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

RECONSTITUIÇÃO PALEO-CLIMÁTICA E PALEO-AMBIENTAL DO PLEISTOCENO TARDIO NO SUL DA PLANÍCIE COSTEIRA DO RIO GRANDE DO SUL

RENATO PEREIRA LOPES

ORIENTADOR – Prof. Dr. Sérgio Rebello Dillenburg
CO-ORIENTADOR – Prof. Dr. César Leandro Schultz

Porto Alegre, Agosto de 2013

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RESUMO

A Planície Costeira do estado do Rio Grande do Sul (PCRS) foi estruturada ao longo do Quaternário por sucessivas oscilações do nível do mar. Alem das oscilações eustáticas, o clima também afetou a região, influenciando nos padrões deposicionais representados pelas fácies expostas em afloramentos e na distribuição dos organismos. O objetivo da presente tese é reconstituir condições climáticas e ambientes da região durante o Pleistoceno tardio, a partir de levantamentos estratigráficos, sedimentologia, datações, e análises de fósseis. A área escolhida para o desenvolvimento da tese foi o Arroio Chuí, localizado no sul da PCRS entre as barreiras II e III, onde afloram seqüências deposicionais que representam ambientes marinho e terrestre. Os resultados mostram que a porção marinha da seqüência exposta ao longo do arroio representa a fácies marinha do sistema deposicional Laguna-Barreira II. Datações em sedimentos e conchas de bivalves coletados nesta fácies indicam que este sistema teria sido formado pelo máximo transgressivo marinho ocorrido durante o estágio isotópico marinho (MIS) 7, há aproximadamente 230 mil anos. As temperaturas do oceano na região durante esse intervalo eram mais quentes do que nos dias de hoje, como evidenciado por espécies de moluscos bivalves e foraminíferos indicativos de águas mais quentes. A camada acima da fácies marinha representa paleossolos e antigos sistemas fluviais, onde ficaram preservados fósseis de grandes mamíferos. Datações feitas nos fósseis desses animais mostraram idades entre 226 e 34 mil anos; análises de isótopos estáveis (^{13}C e ^{18}O) em dentes fósseis mostram que o ambiente era caracterizado por pradarias compostas por gramíneas, arbustos e possivelmente matas de galeria. As características sedimentológicas mostram intercalações entre períodos mais úmidos e outros mais secos. Na camada acima do horizonte que contem os restos de grandes mamíferos não foram encontrados fósseis ate agora, e o aumento na quantidade de silte e presença de nódulos e concreções carbonáticas indicam clima mais seco, provavelmente relacionado ao ultimo máximo glacial (LGM).

ABSTRACT

The Coastal Plain of Rio Grande do Sul state (CPRS) was formed during the Quaternary by successive sea-level oscillations. Besides the eustatic oscillations, the region was also affected by climate changes, which influenced the depositional patterns represented by the facies exposed along outcrops and the distribution of organisms. The objective of this thesis is to reconstruct late Pleistocene climate conditions and environments of the region, using stratigraphic surveys, sedimentology, datings ands analysis on fossils. The area chosen for this work was the Chui Creek, located in the southern CPRS between the barriers II and III, where depositional sequences that represent marine and terrestrial environments are exposed. The results show that the marine portion of the sequence exposed along the banks of the creek represents the marine facies of the depositional system Barrier-Lagoon II. Datings on sediments and bivalve shells from this facies indicate that this system would have been formed by the marine highstand during the marine isotope stage (MIS) 7, around 230 thousand years ago. The ocean temperatures during this interval were higher than today, as indicated by bivalves and foraminifers that indicate warmer waters. The layer above the marine facies represents paleosoils, and ancient fluvial systems where fossils of large mammals were preserved. Datings on these fossils revealed ages between 226 and 34 thousand years; analyses of stable isotopes (^{13}C and ^{18}O) in fossil teeth showed that the landscape consisted of prairies composed by grasses, shrubs and possibly gallery forests. The sedimentary record show intercalated humid and dry periods. The layer above the horizon with large mammalian remains provided no fossils so far, and the increase in silt-sized particles and the presence of carbonate nodules and concretions indicate very dry conditions, probably correlated with the last glacial maximum (LGM).

INTRODUÇÃO

1 - Generalidades

O clima é um sistema complexo resultante da interação entre a atmosfera, superfícies emersas, neve e gelo, oceanos e outros corpos d’água, e seres vivos. Pode ser definido como a expressão estatística das condições climáticas diárias, e é geralmente descrito em termos da média e variabilidade de temperatura, precipitação e ventos ao longo de períodos de pelo menos 30 anos (Bradley, 1999). Os padrões climáticos resultam do balanço entre a radiação solar absorvida e refletida, bem como a emissão absorção e transporte da energia pela atmosfera e oceanos, e configuração e natureza da superfície sólida da Terra (massas continentais) (Hay, 1996). O sistema climático se modifica ao longo do tempo influenciado por sua própria dinâmica interna e por alterações nos fatores externos (forçantes climáticas). Estes incluem fenômenos como erupções vulcânicas e variações na atividade solar. Em décadas recentes, descobriu-se que atividades humanas também têm afetado os padrões climáticos (Le Treut *et al.*, 2007).

O clima da Terra tem oscilado continuamente ao longo da sua história; uma vez que os padrões climáticos influenciam diversos fenômenos naturais relacionados ao clima, como precipitação, circulação oceânica e atmosférica, padrões deposicionais, e processos biológicos, os efeitos do clima sobre esses fenômenos ficam documentados nos registros naturais. As principais fontes de informações paleoclimáticas são geológicas (paleossolos, espeleotemas, depósitos eólicos, etc.), glaciológicas (gases e elementos traços aprisionados no gelo, composição do gelo, etc.), biológicas (palinomorfos, anéis de crescimento em árvores, insetos, corais etc.) e químicas (isótopos estáveis em rochas e materiais orgânicos). Além destas podem ser também utilizadas fontes históricas, mas como estas abrangem um intervalo de tempo muito curto da história da Terra, têm aplicações limitadas. Estudando-se esses registros é possível reconstituir as condições climáticas do passado em extensas escalas de tempo, o que permite visualizar ciclos e padrões, que servem de base para projetar condições climáticas futuras, bem como anomalias. A Paleoclimatologia dedica-se ao estudo das condições climáticas que têm afetado o planeta em épocas anteriores à adoção de observações e registros sistemáticos e instrumentos, e para isso utiliza-se de registros paleoclimáticos encontrados na natureza.

As variações climáticas são resultado basicamente de processos que atuam em escalas de tempo distintas, e podem ser divididas em três categorias: oscilações de longo prazo (ocorrem em escalas de aproximadamente 10^6 a 10^7 anos), oscilações de curto prazo (em escalas de 10^4 a 10^5 anos) e aberrações (escalas de 10^3 a 10^4 anos) (Zachos *et al*., 2001). As variações climáticas de longo prazo são controladas por processos contínuos que atuam em amplas escalas temporais (condições-limites), basicamente condicionados pela tectônica global, como abertura ou fechamento de passagens oceânicas (Haug & Tiedemann, 1998; Lawver & Gahagan, 2003), geografia e topografia continentais (Ramstein *et al*., 1997; Hay, 1996) e concentração de gases do efeito estufa (Petit *et al*., 1999; Pearson & Palmer, 2006; Zachos *et al*., 2008). Uma vez que a tectônica é um processo contínuo e unidirecional, tais variações não são cíclicas, e se estendem ao longo de milhões de anos.

Oscilações climáticas cíclicas, em freqüências da ordem de 10^4 a 10^5 anos, são controladas basicamente por oscilações periódicas ou quase periódicas de três parâmetros orbitais, que constituem os Ciclos de Milankovich (Hays *et al*., 1976):

Excentricidade - oscila em períodos de 400 e 100 ka. Este parâmetro caracteriza a variação da forma da órbita da Terra ao redor do Sol, de elíptica (máxima excentricidade) a quase circular (excentricidade mínima). Essa variação altera a distância média entre o planeta e o Sol, mas seu efeito sobre a taxa de insolação é muito pequeno.

Obliquidade - oscila em períodos de 41 ka, e descreve a inclinação do eixo de rotação da Terra em relação ao plano da eclíptica, que varia entre 22,1º e 24,5º.Quanto maior o ângulo de inclinação do eixo, maior o contraste entre as estações, especialmente em altas latitudes.

Precessão – o ciclo precessional ocorre em função da rotação do eixo do planeta, e tem uma periodicidade de 26 ka. Contudo, é modulado pela excentricidade, resultando em sinais climáticos com periodicidade de 23 e 19 ka. Determina em que pontos ao longo da órbita irão ocorrer as estações, amplificando a sazonalidade em um hemisfério e reduzindo no outro.

2 – O clima na América do Sul entre o Pleistoceno Tardio e Holoceno

Diversos registros sedimentológicos, geomorfológicos e paleontológicos são indicativos das condições climáticas no continente sul-americano desde o final do Pleistoceno. Em resposta às oscilações climáticas relacionadas aos ciclos glaciais-interglaciais, o continente passou por marcantes alterações na paisagem e ecossistemas, que se refletem nos ambientes atuais.

O clima da América do Sul é fortemente condicionado por sua conformação geográfica e topografia. Os oceanos que cercam o continente exercem profunda influência sobre o clima, modulando flutuações extremas de temperatura e grandes diferenças meteorológicas entre verão e inverno. A porção norte está na área de influência de correntes oceânicas quentes, que chegam até 36ºS na margem atlântica e ao Equador na margem pacífica, o que resulta em forte assimetria latitudinal em grande escala. O extremo sul é influenciado pela Corrente Circum-Antártica (ACC); um ramo dessa corrente sobe pela costa atlântica, formando a Corrente das Malvinas; outro, de maior proporção, sobe pela costa pacífica, formando a Corrente de Humboldt. A Cordilheira dos Andes, com 8 mil km de extensão e entre 200 e 400 km de largura, tem o efeito de uma barreira climática, que mantém boa parte do interior do continente situada a leste da cordilheira isolada da influência do oceano Pacífico. Os principais componentes meteorológicos que afetam os padrões climáticos regionais são a Zona de Convergência Intertropical (ITCZ), os ventos alísios, o Anticiclone do Pacífico Sul (SPA), Anticiclone do Atlântico Sul (SAA) e o Anticiclone dos Açores (AA) (Iriondo, 1999).

Devido à conformação geomorfológica e topográfica, na América do Sul as únicas áreas sujeitas a cobertura por mantos de gelo durante os máximos glaciais foram as áreas do extremo sul do Chile e Argentina (da Patagônia à Terra do Fogo) e os picos montanhosos mais altos. A formação dessas coberturas teria sido condicionada principalmente pela disponibilidade de umidade (precipitação); devido ao ambiente mais seco, mesmo nos picos mais elevados dos Andes Bolivianos, com altitudes superiores a 5.500 metros, nunca se desenvolveram glaciares (Clapperton, 1993).

