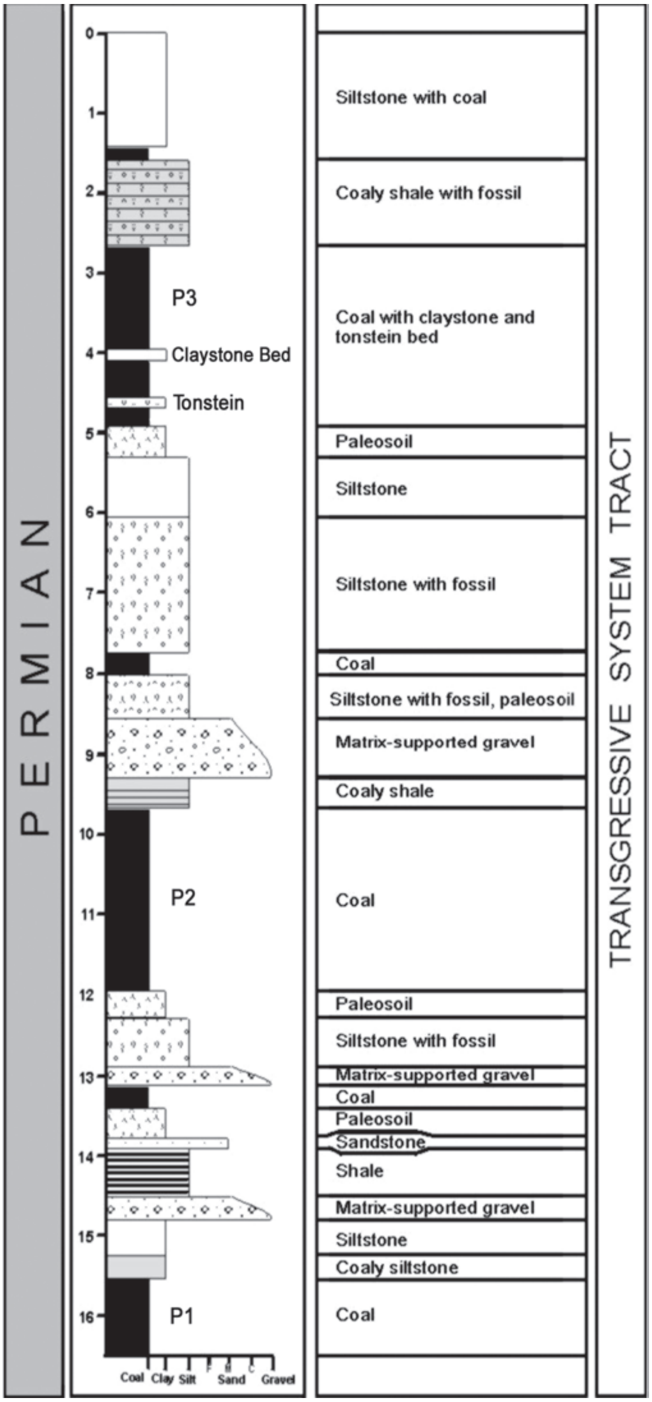

Figure 2. Lithostratigraphic profile of the Faxinal coal succession indicating the beds were the studied samples were collected (P1, P2, and P3).

of Ybert (1975), Burjack (1978), Dias-Fabrício (1981), Bortoluzzi *et al.* (1980), Cazzulo-Klepzig *et al.* (1982), Corrêa da Silva *et al.* (1984), Marques-Toigo *et al.* (1984), Picarelli *et al.* (1987), Araújo *et al.* (1985) and Meyer (1999), demonstrated, in a general way, the presence of rich and diversified palynofloras, dominated by spores derived from herbaceous and arborescent lycopsids. Gymnosperm pollen grains appeared as subordinate components in the palynofloras. In addition, for the majority of the palynoassemblages, organic-walled palynomorphs of doubtful botanical affinity related to algae-like elements or acritarchs were commonly recorded together with fragments of *Botryococcus braunii*.

Although this type of palynoassemblage has been identified for the majority of South Brazilian coals, some compositional differences, however, have been noted for a few coal seams, mainly in terms of the relative abundances of the most important taxa.

Cazzulo-Klepzig (2002) outlined a hypothetical reconstruction for the landscapes of peat-forming environments related to the most important coal seams in the southern Paraná Basin. This study was based on the composition of the palynofloras, botanical affinity of spores and pollen grains, habit of the parent plants, environmental conditions favorable for the growth of the vegetation, quantitative changes in the palynological content among distinct coal beds, and the range of tolerance to changes in salinity shown by algae and algae-like elements. The author emphasized, however, that although palynology and palaeobotany are very useful tools for environmental reconstruction, the limitations of these methods should be taken into account (e.g.: Di Michele & Phillips, 1994).

For the Candiota coal seams, which represent the most economically valuable coals in Rio Grande do Sul State (Figure 1), Cazzulo-Klepzig *et al.* (2005) outlined a tentative palaeo-reconstruction of the peat-forming environment of the two most important coal seams (Lower and Upper Candiota Coal Seams). For a paleoenvironmental interpretation, sequence stratigraphical information (Holz ; 1988; Holz & Vieira, 2001 and Holz & Kalkreuth,2004) was integrated with the palynological and paleobotanical data.

Two distinct scenarios were delineated, related respectively to high sea-level conditions and low sea-level conditions. The peats accumulated in paralic conditions, specifically a lagoon-barrier system, and were influenced by episodic sea-water floods (Figure 2). Although the lowland coastal mires could be sporadically flooded, they were isolated from direct marine influence by a barrier island, precluding major marine ingressions. Meyer (1999) recorded the presence of *Navifusa* and *Cymatiosphaera* in the Lower Candiota coal palynofloras and expanded the paleoenvironmental interpretation for the coal formation.

Focusing on the Charqueadas coalfield, Cazzulo-Klepzig *et al.* (1993) noted the strong compositional similarity between the palynofloras identified and the Candiota coal palynofloras. The detected changes in the plant-communities among the distinct coal seams, reflecting palynofloristic content, were caused by changes in the peat-forming environment. A palaeoreconstruction of the changing environment formation was tentatively outlined, characterized by lateral and vertical organic facies.

For the Faxinal coalfield, the focus of this paper (Figure 1), Guerra-Sommer *et al.* (1983) provide the only palynological studies on the coal seams and document, from preliminary analyses, the palynological content of the coals. These authors mentioned the presence of spores derived from arborescent lycopsids (*Lundbladispora*) together with rare gymnospermous pollen grains (*Potonieisporites*), although illustrations of the diagnostic forms were not coincident with the list of the palynotaxa identified. In addition to miospores, abundant and well-preserved woody fragments and epidermal remains (cuticles) were identified as belonging to gymnosperms. In a tonstein layer interbedded in the uppermost coal seam, a rich compressed megaflora represented by leaves, branches and reproductive structures of glossopterids as well as leaves of cordaites, sometimes preserved as foliar tuffs, was also recorded (Guerra-Sommer, 1983, 1988). Results from analyses of the glossopterid epidermal remains indicate xeromorphic patterns. This author emphasized that remains of cordaites, despite being abundantly represented in the Faxinal megaflora, essentially in the tonstein, are poorly represented in other South Brazilian antracophylic floras.

Together with the pteridophytic spores, Dias & Guerra-Sommer (1994) mentioned for these palynofloras a significant amount of *Maculatasporites minimus* and *Maculatasporites gondwanensis*, considered by some authors as related to fungi, and abundant pollen grains with botanical affinity with gymnosperms, mainly cordaites, conifers and glossopterids. This palynological composition, very similar to that found in the coal seams, is not a common characteristic of the South Brazilian coal palynofloras. Results from petrographic and geochemical analyses (Guerra-Sommer *et al*., 1983) have indicated a significant amount of woody plant- material, suggesting growth of the peat-forming vegetation in a telmatic environment (forest moor).

Based on petrological analyses of the Faxinal coals, Henz (1986) defined the organic matter as derived from woody material, mainly represented by vitrinite, with subordinate exinite and inertinite constituents, which were accumulated in a telmatic environment (forest moor or peat-forming forest vegetation sensu Hacquebard & Donaldson, 1969). The maceral composition of coals indicated reducing conditions and a shallow water table.