Os períodos glaciais ocorridos nas altas latitudes estão relacionados a episódios de intensa atividade eólica (aridez) nas baixas latitudes do Hemisfério Sul. Registros na Austrália, África e América do Sul mostram que fases de aridificação ocorreram entre 65 e 8 ka AP, com maior frequência entre 32 e 8 ka AP; entre 41 e 36 ka, nos três continentes é registrada redução na atividade eólica (Munyikwa, 2005). Na América do Sul episódios de aridificação são representados por dunas fósseis na Bacia do Rio Negro, Rio São Francisco e camadas de loess e areia na Região Pampeana da Argentina (Tatumi *et al.*, 2002; Oliveira, 1999). A intensa aridificação e deflação eólica observadas nos intervalos glaciais estão associadas aos efeitos combinados do clima antártico sobre a ACC e o sistema de ventos oriundos do Pacífico (westerlies). O maior resfriamento da Antártica durante os máximos glaciais, resultou no deslocamento do sistema ACC-westerlies em direção ao equador. Durante o estágio isotópico marinho (MIS) 4, entre 74 e 60 mil anos atrás, o deslocamento foi de aproximadamente 5º-6º, e no MIS , entre 24 e 11 mil anos atrás, em torno de 4º-5º; durante esses episódios a ACC teria atingido até 33º S de latitude. Durante os interglaciais, o aquecimento da Antártica teve efeito inverso, com a retração latitudinal em direção ao Pólo Sul do sistema ACC-westerlies (Kaiser *et al.*, 2005). Na costa chilena, os avanços do sistema tiveram como resultado a intensificação da precipitação e consequente expansão das florestas úmidas para o norte (Heusser *et al*., 2006).

No sul do Brasil ainda são poucos os estudos relativos às condições climáticas e ambientais do Quaternário. As principais contribuições nesse sentido vêm de estudos de palinomorfos obtidos em diversas localidades (Ledru et al., 1996; Behling, 2002; Behling et al., 2004; 2005; Leonhardt & Lorscheitter, 2010).

3 – Objetivos

Estudos feitos no sul da Planície Costeira do Rio Grande do Sul (PCRS) ao longo dos últimos anos têm levantado diversas questões relacionada aos registros sedimentares e fósseis aí encontrados:

- As variações faciológicas encontradas no sul da PCRS estariam relacionadas a condições climáticas distintas das atuais durante a deposição das unidades geológicas?
- Que condições climáticas estariam representadas nos depósitos sedimentares da PCRS?
- De que forma as variações climáticas poderiam ter influenciado os registros sedimentares encontrados?
- Quais mecanismos poderiam ter influenciado o clima durante o intervalo abordado?
- Como a fauna teria sido afetada pelas variações climáticas decorrentes dos ciclos glaciais?
- Como as variações nos ambientes observadas nos registros geológicos se relacionam com registros encontrados em outros locais?

Estas questões são bastante amplas e podem ser abordadas por diferentes ângulos, mas aqui buscou-se obter respostas a partir dos registros sedimentares e paleontológicos encontrados na área de estudo, que compreende basicamente os depósitos expostos ao longo das barrancas do Arroio Chuí.

O objetivo geral desta tese é analisar os registros geológicos e paleontológicos preservados no sul da Planície Costeira do Rio Grande do Sul (PCRS), a fim de identificar indicadores paleoclimáticos e avaliar como as variações climáticas do Quaternário exerceram influência sobre a evolução geológica e ambiental da região.

Espera-se com o cumprimento deste objetivo contribuir para a compreensão dos climas e ambientes do sul do Brasil no intervalo entre o Pleistoceno tardio e o Holoceno, avaliando como as oscilações do clima afetam o meio físico e biota e eventualmente gerando subsídios para prever como mudanças climáticas futuras podem influenciar a região.

4 – Área de estudo

A área definida para este trabalho está situada no extremo sul da PCRS (Figura 1). Nesta área, estão representados essencialmente três dos grandes conjuntos de sistemas deposicionais do tipo laguna-barreira que constituem os depósitos quaternários da PCRS (Villwock & Tomazelli, 1995). Os sistemas aí encontrados englobam dois de idade pleistocênica (Laguna-Barreira II e III) e o sistema holocênico (Laguna-Barreira IV). Cada um destes é caracterizado essencialmente por extensas barreiras arenosas que representam ambientes marinho raso e eólico costeiro; estas barreiras isolam os depósitos correspondentes aos sistemas lagunares, que atualmente são representados pela Lagoa Mirim (Lagunar II), banhados e o Arroio Chuí (Lagunar III) e Lagoa Mangueira e banhados associados (Lagunar IV).

O local escolhido para a realização dos estudos da tese foi o Arroio Chuí, localizado próximo à cidade de Santa Vitória do Palmar. O Arroio nasce no Banhado dos Canelões e flui pela planície formada entre as barreiras II e III, e que corresponde ao sistema Lagunar III. Até a década de 60, o arroio era um curso d’água mais largo e raso do que atualmente (Figura 2), mas em 1963 foi dragado para aprofundamento e modificação do curso com objetivos agrícolas. Durante as escavações do arroio, foram expostas camadas sedimentares ao longo das barrancas, que representam a evolução geológica deste sistema deposicional e contêm importantes registros paleontológicos (Paula Couto & Cunha, 1965; Lopes et al., 2009).

5 – Organização do trabalho

A tese foi elaborada na forma de artigos científicos integrados, conforme a resolução 002/98 do Programa de Pós-Graduação em Geociências da Universidade Federal do Rio Grande do Sul (PPGGEO-UFRGS). Os artigos que integram a tese incluem dois já publicados, e outros três submetidos, além de resumos de trabalhos referentes à tese apresentados em congressos.

O **Capítulo I** abrange basicamente o paleo-ambiente marinho, e consiste de três manuscritos submetidos. O primeiro, intitulado “THE SEA-LEVEL HIGHSTAND CORRELATED TO MARINE ISOTOPE STAGE (MIS) 7 IN THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL”, foi submetido aos **Anais da Academia**

Brasileira de Ciências. Nele é apresentada uma descrição da estratigrafia da fácies marinha exposta ao longo do Arroio Chuí, sua idade estimada, amplitude atingida pelo máximo transgressivo representado por estas fácies e correlação desta unidade com outros locais da costa brasileira.

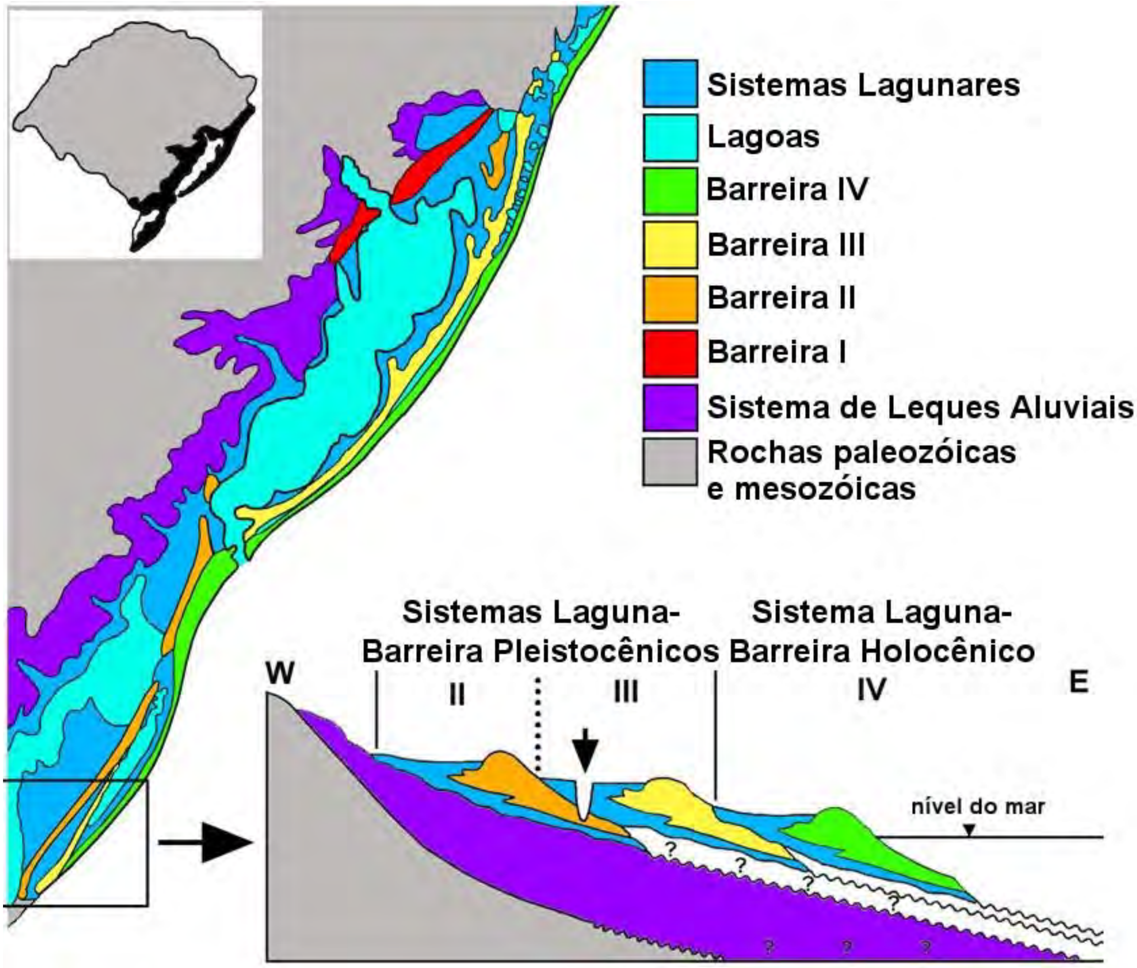

Figura 1 – Esquema dos sistemas laguna-barreira que constituem a PCRS; o retângulo indica a área de estudo, a seta vertical mostra a localização do Arroio Chuí.

Figura 2 – Aspecto do Arroio Chuí antes da dragagem (foto cedida por Jamil Pereira)

O segundo artigo, intitulado “A PLEISTOCENE MARINE MOLLUSCAN ASSEMBLAGE FROM THE SOUTHERN COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL”, foi submetido à **Revista Brasileira de Paleontologia**. Aqui é descrita a assembléia de moluscos fósseis encontrada na fácies marinha, seus aspectos tafonômicos, inferências relativas ao ambiente deposicional em que as conchas foram preservadas, e suas implicações paleo-climáticas.

O terceiro artigo, “ESR DATINGS ON PLEISTOCENE MAMMALS AND MARINE SHELLS FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL” foi aceito para publicação no **Quaternary International**; aqui são descritos os resultados de novas datações feitas em fósseis de mamíferos encontrados no arroio e da datação feita nas conchas encontradas na fácies marinha.

Este capítulo inclui ainda o resumo “FORAMINÍFEROS EM SEDIMENTOS PLEISTOCÊNICOS NO SUL DA PLANÍCIE COSTEIRA DO RIO GRANDE DO SUL”, apresentado na forma de pôster durante a reunião anual da Sociedade Brasileira de Paleontologia (PALEO 2012), onde é descrita a composição taxonômica da assembléia de foraminíferos encontrada junto com as conchas da fácies marinha, bem como suas implicações paleo-climáticas.

O **Capítulo II** abrange basicamente o paleo-ambiente terrestre, e inclui os artigos “BIOSTRATIGRAPHY OF THE PLEISTOCENE FOSSILIFEROUS DEPOSITS OF THE SOUTHERN BRAZILIAN COASTAL AREA”, publicado no **Journal of Mammalian Evolution** n° 20, páginas 69 a 82, e “LATE MIDDLE TO LATE PLEISTOCENE PALEOECOLOGY AND PALEOENVIRONMENTS IN THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL, FROM STABLE ISOTOPES IN FOSSILS OF *TOXODON* AND *STEGOMASTODON*” publicado na **Palaeogeography, Palaeoclimatology, Palaeoecology** n° 369, páginas 385 a 394. O primeiro apresenta questões relativas à posição estratigráfica e distribuição biogeográfica dos mamíferos pleistocênicos encontrados no Arroio Chuí, e possíveis correlações entre a composição da fauna e as variações climáticas. No segundo é apresentada uma reconstrução dos tipos de vegetação consumida e composição isotópica da água ingerida pelos mamíferos *Toxodon* e *Stegomastodon* (= *Notiomastodon*), a partir da qual foi inferido o tipo de ambiente em que esses animais viveram.

Os dados preliminares relativos à estratigrafia foram apresentados no VIII Congresso da Associação Brasileira de Estudos do Quaternário (ABEQUA) e publicados no resumo expandido “GEOLOGICAL AND ENVIRONMENTAL EVOLUTION OF LAGOON

SYSTEM III IN THE SOUTHERNMOST COASTAL PLAIN OF RIO GRANDE DO SUL STATE”. Aqui são apresentadas informações referentes à evolução geológica dos depósitos situados acima da fácies marinha observada no arroio. A seqüência deposicional mostra paleossolos e sistemas fluviais na base, sobrepostos por uma camada de silte arenosos com nódulos carbonáticos, indicando clima progressivamente mais seco.

Outras inferências paleo-ambientais feitas a partir de fósseis de mamíferos encontrados no Arroio Chuí, descritos nos artigos “CHINCHILLIDAE AND DOLICHOTINAE RODENTS (RODENTIA, HYSTRICOGNATHI, CAVIOMORPHA) FROM THE LATE PLEISTOCENE OF SOUTHERN BRAZIL” (Anexo 1) publicado em 2011 na Revista Brasileira de Paleontologia, no. 14, volume 3, páginas 229 a 238 e “NEW REMAINS OF LATE PLEISTOCENE MAMMALS FROM THE CHUÍ CREEK, SOUTHERN BRAZIL” (Anexo 2), publicado em 2012 na Revista Brasileira de Paleontologia, no. 15, vol. 2, páginas 228 a 239. Os mamíferos que tem implicações paleo-ambientais são *Lagostomus* cf. *maximus*, cf. Dolichotis (roedores) e *Catagonus stenocephalus* (porco selvagem), indicadores de ambientes semi-áridos; *Myocastor coypus* (ratão-do-banhado, indicador de ambientes permanentemente úmidos); *Eremotherium* cf. *laurillardi* (preguiça gigante característica da região intertropical das Américas). O artigo do anexo 2 ainda descreve fosseis de cervídeos do gênero *Antifer*, que se extinguiu na Região Pampeana da Argentina há aproximadamente 120 mil anos mas sobreviveu até o final do Pleistoceno no Rio Grande do Sul Uruguai e norte do Chile.

6 – Metodologia

Os dados apresentados nesta tese foram coletados entre 2009 e 2011, através de trabalhos de campo no Arroio Chuí, feitos em parceria com o Museu Coronel Tancredo Fernandes de Mello, de Santa Vitória do Palmar. Foram feitas diversas saídas de um dia de duração, e mais duas saídas com permanência em acampamento de sete dias em 2010 e 2011, cobrindo aproximadamente 10 km da extensão do arroio. Os trabalhos de campo envolveram levantamentos estratigráficos para visualização da faciologia das barrancas, medições da espessura das camadas e coletas de fósseis e de sedimentos para análises sedimentológicas e datações.

Cada perfil foi aberto, descrito e amostras de sedimento retiradas, bem como fósseis que eventualmente foram encontrados. As análises granulométricas e morfoscópicas foram feitas no Laboratório de Geologia e Paleontologia da FURG; os fósseis encontrados foram tombados no museu.

As análises isotópicas e datações por TL foram feitas em parceria com Ana Maria Ribeiro e Jorge Ferigolo, do Setor de Paleontologia do Museu de Ciências Naturais da Fundação Zoobotânica do Rio Grande do Sul. As amostras de esmalte dentário de mamíferos para análises isotópicas foram processadas no Núcleo de Estudos Geoquímicos – Laboratório de Isótopos Estáveis (NEG-LABISE) da Universidade Federal de Pernambuco (UFPE). As datações por TL foram feitas na empresa Datação Comércio e Serviços, de São Paulo.

As datações por ESR foram feitas em parceria com o laboratório de Física da USP de Ribeirão Preto e com o Instituto de Pesquisas Energéticas e Nucleares (IPEN) da USP de São Paulo.

A identificação dos fósseis apresentados na tese foi feita por consultas a descrições publicadas e comparação com materiais de coleções osteológicas, com apoio de especialistas.

7 - Conclusões

- A estratigrafia, icnofósseis e fósseis de moluscos encontrados na fácies marinha exposta ao longo do Arroio Chuí indicam ambiente marinho raso, sob condições de elevada sedimentação. A ausência de variações faciológicas sugere agradação da costa, seguida de regressão marinha.

- Datações por termoluminescência (TL) em sedimentos e ressonância do spin do elétron (ESR) nas conchas da fácies marinha indicam que a Barreira II teria sido formada durante o MIS 7, mais precisamente durante o sub-estágio 7e, há aproximadamente 220-240 mil anos.

- O nivelamento altimétrico feito no arroio mostra que a amplitude máxima da transgressão que formou a Barreira II teria atingido aproximadamente 10 metros acima do atual, mas existe a possibilidade de essa amplitude ter sido influenciada por neotectônica posterior.

- A presença na assembléia fossilífera de moluscos que atualmente vivem apenas em áreas mais quentes ao norte do Rio Grande do Sul, e as espécies de foraminíferos associadas, indicam condições oceanográficas mais quentes durante o Pleistoceno médio. Condições similares inferidas a partir de fósseis da última transgressão marinha sugerem que os máximos transgressivos podem ser caracterizados como hipsitérmicos.

- A transição entre a fácies marinha e o ambiente terrestre é caracterizada pela presença de paleossolos e sistemas fluviais, estes provavelmente formados sob condições de elevada pluviosidade correlacionada a um período de baixa insolação (= baixa amplitude da precessão) há aproximadamente 220 mil anos atrás. Um sistema fluvial erosivo datado por TL em aproximadamente 173 mil anos também coincide com um período similar, reforçando que a precipitação no sul do Brasil é controlada basicamente pela precessão, como já inferido a partir de estudos em espeleotemas.

- A assembléia fóssil encontrada no Arroio Chui abrange o período entre 226 e 34 mil anos atrás, como indicado pelas datações por ESR. A escassez de fósseis mais antigos que 50 mil anos pode resultar da destruição desses restos devido a retrabalhamento pós-deposicional, condicionados por episódios de reativação fluvial durante fases úmidas.

- A presença na assembléia de mamíferos característicos da Fauna Pampeana (temperada) como *Antifer* e *Doedicurus*, e de táxons provenientes da Fauna Brasiliana (intertropical) como *Eremotherium*, indica migrações latitudinais das zonas climáticas. Durante fases mais frias (glaciais) a zona temperada teria migrado ate 750 km para norte, como inferido também a partir de registros polínicos no sudeste e sul do Brasil, enquanto durante fases quentes (interglaciais e interestadiais) a zona subtropical teria migrado para sul.

- Os fósseis de *Catagonus stenocephalus*, *Lagostomus* cf. *maximus* e Dolichotis sp. indicam clima semi-árido, provavelmente correlacionado ao último máximo glacial (LGM), como indicado também pela deposição de grande quantidade de silte.

- Análises de isótopos de carbono (^{13}C) em dentes dos mamíferos *Toxodon* e *Stegomastodon* (= *Notiomastodon*) coletado no Arroio Chui indicam que a vegetação na época em que esses animais viveram era composta por gramíneas, arbustos e possivelmente matas de galeria, uma paisagem semelhante ao cerrado atual.

- Os valores de isótopos de oxigênio (^{18}O) encontrados em *Stegomastodon* indicam que esses animais são bons indicadores da composição isotópica da água meteórica (proveniente da precipitação). Os valores mais altos observados em *Toxodon* sugerem que estes animais não teriam hábito semi-aquático similar ao dos hipopótamos, como originalmente proposto.

- A sedimentologia indica que o clima regional se tornou semi-árido, como indicado pela elevada proporção de silte e presença de nódulos carbonáticos, que são formados sob condições de precipitação inferiores a 500 mm/ano. Esta fase seca teria ocorrido após aproximadamente 34 mil anos (inferido a partir das datações nos dentes de mamíferos), indicando correlação com o ultimo máximo glacial (LGM), ocorrido entre 25 e 18 mil anos atrás, aproximadamente.

- Os registros geológicos e paleontológicos apresentados e suas implicações paleoclimáticas mostram que as condições ambientais no sul do Brasil, tanto em terra quanto no oceano, têm sido controladas ao longo do Quaternário (ao menos entre o Pleistoceno tardio e Holoceno) pelas variações latitudinais das zonas climáticas, influenciadas pelos padrões orbitais (ciclos de Milankovitch), especialmente a Precessão e Obliqüidade.

- Essas variações têm afetado diretamente a distribuição da fauna e flora no sul do Brasil (e provavelmente no norte do Uruguai, da Argentina e do Chile), proporcionando a dispersão para o norte de organismos pampeanos / patagônicos durante fases mais frias e a dispersão para o sul de organismos brasilianos durante fases mais quentes.

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CAPITULO I - O PALEO-AMBIENTE MARINHO

Parte 1 - Artigo “THE SEA-LEVEL HIGHSTAND CORRELATED TO MARINE ISOTOPE STAGE (MIS) 7 IN THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL”, submetido aos **Anais da Academia Brasileira de Ciências**.

Parte 2 – Artigo “A PLEISTOCENE MARINE MOLLUSCAN ASSEMBLAGE FROM THE SOUTHERN COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL”, submetido à **Revista Brasileira de Paleontologia**.

Parte 3 - Artigo “ESR DATINGS ON PLEISTOCENE MAMMALS AND MARINE SHELLS FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL”, aceito para publicação no **Quaternary International**.

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THE SEA-LEVEL HIGHSTAND CORRELATED TO MARINE ISOTOPE STAGE (MIS) 7 IN THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL

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THE SEA-LEVEL HIGHSTAND CORRELATED TO MARINE ISOTOPE STAGE (MIS) 7 IN THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL

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ABSTRACT

The coastal plain of the Rio Grande do Sul state, in southern Brazil, includes four barrier-lagoon depositional systems formed by successive Quaternary sea-level highstands, correlated to marine isotope stages (MIS) 11, 9, 7 and 1, but precise datings are lacking. Here is described a marine highstand older than 125 ka BP, based on the stratigraphy, ages and fossils of the marine facies of a coastal barrier. This facies is mostly covered by younger sediments, but is well-exposed along the banks of Chuí Creek. It is composed of fine, well-sorted quartz sand with ichnofossils *Ophiomorpha nodosa* and *Rosselia* sp., and shell concentrations. The sedimentary record indicates coastal aggradation, followed by sea-level fall and progradation of the coastline. Thermoluminescence (TL) and electron spin resonance (ESR) ages from sediments, shells and mammalian fossils point to an age of ~230 ka for the end of this marine transgression, thus correlating it to MIS 7 (substage 7e). Altimetric data point to a maximum amplitude of some 10 ± 1 meters above present-day mean sea-level, but it is possible that neotectonics affected this record. Paleoclimatic conditions at the time of the highstand and correlations with other deposits in the Brazilian coasts are also discussed.