Data from sequence stratigraphical studies of the Faxinal coal-bearing sequenceare very important for a paleoecological interpretation, but to date have not been published.

The present study takes into account the peculiar composition of the palynofloras, reflecting a different type of peat-forming vegetation than that of other well recognized coal palynofloras from the Paraná Basin. This study was also modulated in order to provide an accurate palynological revision aimed at reviewing and characterizing qualitatively and quantitatively the palynofloristic content as well as defining the peat-forming plant-communities related to the Faxinal coal seams. Additional objectives were to interpret the environmental conditions of peat-accumulation and to reconstruct tentatively the landscape under which Faxinal peats accumulated and differed from the other known Brazilian coals.

GEOLOGICAL SETTING

The Paraná Basin is a large intracratonic basin, located in the central-east part of the South American Platform, covering a surface area of about 1,700,000 km^2. According to Milani *et al*. (1998) the basin comprises six stratigraphic megasequences bounded by interregional unconformities. The Carboniferous-Early Triassic megasequence includes the major coal-bearing strata related to isolated coalfields cropping out from the southernmost part of Rio Grande do Sul State through Santa Catarina State, to the northern portion of Paraná State (Figure 1). The overall transgressive trend at the top of Itararé Group, the basal sedimentary unit in the study area, is essentially represented by marine deposits and points to a relative rise in sea level rise that was later interrupted during the Rio Bonito deposition. Coal occurrences are historically assigned to the Rio Bonito Formation, a fluvial to marine sandstone and shale- rich lithostratigraphic unit of Early Permian age.

The Faxinal coalfield is located in Guaíba city (UTM N665,5; E432,7). Prior stratigraphical and sedimentological studies (Paim *et al*., 1983; Piccoli *et al*., 1983) linked the depositional conditions to the presence of alluvial fans that blocked the fluvial sedimentation creating favorable areas for organic matter accumulation. Applying sequence stratigraphy methods, Holz *et al.* (2000) and Holz & Kalkreuth (2004) developed a model for palaeoenvironmental evolution of the coal-bearing strata of the South Brazilian coalfields. In this model, the most economically important coal seams occur within the transgressive tract of Sequence 2 as part of a barrier-lagoon system.

MATERIALS AND METHODS

For the present study, samples were collected from three coal beds in the Faxinal coal-bearing strata, as indicated in the columnar profile (Figure 2 - P1, P2 and P3). Extraction of the palynomorphs from samples was carried out using a routine process developed at the Geological Survey of Canada (GSC). Samples were processed in Schulze's solution (65% nitric acid, HNO3) saturated with potassium chloride (KClO3), and neutralized in potassium hydroxide (KOH), enabling the rapid maceration of palynomorphs. Only samples from coal seams 1 and 2 were taken for the study. Palynomorphs from coal seam 3 were poorly preserved.

A visual count of a minimum of 200 miospores was undertaken to determine the relative proportions of miospore taxa. Palynological slides are stored at the Department of Geology of the Geological Survey of Canada.

Assignments of dispersed spores and pollen grains to their respective parent-plant groups, such as lycopsids, ferns, sphenopsids, glossopterids, cordaites and conifers, were based on compilations of Balme (1995) and Quadros *et al*. (1995). Paleoecological interpretation for the other organic-walled palynomorphs followed mainly concepts adopted by Tiwari *et al*. (1994), Batten & Grenfell (1996), Guy-Ohlson (1992), Cazzulo-Klepzig (2001), and accurate criteria of other authors to infer the paleoecology of *Botryococcus* mentioned below.

PALYNOLOGY

There is strong similarity in the palynological results from the main coal seams analysed, with a dominance of bisaccate pollen grains produced by arborescent vegetation, with the following species: *Alisporites australis*, *Scheuringipollenites medius*, *S. minimus*, *Limitisporites rectus* and *Vesicaspora wilsonii*. Within this group, *Scheuringipollenite*s and *Alisporites* are the most abundant bisaccate pollen found (more than 55%). These pollen grains reflect the remarkable presence of glossopterids in the ancient vegetation (Gould & Delevoryas, 1977).

Monosaccate forms are common (around 12%) and show a low species diversity being represented by only three species: *Cannanoropollis korbaensis*, *Potoniesporites braziliensis*, and *Plicatipollenites malabarensis*. Among these, Cannanoropollis is proportionally the most abundant in the assemblage. The number of monosaccate genera identified in the palynoflora indicates that the cordaites also constituted an important component in the palaeoplant-communities.

Striate pollen grains, reflecting the presence of conifers (more than 12%) are indicated by the record of distinct species of Protohaploxypinus, mainly *Protohaploxypinus limpidus*, *Protohaploxypinus hartii*, and *Protohaploxypinus* spp.

The number of trilete spores is relatively low and represents only a small proportion of the miospore fraction (around 17%), which is the opposite of the palynological content in the majority of other South Brazilian coals. The most common spores are derived from sphenopsids and filicopsids (around 10%): *Calamospora sahariana*, *Calamospora plicata*, *Convolutispora candiotensis*, *Deltoidospora directa*, *Granulatisporites*, *Granulatisporites micronodosus*, *Leiotriletes virkki*, *Punctatisporites gretensis* and *Murospora torifera*. The genus *Lundbladispora*, the most abundant spore in South Brazilian coals, is rare (3%). Palynological studies of the tonstein interlayered in the uppermost coal seam indicated a strong similarity between the two palynofloras.

Organic-walled palynomorphs of uncertain botanical affinity (*incertae sedis* or acritarchs), commonly found in the coal palynofloras of the southern Paraná Basin, such as *Portalites*, *Tetraporina*, *Brazilea*, *Quadrisporites* and *Maculatasporites*, are extremely rare in the Faxinal coals (less than 2%). Cazzulo-Klepzig (2001) emphasized the palaeoecological significance of these palynomorphs for peat-environment reconstruction, particularly their relation to the gradient from fresh, to brackish, to marine conditions. The coccal algae *Botryococcus*, considered as a good palaeoecological marker, is commonly found in other coal seams but it was not recorded in the Faxinal coals. This microalga has been supposed to be more widespread in lagoonal and lacustrine environments with low salinity (Guy-Ohlson, 1992), although *Botryococcus* has been recognized as having a wider tolerance to salinity compared to other microfossils (Grice *et al*., 1998; Zippi, 1998; Vincent & Tyson, 1999; Versteegh *et al*. 2004).