Keywords: Coastal Barrier; Chuí Creek; MIS 7; Pleistocene; Chronostratigraphy

1. INTRODUCTION

The Quaternary System encompasses the last 2.58 million years of Earth's history, and has been characterized by glacial-interglacial cycles, represented mostly by the waxing and waning of ice sheets, most notably in the Northern Hemisphere (Pillans and Naish, 2004; Head et al., 2008; Gibbard et al., 2010). Besides affecting terrestrial environments due to changes in patterns of atmospheric circulation and moisture, latitudinal displacement of ecosystems and cooling, another important effect of these cycles has been the sea-level (eustatic) oscillations. Although regional isostasy, faulting and uplifting in coastal areas also play an important role in relative sea-level changes, the oscillations are directly linked to variations in the volume of the ice sheets, thus variations in the ratio of oxygen isotopes ($^{16}O/^{18}O$) in microfossils and gases recovered from deep-sea and ice cores are used as proxies for changes in sea-levels, by assuming a relationship between these ratios and ice volumes.

Although recorded in coastal areas all around the globe since the XIX century (e.g. Darwin, 1846), direct, reliable and well-preserved indicators of past sea level highstands older than the Pleistocene marine transgression of ~125 ka BP, correlated to marine isotope stage (MIS) 5, are relatively scarce throughout the globe. While oxygen isotope curves obtained from benthic foraminifera are used as indirect evidence of sea level oscillations through correlation with past ice volumes (Imbrie et al., 1984; Pisias et al., 1984, Martinson et al., 1987), direct records in coastal areas are represented by paleo-shorelines that contain datable geomorphological features such as raised terraces, wave-cut notches and aeolianites (Pirazzoli et al., 1991; Hearty and Kinder, 1995; Barreto et al., 2002) and other materials such as corals, vermetids or speleothems (Gallup et al., 1994; Angulo et al., 2006).

In the Brazilian coast, the Holocene highstand of ~6-5 ka BP (MIS 1) is well-represented by several records, despite of some discrepancies regarding its timing and amplitude (Martin et al., 2003; Angulo et al., 2006). Good records of the transgression correlated to MIS 5 are found in some areas (Poupeau et al., 1988; Suguio et al., 2003, 2011; Tomazelli and Dillenburg, 2007) but the situation is complex for older transgressive events; so far only the northeastern Brazilian coast has provided features recognized as formed by the marine transgression during MIS 7 (Barreto et al., 2002; Suguio et al., 2011). In the Coastal Plain of Rio Grande do Sul state (CPRS), in southern Brazil, records of sea level oscillations prior to MIS 5 were reported from microfossils in drilling cores (Closs, 1970; Carreño et al., 1999) and geomorphological features (Poupeau et al., 1988; Villwock and Tomazelli, 1995; Tomazelli et al., 2000).

The absolute chronologies and amplitudes of past sea-level oscillations in the coast of Rio Grande do Sul, however, are not well defined yet. This problem arises from the fact that most of the geomorphological units formed by sea-level highstands represent the aeolian facies of coastal barriers; these deposits are usually reworked by erosion, aeolian reactivation and/or vegetation growth. Besides, the CPRS is composed essentially of siliciclastic sediments, devoid of consolidated structures that could contain paleo sea-level indicators such as vermetids or erosion notches; thus, most reliable sea-level indicators would be found in well-preserved deposits representing the marine facies of the barrier systems. However, the marine facies of the barrier systems are usually covered by younger sediments and coastal lakes. So far, the ~125 kyr-old Barrier System III is the only Pleistocene unit whose marine facies is well-preserved and exposed (Tomazelli and Dillenburg, 2007).

Here is presented a description of the marine facies of the Barrier System II, from outcrops found in the southern sector of the CPRS, with information regarding the amplitude and chronology of the marine highstand that was responsible for the origin of this depositional system. Correlations with other deposits and paleoclimatic inferences from fossils and sedimentary features are also presented.

2. GEOLOGICAL SETTING

The CPRS (Figure 1) is located in the southernmost portion of the Brazilian coast. This geomorphological unit is some 620 km-long and up to 100 km-wide, located between the latitudes 29°18’31”S and 33°43’17”S, and it is the uppermost portion of the Pelotas Basin, the southernmost marginal basin of the Brazilian coast. This basin is composed of terrigenous siliciclastic sediments eroded from older geological units located landwards, accumulated in the coastal area since the split between South America and Africa in the Late Cretaceous; its maximum thickness is of some 10,000 meters (Closs 1970; Bueno et al. 2007; Barboza et al. 2008). During the Quaternary, sea-level oscillations correlated to glacial cycles reworked the uppermost sediments of the Pelotas Basin, as evidenced by facies changes and microfossil assemblages recovered from drilling holes (Closs 1970; Carreño et al. 1999).

The first systematic geological survey of the CPRS was presented by Delaney (1965). That author followed the classical lithostratigraphy and proposed the name “Itapoã Formation” for the aeolian deposits found along the coastal plain, while the marine deposits were named “Chuí Formation”; these units were considered of Quaternary age because they overlie the Tertiary

"Graxaim Formation". During the 1980s, new geological surveys led to a revision of the geology of the CPRS, and it became clear that the units grouped together as "Itapoã" and "Chuí" formations were in fact several distinct units deposited during different time intervals in response to distinct marine transgressions.

The new surveys led to the replacement of the classic lithostratigraphic scheme of Delaney (1965) by the concept of depositional systems formed by chronocorrelated facies and facies associations (Tomazelli and Villwock, 2005). Following this scheme, the CPRS is divided in two major depositional systems: an Alluvial Fans System (the former "Graxaim Formation") of Miocene-Pliocene age (Closs, 1970) and four barrier-lagoon depositional systems, each one correlated to a sea level highstand during a Quaternary interglacial epoch (Villwock and Tomazelli, 1995). The Pleistocene marine highstands are recognized mostly by the aeolian facies of the barrier systems; deposits that represent the marine facies of these systems are usually covered by younger sediments. Precise indicators of paleo sea-level highstands are scarce in these coastal barriers; the only reliable records of Pleistocene sea levels known so far are ichnofossils *Ophiomorpha nodosa* preserved some 5 to 7 meters a.s.l. in shallow marine facies of the Barrier System III (Tomazelli and Dillenburg, 2007).

The southernmost portion of CPRS is dominated by two Pleistocene (II and III) and one Holocene (IV) barrier-lagoon systems. Each system was chronologically correlated by Villwock and Tomazelli (1995) with the calibrated δ^{18}O curves of Imbrie *et al.* (1984), thus attributing an age of ~325 ka (MIS 9) for system II, ~125 ka (MIS 5) for system III and ~6 ka (MIS 1) for system IV. TL datings on sandstones exposed on the shoreline beneath the Holocene sediments of the Barrier IV System provided age of 109 ± 7.5 ky BP, reinforcing the proposed age for the Barrier System III (Buchmann and Tomazelli, 2003).

3. THE BARRIER SYSTEM II

The Barrier System II is well-represented along the southern sector of the CPRS, stretching almost continuously for more than 200 km in the same SW-NE orientation of the coastline. The only important interruption is in the area of Taim, where a negative gravimetric anomaly suggests the existence of deformation features in the underlying bedrock, formed during the opening of the South Atlantic (Rosa et al., 2007; 2009). Only a small portion of this barrier is preserved in the northern area of the CPRS (Poupeau et al., 1988; Villwock and Tomazelli, 1995).

The aeolian deposits of this system reach up to 25 meters above present sea-level and are composed of siliciclastic, well-sorted fine to medium quartz sand with feldspars, iron oxide crusts and nodules, diagenetic clays and small amounts of organic matter. The primary sedimentary structures have been obscured due to diagenetic processes, but the physical properties of the grains clearly indicate aeolian deposition (Villwock and Tomazelli, 1995).

The low topographic area located landwards of the barrier is occupied by a large water body (Mirim Lake). The barrier gently dips seawards, where it is covered by younger sediments of the Barrier-Lagoon System III. The only area known so far where the marine facies of the barrier outcrops is along the Chuí Creek, near the town of Santa Vitória do Palmar (Figure 2a). This fluvial system flows in a NE-SW direction until the town of Chuí, where it turns SE following the Chuí faulting zone. The creek was a shallow water course that was further deepened in the early 1960s to drain the surrounding wetlands and provide area for agriculture.

3.1. Stratigraphy of the Marine Facies

The deepening of the creek exposed marine sediments at the base of the banks; these are overlaid by a terrestrial sequence formed by paleosoils, aeolian and fluviolacustrine facies that contain remains of Pleistocene mammals (Figure 2b, c; Lopes et al., 2009). The first stratigraphic description of the deposits exposed along Chuí Creek was presented by Soliani (1973), who correlated the marine sediments to the “Chuí Formation” of Delaney (1965) and assigned the overlying fossil-bearing strata to a new unit which he called “Santa Vitória Formation”.

Under the new concept adopted since the 1980s, the marine sediments exposed along the creek are recognized as the marine facies of the Barrier II. These sediments constitute the uppermost portion of the highstand systems tract of the Barrier System II (HST_2), while the overlying sediments are part of the Lagoon System III, represented by fluvial and aeolian facies and paleosoils, according to the stratigraphic scheme proposed by Rosa (2012).

Some 2 meters of this facies outcrop above the creek bed; drillings with hand auger indicate that it is more than 10 meters in thickness. At least three types of contact between the marine facies and the overlying terrestrial sediments have been identified (Figure 3). One is characterized by paleosoils developed directly on top of the marine facies, with root traces, mud-filled root cavities and usually mottled by iron oxide (Figure 3a); sometimes aeolian deposits are also found on this interval (see Figure 3c). Other type is fluvial-concordant (Type I, Figure 3b), characterized by massive sand layers containing mud intraclasts and mammalian remains; the absence of erosive surfaces indicates a gradual transition from marine to fluvial facies. This type of fluvial system was probably established when regional base level was still high, before sea-level had fully retreated after the marine highstand. The third type of contact is fluvial erosive (Type II, Figure 3c), found along the banks as 30 to 40 cm-thick dark brown sand lenses that erode into the underlying marine sediments, contain vertebrate fossils and mud intraclasts, and are interpreted as oxbow lakes (Lopes et al., 2009). At least five of these lenses have been observed so far along the banks, and the erosive contact with the underlying marine sediments indicate that this type of fluvial system was formed at a time when the regional base level was lowered, i.e., when sea-level had fully retreated. One dating by thermoluminescence (see below) reinforces this interpretation.

The marine facies is composed of fine, well-sorted siliciclastic sand with some amounts of biogenic carbonate, heavy minerals, muscovite and some minerals of terrigenous origin. Primary sedimentary structures are well-represented by cross and parallel stratifications (Figure 3b, c). The presence of several erosion surfaces, ichnofossils and some shell concentrations (see below) suggest the occurrence of storm events. The sedimentary structures and ichnofossil content indicate that this facies was deposited under similar conditions (upper shoreface-foreshore) of the Facies B described from the Barrier System III (Tomazelli and Dillenburg, 2007).