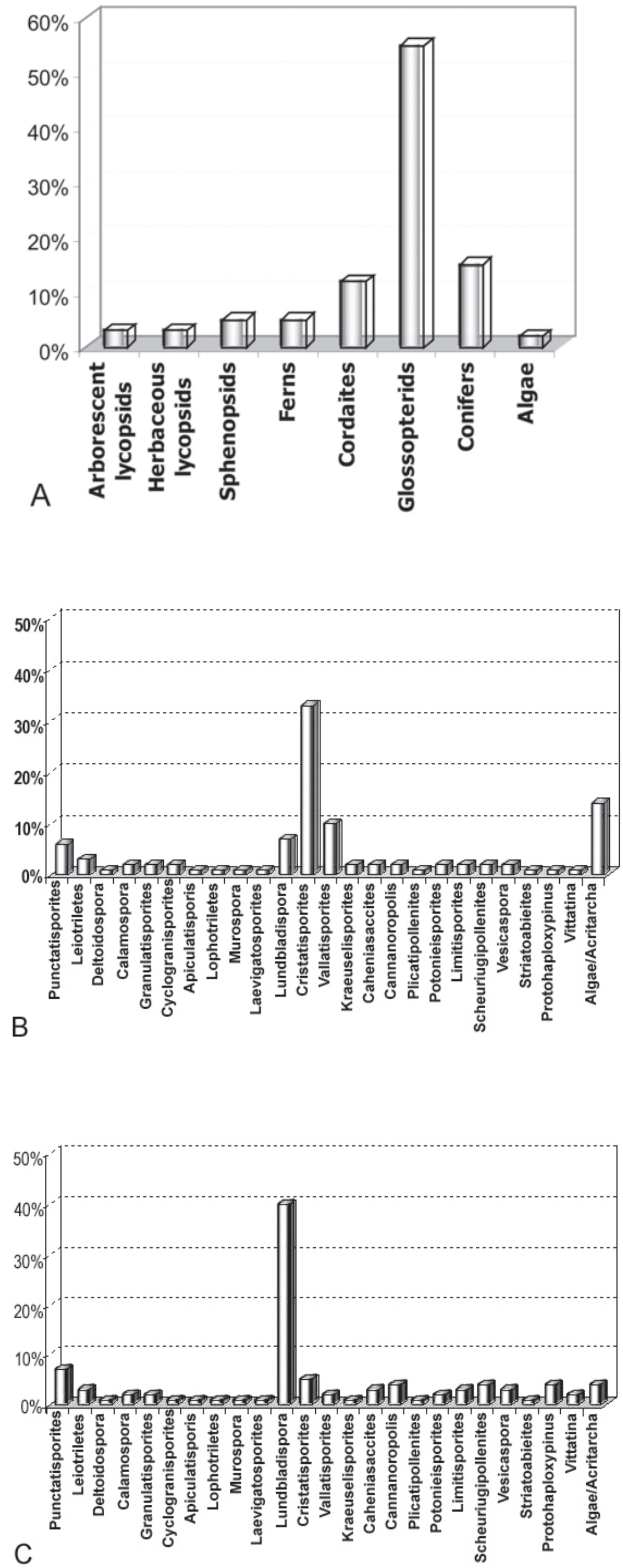

Figure 3. Histograms showing the relative abundance of major group of spores, pollen and other palynomorphs in the Faxinal coal seams (**A**), in the Lower Candiota coal seam (**B**); and in the Upper Candiota coal seam (**C**).