The ~2 meter-thick marine layer exposed along the banks of the creek clearly indicates a sea-level rise, but from the base to the top portion of the layer there are no visible faciological changes. In a shallow slope coast such as the one of Rio Grande do Sul (between 0.03° and 0.08°; Dillenburg et al., 2009), a sea-level rise would result in increased depth and lateral migration of facies, thus lower shoreface (finer) sediments would be deposited on top of upper coarser sediments of the shoreface. The absence of fine sediments in the marine facies and the persistence of shallow marine conditions throughout the exposed portion of the sequence, however, show that there were no faciological changes despite of the sea-level rise. This suggests that sea-level rise was accompanied by high sedimentation rates, which resulted in aggradation of the coastline, followed by sea-level fall and progradation.

3.2. Fossil content

Until recently, only ichnofossils have been found in the marine facies (Lopes et al., 2001). The most conspicuous ichnofossil is *Ophiomorpha nodosa*, consisting of pellet-lined vertical shafts and horizontal galleries (Figure 3d), produced by thalassinidean crustaceans. This ichnofossil is regarded as an indicator of shallow marine conditions (Frey et al., 1978; Pollard et al., 1993), and is also common in the marine facies of the Barrier System III (de Gibert et al., 2006; Tomazelli and Dillenburg, 2007).

Other type of ichnofossil is *Rosselia* sp. (Figure 3e), produced by terebellid polychaetes in shallow marine settings (Nara, 2002). These traces are conical-shaped vertical galleries, usually nested within each other. This ichnofossil is usually spindle-shaped, but the conical shapes of those found in Chuí Creek indicate truncation by storm events. Both *Ophiomorpha* and *Rosselia* are found from the lower to the upper level of the marine facies. Other smaller galleries have not been identified, and have been probably produced by other small invertebrates (Figure 3c).

The only body fossils found so far in the marine facies consist of molluscan shells, ostracod carapaces and foraminiferal tests, forming at least four densely-packed concentrations (Lopes and Simone, 2012). These concentrations consist of marine, mostly shallow-living infaunal bivalves, and include complete, well-preserved specimens and small, rounded and unidentifiable fragments. Because the four concentrations outcrop at the same stratigraphic position, contain essentially the same taxa and exhibit the same pattern of preservation, it is assumed that they represent a single isochronous taphocoenosis (Lopes and Simone, 2012). The association between complete shells, including articulated bivalves and ostracodes, and smaller, much abraded fragments, seems to indicate that a storm event was responsible for the deposition of this assemblage. Vertical shafts of *O. nodosa* have been observed crossing one of the shell concentrations.

The ostracods have not been described yet, but the foraminifera include mostly *Ammonia beccari* forma tepida, *Buccella peruviana* and *Elphidium discoidale*, besides few individuals of other genera (Lopes and Bonetti, unpublished data).

3.3. Timing and amplitude of the marine highstand

As an attempt to establish a more precise chronology for this marine highstand, fossil shells and mammalian remains were subject to dating by electron spin resonance (ESR), and sediments extracted from the marine and overlying terrestrial beds exposed along the creek were dated using thermoluminescence (TL). The only absolute ages obtained so far for the Pleistocene deposits of the CPRS are from the Barrier System III (Poupeau et al., 1988; Buchmann and Tomazelli, 2003).

The first ESR ages for mammalian fossils from Chuí Creek provided ages of 226 ± 35, 42 ± 3, 38 ± 2 and 34 ± 7 thousand years (Lopes et al., 2010). The ~226 kyr-old sample was collected at the lowermost portion of the fossil-bearing layer, just above the marine sediments, and its age, much older than previously estimated (e.g. Lopes et al., 2009) raised the question of whether the marine facies below could represent a transgression younger than MIS 9 (about 325 kyr BP), which was originally proposed by Villwock and Tomazelli (1995).

As an attempt to test this assumption and refine the regional chronostratigraphy, four sediment samples were collected for age determination using TL dating. One sample was collected from the shallow marine facies, about 1 meter below the marine-continental transition (Figure 4a), and one other was extracted from fossil-bearing aeolian sediments located ~1 meter above, at the basis of the continental sequence (Figure 4b). The two other samples were also collected from the continental unit, but in different points along the banks. One was extracted from a fossiliferous dark sand lens which represents one fluvial-erosive facies (Figure 4c), and the other was collected from paleosoils positioned some 0.5 m above the top of the marine facies (Figure 4d).

The TL ages were determined at Datação Comércio e Prestação de Serviços Ltda. (São Paulo, Brazil) using the multiple aliquote regeneration (MAR) protocol. The sediments from the shallow marine facies provided an age of 235.5 ± 23.5 kyr BP, and the sediments collected near the mammalian fossils were dated on 214 ± 21 kyr BP. The sample from the fluvial sand lens was dated on 173 ± 22 kyr BP, while the sample from the paleosoil was dated on 132 ± 18 ky BP, respectively (Figure 4).

In addition to the TL datings, fifteen molluscan shells, plus other six mammalian teeth from the fluvial facies were also selected for dating using ESR. The shells were collected from three of the concentrations at the lower portion of the marine facies, and a mean age of 224 ± 24.6 ka was obtained (Lopes et al., unpublished data). This age is younger than the 'real' age due to the high Uranium concentrations observed in several specimens; considering that ~224 ka should be considered the minimum age of these shells, an estimated age closer to ~235-240 kyr BP, within the error margin, would be consistent with the TL ages obtained from the overlying sediments. This estimate is consistent with the oceanographic conditions indicated by the taxonomic composition of the molluscan assemblage (see below). The mammalian teeth provided ages between 80±10 kyr and 42±3 kyr, consistent with the previous ESR datings (Lopes et al., 2010).

The altimetric data were obtained with Total Station, using as reference a nearby geodetic reference level (RN1968U, 33°36'03"S / 053°19'54"W), complemented by digital elevation models of the Shuttle Radar Topography Mission (SRTM). The results show that the contact between the marine and continental sequences observed along the creek (see Figure 2) is positioned some 9.5 meters above mean sea-level (a.s.l.). Subsurface features detected with ground-penetrating radar (GPR) surveys between the Barrier Systems II and III show that the height of this contact varies between ~12 and 8,5 meters a.s.l. (Rosa, 2012), thus, a mean amplitude of some 10 ± 1 meters a.s.l for this record of the marine highstand seems reasonable.

4. DISCUSSION

4.1. Amplitude of the transgression

The marine facies of the Barrier System II described here is the first paleo sea-level indicator older than MIS 5 with good stratigraphic control and associated datings found in the CPRS. The obtained data improve the estimates for the late Pleistocene-early Holocene sea-level curve for southern Brazil (Figure 5). The estimated amplitude is of some 7±1 m a.s.l for the MIS 5 highstand (Tomazelli and Dillenburg, 2007), and of 4±1 m for the Holocene highstand (Martin et al., 2003; Angulo et al., 2006; Caron, 2007). Although Villwock and Tomazelli (1995) estimated amplitudes between 18 and 24 meters a.s.l for this transgression, based on terraces cut along the western margin of Mirim Lake and Patos Lagoon, the sedimentary record suggests a lower amplitude; thus it is possible that those terraces represent an older marine transgression.

A comparison among paleo sea-level records found around the globe show that estimates of the amplitude of highstands during MIS 7 are highly variable (Table 1), but are below the values found for the Barrier System II. While some data indicate that the sea level during that interval did not reach amplitudes comparable to present mean sea-level (Dutton et al., 2009; Bard et al., 2002; Schellmann and Radtke, 2004), other records indicate sea levels equal or higher than the present one (Bezerra et al., 1998; Vesica et al., 2000). This variability is likely to be caused by different dating methods employed (U/Th series, ESR), by differences among dated materials (corals, vermetids, shells, sediments) and by the tectonic history of each site, as is the case for Holocene deposits in northeastern Brazil (Barreto et al., 2002; Suguio et al., 2011). Moreover, it shows that it is not possible to establish a single global sea-level curve for any specific time interval based solely on stratigraphic records.

The $^{16}O/^{18}O$ ratio ($\delta^{18}O$) obtained from tests of benthic foraminifera have been used as a proxy for global sea-levels because the isotopic composition of ocean water is considered to be covariant with ice volumes (Shackleton, 1967; Shackleton and Opdyke, 1973; Imbrie et al., 1984; Martinson et al., 1987). This relationship, however, is not straightforward, because the isotopic composition of the tests is also affected by ocean water temperature, salinity and isotopic composition (Goy et al., 2006; Siddal et al., 2007). The isotopic composition of the ice caps may vary due to regional fluctuations of isotopically heterogeneous glaciers or to increase in size and elevation of the ice sheets; the $\delta^{18}O$ signal of these ice masses is transferred to seawater when they melt at the end of glacial phases or when they collapse due to instability (Mix and Ruddiman, 1984; Berger, 2008). This implies that the collapse of an ice sheet with high $\delta^{18}O$ values during an interglacial may result in several meters of marine transgression and still produce an isotopic signal similar to that observed during glacial times (and lower sea-levels). This could explain (at least in part) the apparent discrepancies between sea-levels estimated from isotopic values and those inferred from stratigraphic records.

Nevertheless, the oxygen isotope curves are regarded as reliable indicators of the timing of marine highstands/lowstands. The available curves show that MIS 7 is characterized by three substages, 7e, 7c and 7a, from older to younger (Imbrie et al., 1984), each one marked by an isotopic event peak (7.5, 7.3 and 7.1, respectively). The curves show the highest peaks usually occur at the beginning of the interglacials (Figure 6), and are followed by progressive fall punctuated by minor oscillations (Hodell et al., 2000). Although sea-level variations seem to mirror this pattern, the amplitude of the highstands are influenced not only by variations in ice volume, but probably also by the isostatic response of the shelf to increasing water load, and will be a function of mantle rheology, the amount and rate of meltwater discharged into the oceans and of the coastline geometry (Lambeck et al., 2012).

The eastern South America coastline is a passive margin, characterized by trailing-edge coasts, thus considered stable in terms of large-scale tectonics. Nevertheless, there are evidences of tectonic processes related to the opening of the Atlantic Ocean during the Tertiary and possibly during the Quaternary. The most conspicuous evidences of neotectonics are found in the southeastern and northeastern portions of the Brazilian coast (Suguio and Martin, 1996; Bezerra et al., 1998; 2003; Barreto et al., 2002), where deposits correlated to MIS 7c and positioned between 1.3 and 7.5 meters a.s.l (lower than the 11 to 20 meters a.s.l. terraces of MIS 5) are considered to represent downfaulted blocks. Although Delaney (1962) proposed that the coastal barriers of Rio Grande do Sul state have been formed by vertical tectonic movements, the southern Brazilian coast has been regarded as tectonically stable, which favored the development of the large barrier-lagoon systems in response to the Quaternary sea-level oscillations (Villwock and Tomazelli, 1995).

Fonseca (2005) reported some deformations and microfaultings in deposits of the Barrier System II in the northern sector of the CPRS, and regarded these features as evidence of neotectonics. Such features, however, have not been observed so far in Barrier System II deposits in the southern portion of the coastal plain.