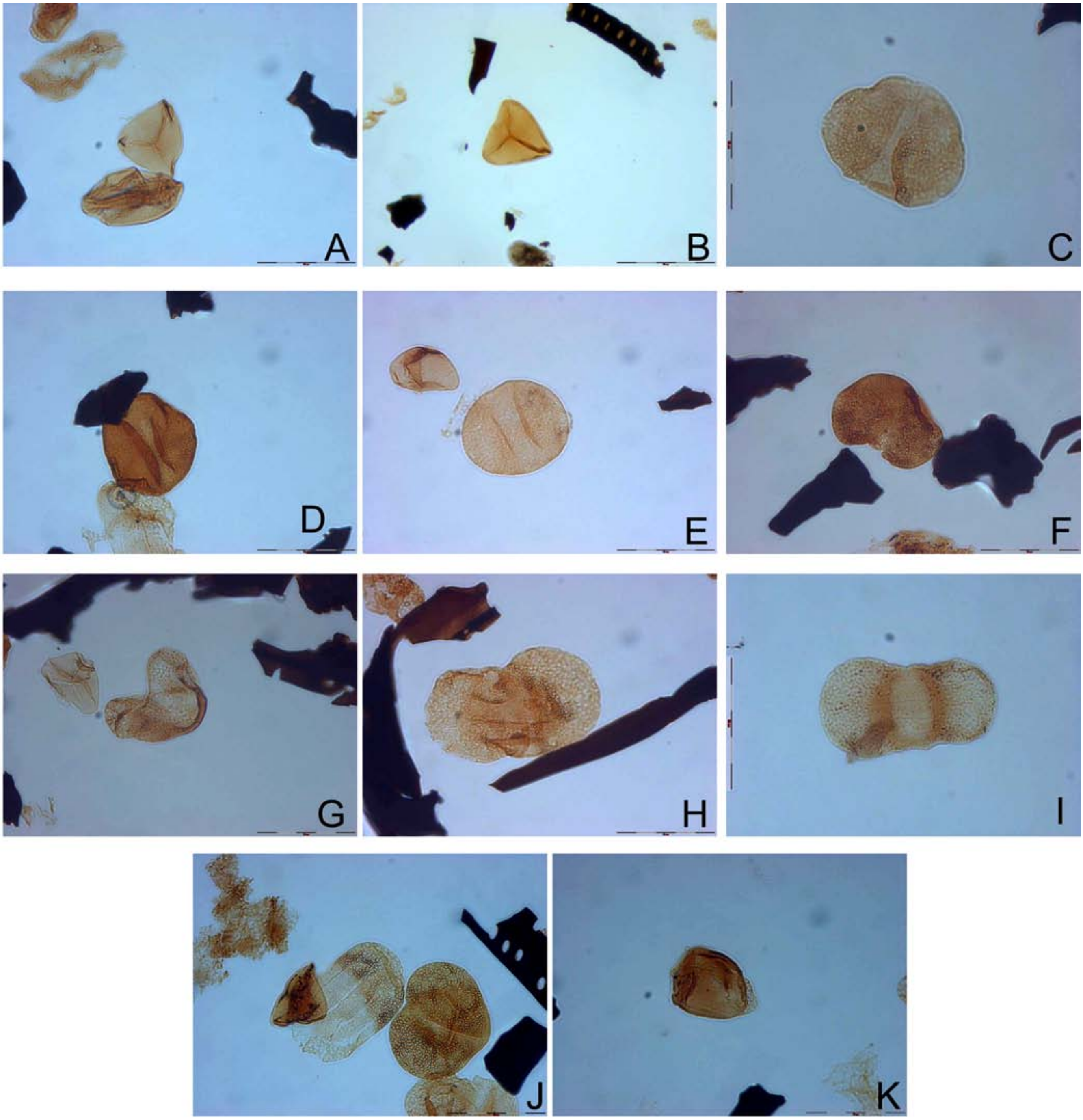

Figure 4. A, *Deltoidospora directa* (Balme & Hennely) Hart, 1965 and *Calamospora sahariana* Bharadwaj, 1953; **B**, *Granulatisporites angularis* Staplin,1960; **C**, *Scheuringipollenites medius* (Burjack) Dias-Fabricio, 1981; **D**, *Scheuringipollenites ovatus* (Balme & Hennely) Foster, 1975; **E**, *Alisporites splendens* (Leschik) Foster, 1979; **F**-**G**, *Vesicaspora wilsonii* (Schemel) Wilson & Venkatachala, 1963; **H**, *Protohaploxypinus hartii* Foster, 1975; **I**, *Protohaploxypinus amplus* (Balme & Hennely) Hart, 1964; **J**, *Protohaploxypinus limpidus* (Balme & Hennelly) Balme & Playford, 1967; **K,** *Vittatina* sp.

The palynological content, dominated by pollen derived from arborescent vegetation, and characterized by a scarcity of algal forms, demonstrates significant compositional differences in relation to the coal palynofloras identified in other South Brazilian coals (Cazzulo-Klepzig, 2002). This paleofloristic feature, showing a dominance of woody tissues, tracheids and cuticular fragments was also previously noted in the petrological analyses of Guerra-Sommer *et al*. (1983) and Henz (1986).

These differences could be caused by topological features or different stages in paleoecological succession (Cairncross & Caddle, 1998; Glasspool, 2003). In relation to the parent plants, although it is possible to outline the probable peat-forming vegetation on the basis of the palynological composition, it is important to take into account that whenever the problem of dispersed spores and pollen is considered, a fossil plant community tends to be underestimated (Traverse, 1988; Nichols, 1995). Cairncross & Caddle (1998) and Glasspool (2003) describe the complex relationship between the proportion of spores and pollen grains relative to the abundance of their parent plants, considering that the palynological record may not provide a true representation of the types and relative abundance of plants within peat-forming vegetation. Distinct factors such as differential spore and pollen production, introduction into the mires of extraneous, regional pollen grains, and oxidation of the palynological material, can lead to a misrepresentation of the original mire vegetation. On the other hand, organic-walled palynomorphs commonly found in South Brazilian coals, such as algae-like forms and acritarchs, can be often estimated due to different preparation methods (a large-mesh size allows small microfossils to be lost), transport, and potential for preservation. Figure 3 shows a comparison between the relative abundance of the most important plant groups reflected in coal palynofloras of Faxinal and Upper and Lower Candiota.