Despite of the apparent absence of features indicative of neotectonic processes on the surface, some features on the underlying bedrock have the potential to influence the coastal tectonics. The most important tectonic feature in the CPRS is the Pelotas Fault that runs in a NE-SW direction beneath Patos Lagoon and Mirim Lake (see Figure 1). In the area of Mirim Lake, the fault is considered normal with a vertical component to SE, but there are no reliable data regarding this (Saadi et al., 2002). Other subsurface features in the southern CPRS include the E-W negative gravimetric anomaly at Taim and the positive E-W to NW-SE Mirim Lake Anomaly (Rosa, 2009). The Taim Anomaly is related to sediment-filled fault system, while the Mirim Lake Anomaly is related to fractures filled by Mesozoic magmatic rocks. If these fractures have been reactivated during Quaternary times, then it seems possible that the southern sector of the CPRS has been uplifted along the Pelotas Fault, which could explain the relative absence of deposits correlated to the Barrier System II in the central and northern sectors of the plain.

Besides local tectonics, another possible explanation for the uplifting involves large-scale processes affecting the South American plate. The westwards movement of the plate would result in crustal thickening and vertical thrusting and uplifting along the eastern coast of South America due to horizontal compression (Pedoja et al., 2011). Those authors also observed that uplift rates estimated from deposits correlated to MIS 5 decrease from south to north, which could be related to differences in elastic thickness between the Patagonian Massif and the Brazilian Shield. By assuming an altitude of 6 to 8 m a.s.l. for the highstand of MIS 5e in Rio Grande do Sul (Tomazelli and Dillenburg, 2007) an estimated uplift rate of 0.06 mm/yr is obtained; if this value is extrapolated for MIS 7 (considering an age of ~230 ka for the maximum highstand, see below) it would result in an amplitude of ~13-14 meters a.s.l., higher than the observed record. This implies that if the southern Brazilian coast has been subject to uplifting since the middle-late Pleistocene, the uplifting rates have varied through time.

Most paleo sea-level records indicate that the amplitude of the MIS 5 highstand was close to that of MIS 7. Along the Argentinean coast of Patagonia, for example, the absence of features correlated to MIS 7 indicates that the MIS 5 highstand reached amplitudes equal or higher than the former (Rostami et al., 2000). If in the CPRS the amplitudes of both highstands were similar, then the estimated difference of 1 to 5 meters between the MIS 5 (7±1m a.s.l) and MIS 7 (10±1m a.s.l) highstands could indicate that the Barrier System II in the southern sector of the CPRS was uplifted to altitudes higher than those reached by the following highstand of 125 ka BP. This could also explain the absence in the continental sequence exposed along the banks of Chuí Creek of lacustrine facies of the Lagoon System III, which are likely to be preserved only closer to the Barrier III, as shown in Figure 2b, and possibly explain the relative absence of the Barrier System II in the central and northern sectors of the coastal plain.

4.2. Chronology of the transgression

Both TL and ESR ages presented here indicate that the Barrier System II was formed by the marine transgression correlated to MIS 7. Despite of the apparent discrepancy between the shells (mean age = ~224 ka) and the overlying marine sediments (~235 ka), it should be taken in account that the shells exhibit younger ages due to excessive Uranium uptake (Lopes et al., 2012), thus their 'real' ages are probably closer to 235-240 ka. An age of ~238 ka BP would be consistent with warmer sea waters (see below) recorded for the isotopic event 7.5 (Figure 6), and also with most accepted ages for the MIS 7e marine highstand, from 237 to 228 ka BP (Robinson et al., 2002; Goy et al., 2006; Dutton et al., 2009).

The lowest δ^{18}O values during MIS 7 for the Atlantic (Figure 6) and Pacific oceans (Lisiecki and Raymo, 2009), derived from several deep-sea cores, is the isotopic event 7.5; some paleo sea-level records (Table 1) also indicate that the highest amplitude of sea-level was reached around this time (Lea et al., 2002). Other records, however, correlate the highest peak to the event 7.3 (MIS 7c, Barreto et al., 2002; Walbroeck et al., 2002; Suguio et al., 2011) or to the event 7.1 (MIS 7a, Gallup et al., 1994; Hearty and Kindler, 1995; Goy et al., 2006).

The ESR age of ~226 ka BP from a tooth of the extinct mammal *Toxodon* collected from a Type 1 fluvial facies at the transition between the marine and terrestrial sequences exposed along Chuí Creek (Lopes et al., 2010) suggests that sea-level was already falling around this time, which would be consistent with the end of MIS 7e, around 228 ka BP (Robinson et al., 2002). The absence of erosional featureas indicative of fluvial incision, however, which would be expected if regional base level was lower than the fluvial system (Catuneanu, 2006), indicate that sea-level was still relatively high around 226 ka BP. The TL age obtained from the fossil-bearing aeolian sediments above the marine-terrestrial transition indicates that sea-level had fully retreated around ~214 ka BP, and the ~207 ka ESR age of a mammalian tooth from the continental shelf (Lopes et al., 2010) shows that sea-level was already below present level at this time. The TL age of ~173 ka BP from the dark sand lens, interpreted as a meandering fluvial system that incised the underlying marine facies due to lowered regional base level, is also consistent with an interval of lower sea-level.

Substages 7e and 7c are separated by an interval marked by a sharp increase in the return to almost full glacial conditions (isotopic event 7.4), indicated by increase in δ^{18}O values and decrease in temperatures (Hodell et al., 2000; Lang and Wolff, 2011; Figure 6) which are likely to represent ice expansion and thus sea-level fall. The absence of marine sediments in the upper levels of the banks of Chuí Creek indicate that sea-level did not reach similar amplitude during MIS 7c or 7a, despite of the return to interglacial conditions during these substages.

4.3. Paleoclimatic inferences

MIS 7 is marked by three oxygen isotope peaks, with the highest and oldest (7e) generally considered to be characterized by fully interglacial conditions, while the following substages (7c and 7a), although weaker, are also considered full interglacials according to some records (Lang and Wolff, 2011). The transition from MIS 8 to MIS 7 (Termination III) occurred around 250 ka BP, and full interglacial conditions were reached around 237 ka BP (Robinson et al., 2002; Cheng et al., 2009).

Some of the fossil mollusks found within the marine facies point to paleoclimatic conditions different than the present ones in the CPRS. The presence of four bivalve taxa (*Anomalocardia brasiliana*, *Arcinella brasiliana*, *Chione cancellata* and *Chione paphia*) that today inhabit only warmer waters in areas to the north of Rio Grande do Sul state, at about 28°S (Lopes et al., 2012b indicate warmer conditions. *Anomalocardia* and other 'Brazilian' (warm water) taxa have also been recorded in Pleistocene and Holocene deposits of Uruguay and Argentina (up to 38°S), and this have been regarded as caused by stronger southwards influence of the Brazil Current (BC) (Martínez et al., 2006; Aguirre et al., 2011).

The oceanographic conditions in the southwestern Atlantic Ocean (up to ~41°S) today are under the direct influence of the warm BC, which constitutes the southern branch of the warm South

Equatorial Current, and the cold Malvinas Current (MC) which branches from the Antarctic Circumpolar Current (ACC) and has been reaching southern Brazil since the Pliocene (Coimbra et al., 2009); the confluence between both currents forms the Subtropical Front (STF). The southwards influence of the BC and associated water masses is controlled mostly by two seasonal processes: one is the shift of the intertropical convergence zone (ITCZ) to the south of the equator during austral summer (Emílsson, 1960; Johns et al., 1998); the other is the intensification of the ACC (and consequently northwards displacement of the MC) during austral winter (Matano *et al.*, 1993; Wainer *et al.*, 2000).

It is likely that in geological timescales precession-driven cyclic variations of Southern Hemisphere insolation also control the latitudinal displacement of the ITCZ, and consequently of the range and intensity of the BC. Conditions of stronger southwards influence of the BC in the Late Pleistocene and Holocene are correlated to the insolation-driven shift of the ITCZ (Toledo et al., 2008). The interval between 235 and 225 ka BP was marked by higher Southern Hemisphere insolation (Figure 6), thus it seems probable that the BC was also stronger during this time.

On the other hand, temperature changes in the Atlantic sector of the Southern Ocean could have also contributed for general warmer oceanographic conditions in southern Brazil. Warmer than present temperatures (hypsithermals) are generally observed during the early phases of interglacial stages and are followed by cooling (neoglacial) phases (Emiliani, 1972; Hodell et al., 2000). Hypsithermal conditions in the Southern Ocean, with summer sea surface temperatures (SSSTs, Figure 6) 1–5°C warmer than today, happened during the isotopic events 7.5, 7.1, 5.5, and the early Holocene, as indicated by paleotemperature reconstructions from planktonic foraminifera and the absence of ice-rafted debris (Becquey and Gersonde, 2002, 2003). Warmer atmospheric temperatures in Antarctica at these intervals are also inferred from Deuterium and CO_2 concentrations found in Vostok ice cores (Petit et al., 1999, Figure 6) and are likely to have contributed for this hypsithermal (Cheng et al., 2009). Low obliquity (Figure 6) may have also contributed for warmer temperatures in Antarctica around ~235 ka BP, because such condition results in less seasonal temperature variations.

The ~2°C warming recorded during MIS 7.5 in the Southern Ocean was marked by a polewards migration of the STF, also indicated by reduction in ice-rafted debris from deep sea cores (Becquey and Gersonde, 2002; 2003; Kanfoush et al., 2002). The reduction in sea ice cover around Antarctica during the Holocene hypsithermal (~10 to 5 ka BP) indicates that circumpolar water fronts and air masses have retreated polewards at this time (Domack *et al.*, 2001; Hodell *et al.*, 2001; Lamy *et al.*, 2002), which probably occurred also during past hypsithermals. This retreatment would weaken the ACC, and consequently reduce the equatorwards influence of the MC, thus allowing the BC to reach farther south than during colder intervals. The association of weakened MC, insolation-enhanced BC, low obliquity and warmer Southern Ocean during MIS 7.5 could have been responsible for the shift of the 'Brazilian' molluscan fauna to higher latitudes than their present-day distribution. Thus, not only the datings but also the paleoclimatic inferences from the molluscan taxa indicate that the Barrier System II was formed by a transgression during an hypsithermal at the beginning of the interglacial epoch.

Besides the Barrier II, warm water marine mollusks have also been recorded in deposits correlated to the Holocene highstand of ~5-6 ka BP and located some 3 meters a.s.l. (Caron, 2007). This interval has also been considered as an hypsithermal, based on the presence of Holocene beach rocks in the Brazilian and Argentinean coasts and large accumulations of molluscan remains found in the Todos os Santos Bay and Araruama Lagoon in northeastern and southeastern Brazil, respectively, and interpreted as representing episodes of increased biological productivity (Suguio, 2001). The presence of vermetids found some 2 meters a.s.l. and dated as of ~5.4 ka BP in Laguna and Imbituba (~28°S) also point to warmer conditions, because these organisms do not live to the south of 22°S today (Angulo et al., 1999). Although paleoclimatic indicators have not yet been found in deposits correlated to MIS 5 (~125 ka BP), it seems that the highstands recorded in the Brazilian coast have been marked by warmer oceanographic conditions.

The marine-terrestrial transition represented in the sedimentary record exposed along the banks was gradual, represented either by aeolian sediments/paleosoils right on top of the marine sediments, or by the Type 1 fluvial facies. The presence of fluvial systems at the transition could be related to paleoclimatic conditions, i.e, high precipitation regimes that would result in increased fluvial discharge and sedimentary input. Precipitation in southern Brazil is basically controlled by two seasonal processes: the South America summer monsoon (SASM), that brings tropical moisture from Amazonia through a low-level jet (LLJ), and the winter precipitation of extratropical origin, controlled by the northwards displacement and enhancement of the polar fronts. The amount of precipitation is higher during winter than during summer, and the same pattern also operates in orbital timescales, because the interplay between tropical/extratropical precipitation is controlled by the precessional 23-ka cyclic oscillations in insolation, with increased precipitation during periods of low Southern Hemisphere summer insolation, due to higher northwards influence of the polar fronts. Conversely, intervals of high summer insolation, when precipitation is mostly of tropical origin, tend to be less humid in southern Brazil (Cruz et al., 2005; 2009).

After the Barrier II was formed, all fluvial discharge from the continent became trapped by the Mirim Lake, and would not reach the shoreline (see Figure 1). Considering that the area of Chuí Creek is located seawards of the barrier, the only discharges that could contribute to coastal sedimentation during the marine highstand would have been small washouts and streams of pluvial origin formed on this side of the barrier. Today, this mechanism is the only source of sediment transport from the backbarrier to the shoreface in most of the coast of Rio Grande do Sul state, and is more expressive during winter because of the higher amount of precipitation during this season (Figueiredo and Calliari, 2005; Figueiredo et al., 2007). Considering that in orbital timescales the precipitation in southern Brazil is driven by precessional variations of insolation (Cruz et al., 2005; 2009), it is likely that periods of lower insolation in the past have been marked by increased amount and volume of washouts and consequently of higher terrigenous sedimentary input to the shoreline.

The mud intraclasts found in the Type 1 fluvial facies (Figure 3) probably represent terrigenous sediments, given that no mud have been found in the marine facies.

The insolation values for southern Brazil were much lower than today around 215-227 ka BP, due to a combination of low precessional and high eccentricity values, plus high obliquity (Figure 6), thus resulting in increased seasonal (mostly during winter) precipitation. The Type 1 (concordant) fluvial facies represented in the sedimentary record exposed along Chuí Creek at the marine-terrestrial transition seems consistent with high sediment input, possibly representing material eroded from the nearby aeolian facies of the barrier by increased pluviosity and discharged into the shoreline through washouts. For comparison, conditions of low insolation, high eccentricity and probably high precipitation rates are also observed around 173 ka BP (Figure 6), thus consistent with increased fluvial activity represented by the Type 2 (erosive) fluvial facies dated by TL.

4.4. Correlations

Along the Brazilian coast the Holocene transgression, also called Santos (or Last) Transgression is well-represented by several deposits with good altimetric control and absolute ages which show that the maximum amplitude of some 4±1 meters a.s.l. was reached between 6 and 5 ka BP (Suguio et al., 1985; Angulo et al., 1999; 2006; Martin et al., 2003, Caron, 2007; Dillenburg et al., 2009). There are relatively few Pleistocene units with well-established chronostratigraphic setting; most of the data are from deposits correlated to the ~125 ka BP transgression, also called Cananeia or Penultimate Transgression. In southeastern Brazil (São Paulo state) the Cananeia Formation is well-constrained by several absolute TL ages (Suguio et al., 2003; Watanabe et al., 2003). In northeastern Brazil (Bahia state), Martin et al. (1982) identified this transgressive event on the basis of Io/U datings on corals. The Touros Formation that outcrops along the coast of Rio Grande do Norte state, provided luminescence ages of 117-110 thousand years (Barreto et al., 2002), consistent with the ~110 ka BP age obtained for the Barrier System III (Buchmann and Tomazelli, 2003). Other marine terraces found along the coasts of Bahia, Sergipe and Alagoas states were tentatively correlated to this transgressive event (Bittencourt et al., 1979; 1983), but without absolute ages.

Besides the Barrier System II in Rio Grande do Sul, the only other units recognized as representing the MIS 7 transgressive event on the basis of absolute ages are the aforementioned deposits from northeastern Brazil dated by Barreto et al. (2002) and Suguio et al (2011) that belong to the Barra de Tabatinga Formation, and provided TL and OSL ages between 215 and 220 ka (MIS 7c). The discrepancy in ages between the transgressive deposits of MIS 7 found in Rio Grande do Norte and Rio Grande do Sul could be explained by analytical factors (resolution, calibration, etc) or by the distinct depositional histories between these sites, but could also represent a delayed eustatic signal in the northeastern area, due to its greater distance from the nearest ice sheet (Antarctica) and hence from the deformational bulge produced in the crust by this sheet, as proposed by Lambeck et al. (2012).

The presence of MIS 7 highstands in southern and northeastern Brazil (distant some 4.000 km from each other) indicate that other deposits correlated to this marine highstand are likely to be found in other areas along the coast. Several marine terraces found along the coasts of Sergipe, Bahia, São Paulo, Paraná and Santa Catarina states, considered as evidences of the “Older Transgression”, could possibly indicate the MIS 7 highstand, but lack absolute datings for any conclusive correlation (Figure 7).

5. CONCLUSIONS

The portion of the marine sequence exposed along Chuí Creek represents the uppermost portion of the highstand systems tract of the Barrier System II, and constitute the first good direct evidence of a maximum sea-level highstand older than MIS 5 recorded in southern Brazil. The TL and ESR ages, and the stratigraphic sequence along Chuí Creek indicate that this sea level highstand is correlated to MIS 7, reached some 10 meters a.s.l. around ~230 ka BP and was retreating around ~226 ka BP. Although the timing of the highstand is consistent with other records of MIS 7e, the amplitude is much larger than most records; despite the fact that the southern Brazilian coast is considered tectonically stable, this could indicate the influence of local neotectonics or tectonic processes operating on continental scales. Variations in altitudes between Pleistocene and Holocene deposits along the southeastern and northeastern portions of the Brazilian coast are related to neotectonic processes, but further research is needed in order to evaluate whether the amplitude of the MIS 7 highstand in southern Brazil was influenced by such processes.

The presence within the marine facies of bivalve species that today live only to the north of Rio Grande do Sul state suggests warmer oceanographic conditions in the past, possibly related to orbitally-driven increased southwards influence of the Brazil Current and/or warming of the Atlantic sector of Southern Ocean during the hypsithermal phase (isotopic event 7.5) of MIS 7e.

The sedimentary record exposed along Chuí Creek indicates that the marine-terrestrial transition was gradual and occurred around 230 ka BP. This transition is coincident with an interval of low Southern Hemisphere insolation and probably high pluviosity, which produced high input of terrigenous sediments through washouts and increased fluvial activity.

The ages also improve the chronology of the Pleistocene barrier-lagoon depositional systems of the CPRS, by showing that the Barrier-Lagoon System II was formed around 230 ka BP rather than 325 ka BP (MIS 9), as previously proposed. This leaves open the question of whether the older system (Barrier-Lagoon I) is correlated to MIS 9 or represents an older transgression.

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FIGURE CAPTIONS

Figure 1 – a: Location of the CPRS, in southern Brazil; b: Subdivisions of the CPRS, with geomorphological features mentioned in the text indicated; the dashed line shows the Pelotas Fault; c: transect of the barrier (B) and lagoon (L) systems found in the southernmost portion of the CPRS.

Figure 2 – a) Satellite image of the southernmost CPRS showing the location of Chuí Creek and the Pleistocene depositional systems (‘L’ = Lagoon Systems, ‘B’ = Barrier Systems; b) Schematic configuration of the Pleistocene depositional systems in the southern CPRS (modified from Rosa, 2012); c) General stratigraphic sequence exposed along the banks showing the boundaries between depositional environments; the arrow indicates a dark sand lens formed by an erosive fluvial facies (Type 2, see explanation in the text).

Figure 3 – a) Aspects of the marine-terrestrial transition: paleosoils (left), fluvial concordant (Type 1, in the middle; the arrows indicate mud intraclasts, each division of the scale = 10 cm) and fluvial

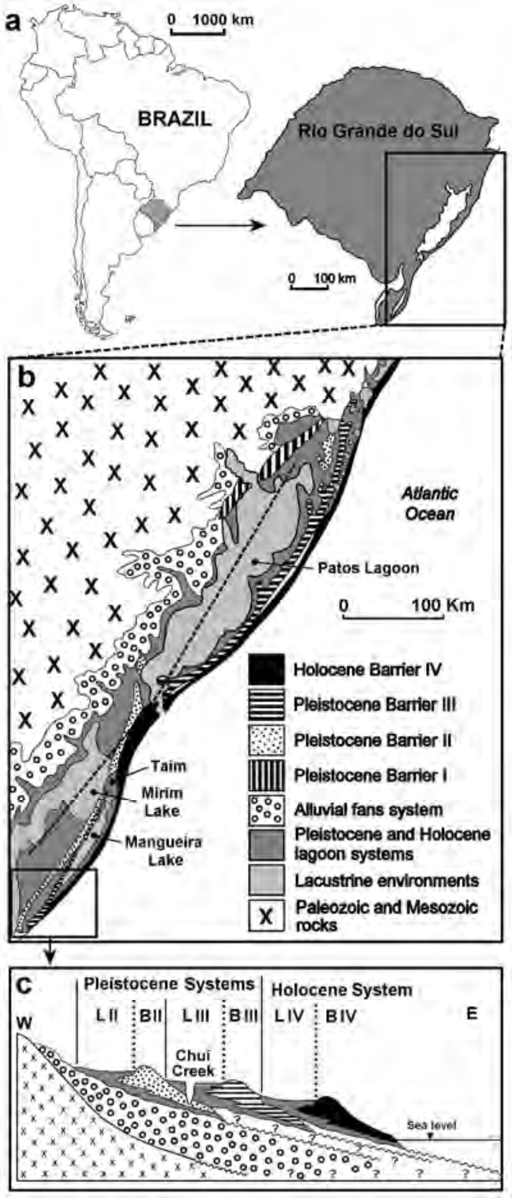
erosive (Type 2, on the right); b) Detail of the parallel- and cross-stratifications; c) Shallow marine sediments (Sm) truncated by aeolian sediments (Ae) on the upper part of the marine facies; d) Ichnofossil *Ophiomorpha nodosa*; e) Association of *Rosselia* sp. (Ro), *O. nodosa* (On) and unidentified (NI) ichnofossils. The horizontal surfaces and truncated *Rosselia* suggest erosion by storm events.

Figure 4 – Composite stratigraphic section of the banks (on the left) showing the results of TL and ESR datings; on the right, pictures of the poits where the sediment samples were collected (indicated by letters and black circles). The horizontal arrows point the marine-terrestrial transition; vertical black arrows indicate mammalian remains, and the white one indicates an ichnofossil *O. nodosa* (divisions of the scale = 10 cm); the facies are shallow marine (a), aeolian (b), fluvial erosive (c) and paleosoil (d).