PALEOENVIRONMENTAL INTERPRETATION

Different conditions for the peat-formation can be inferred for the Candiota and Charqueadas coalfields, compared to those of Faxinal (Cazzulo-Klepzig *et al*., 1993, 2005). Considering the peculiar palynological and palaeobotanical features shown by the coals of Faxinal, the palynofloras, which are dominated by glossopterids, small cordaites and conifers, have a low representation of pteridophytic spores, a small fraction of algae-like forms and absence of *Botryococcus*. On the other hand, the abundance of woody plant material and cuticular fragments belonging to arborescent plants (mainly cordaites and glossopterids), found together with palynological assemblages that reflect the same vegetation (Guerra-Sommer *et al*., 1983), emphasize the presence of different peat-forming plant communities in relation to those recorded for other South Brazilian coal seams.

Although the cordaites, glossopterids and some conifers have been linked to mesophytic-xerophytic environments, for the palaeoenvironment interpretation of Faxinal coal-bearing strata, it is important to recognize some of their palaeoecological features , in order to explain their presence in areas adjacent to the mire. According to Guerra-Sommer (1988), the epidermal morphology of the cordaites identified in the Faxinal coals could represent a mechanism to prevent dessication or a response to changes in compositional features of the soil, such as a deficit in N or in chemical characteristics of the available water in the mires. Such physiological and morphological features could have permitted these plants to partition the ecological resources of the mire.

Cridland & Morris (1963) and Falcon-Lang (2005) mentioned the very large ecological amplitude of cordaites and the possibility of these plants representing mangrove trees. These papers discussed the possibility that the cordaites occasionally experienced brackish incursions and adapted to elevated salinity by modification of the rooting system and leaves and demonstrated that some species grew in coastal plains. Small cordaites, flourishing in marine-influenced coastal habitat, in close proximity to the brackish sea coast, adapted to periodically submerged conditions. In the same way, arborescent lycopsids could also tolerate these palaeoecological features (Habib & Growth, 1967). According to Raymond (1988), some cordaites could live in lowlands, co-occurring with calamiteans, tree-ferns and lycopsids, typical of hygrophylous-mesophylous environments.

According to DiMichele & Aronson (1992), hydraulic and energetic competition of phothosynthetic and reproductive activities may have made Paleozoic glossopterids, more vulnerable to fluctuations in water supply, influencing their occupation of drier areas adjacent to the mire. Knoll & Niklas (1987) concluded that xeromorphic structures shown by some glossopterids, as identified in the Faxinal coal seam (Guerra-Sommer *et al*., 1992), can be indicative that they originally grew in higher lands. In the Permian, they could have migrated to peat-forming environments in lowlands, co-occurring with lycopsids, ferns and sphenopsids. The high representation of arborescent glossopterids and cordaites with deciduous leaves and the relatively low abundance of herbaceous plants with perennial leaves in the megaflora of Faxinal are indicative of an hypoauthochtonous taphocenose (Birks & Birks, 1980). On the other hand, the low compositional variation of the Faxinal megaflora also reflected in the palynoflora, could indicate that the habitat in which these plants grew were intrinsically stressful conditions (DiMichele *et al*., 1985).

The Faxinal mire landscape was likely located in a more inland area than that of Candiota. In Faxinal, coal was formed in wet forest swamp environments, situated in a marine-influenced lower delta plain setting, presenting favorable conditions to the development of arborescent vegetation (Figure 5). This is in opposition to the conditions under which Candiota and Charqueadas coals formed. The dominance of arborescent vegetation, low proportion of arborescent lycopsids and scarce record of algal elements define this scenario (Figure 6).

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Figure 5. Reconstruction of the landscape unit and plant-communities related to the peat-forming coal in high relative sea level (Faxinal coal seam and Lower Candiota coal seam, plant communities are detailed in Figure 6); **1**, hydrophylous plant-community; **2**, hygrophilous plant-community; **3**, hygrophylous/mesophylous plant-community; **4**, mesophylous plant-community; **5**, xerophylous plant community.

Figure 6. Dominant plant-communities in the landscape unit related to the Faxinal coal seams: **1**, algae and algae-like elements (hydrophylous plant-community); **2**, herbaceous and/or shrub like plants (lycopsids, ferns and sphenopsids (hygrophylous plant-community); **3**, arborescent lycopsids(hygrophylous/mesophylous plant-community); **4**, cordaites and glossopterids (mesophylous plant-community); **5**, conifers (xerophylous plant-community).

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