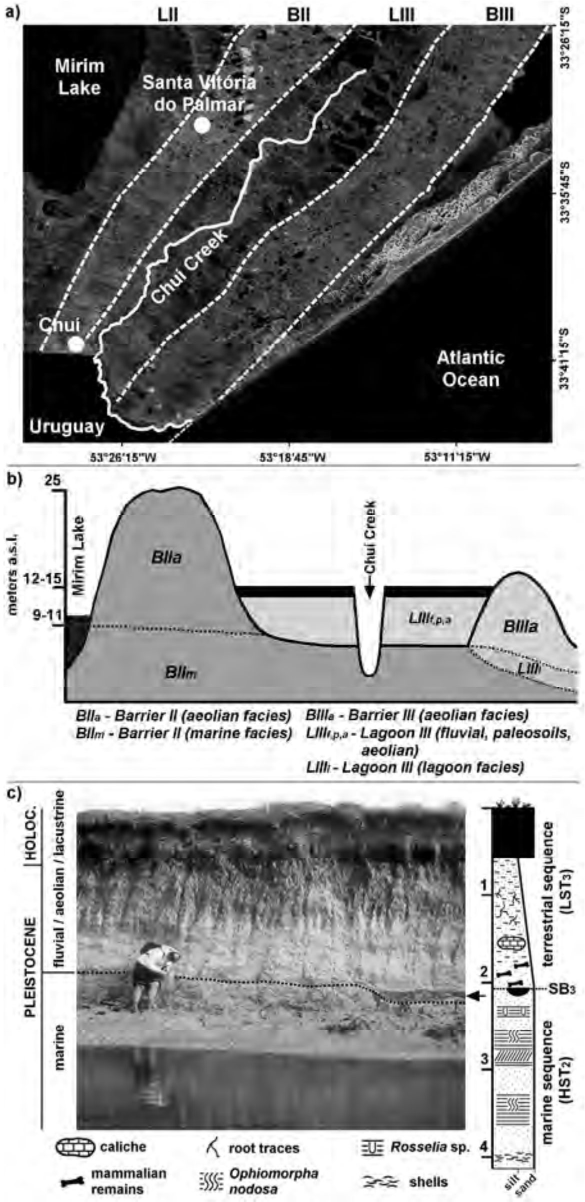
Figure 5 – Late Quaternary sea-level oscillations recorded in the CPRS, based on data from Caron (2007), Tomazelli and Dillenburg (2007), Rosa (2012) and this paper (amplitudes of the lowstands from Rohling et al., 1998). Error bars are ±1 m.

Figure 6 – From top to bottom: a) oxygen isotope curve from Atlantic Ocean deep-sea cores (Lisiecky and Raymo, 2009) with corresponding marine isotope stages, shaded areas are glacial phases; b) summer sea-surface temperatures of the Southern Ocean (Becquey and Gersonde, 2002) with hypsithermal phases indicated; c) temperature variations at the inversion level in Antarctica from Deuterium in Vostok ice core (Petit et al., 1999); Southern Hemisphere summer insolation (d), eccentricity (e) and obliquity (f) values for the last 250 ka (from Berger, 1978).

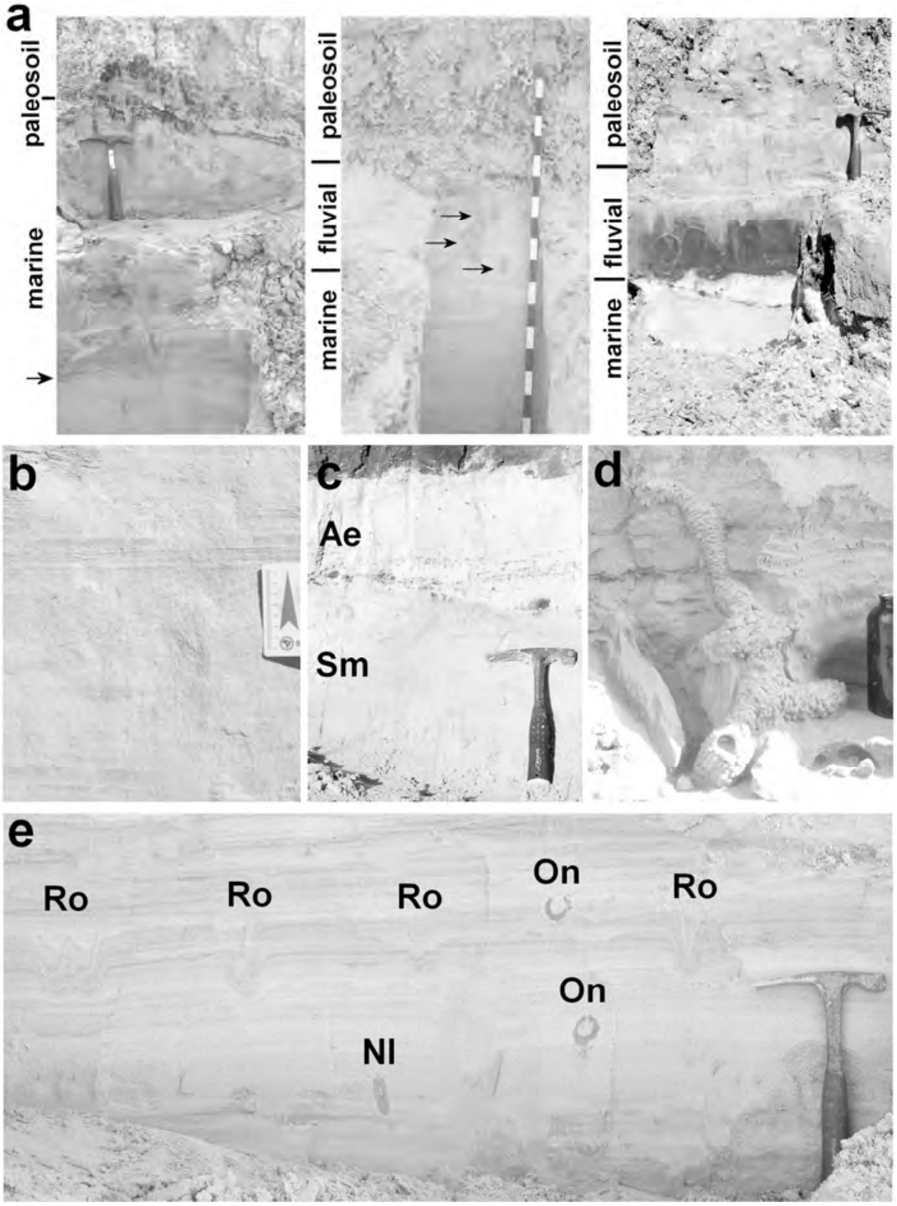
Figure 7 – Chronostratigraphic correlation of the depositional systems of the CPRS with other Quaternary units recognized along the Brazilian coast.



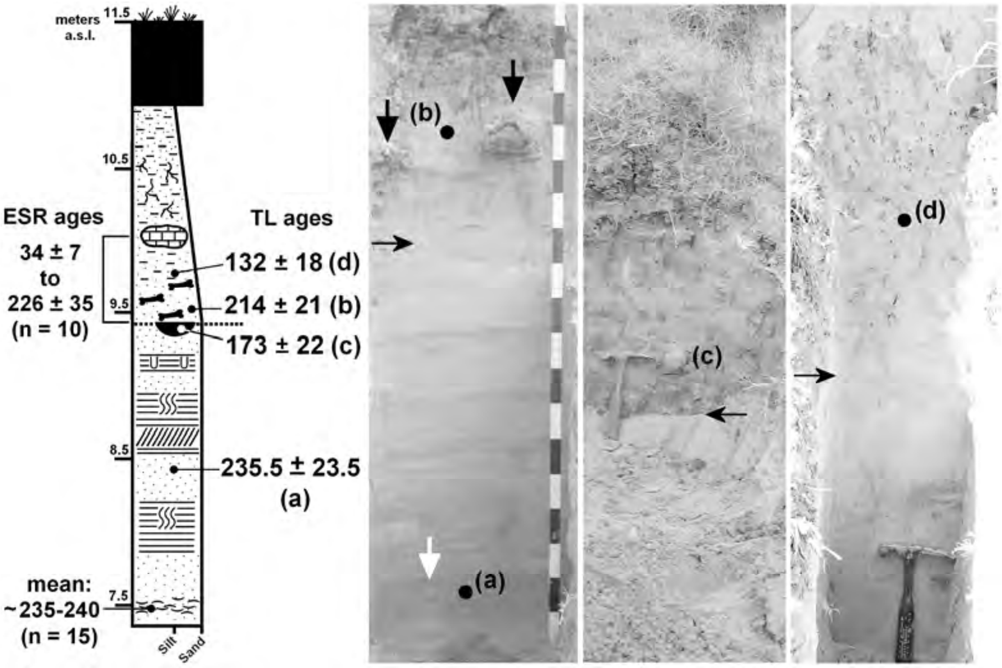
a: Location of the CPRS, in southern Brazil; b: Subdivisions of the CPRS, with geomorphological features mentioned in the text indicated; the dashed line shows the Pelotas Fault; c: transect of the barrier (B) and lagoon (L) systems found in the southernmost portion of the CPRS.
134x313mm (300 x 300 DPI)



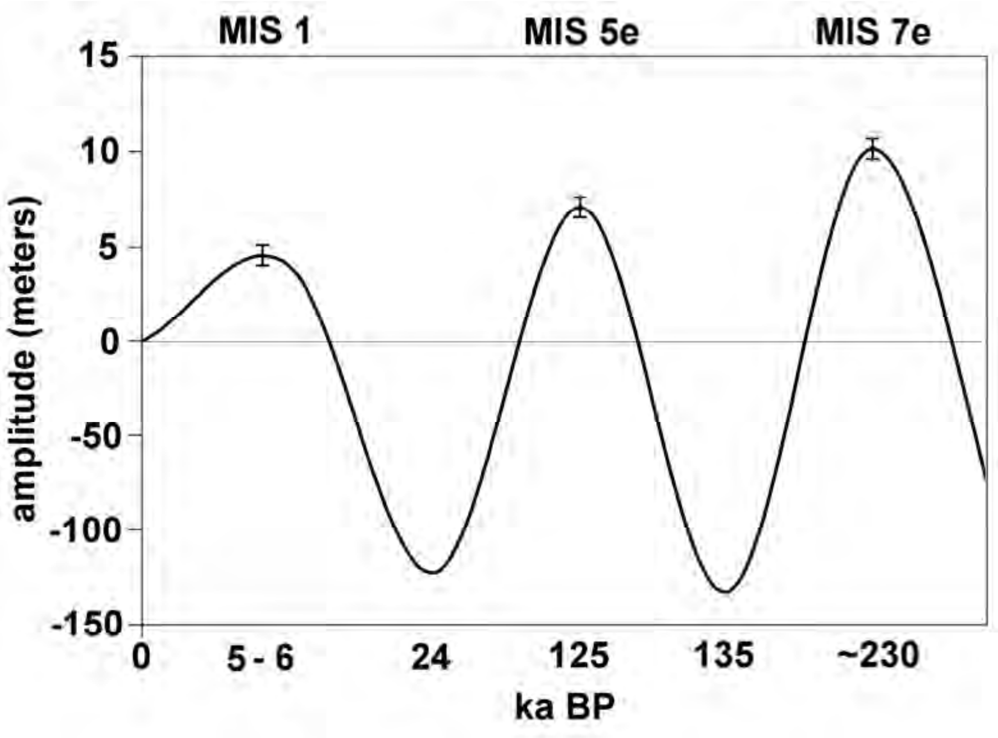
a) Satellite image of the southernmost CPRS showing the location of Chuí Creek and the Pleistocene depositional systems (‘L’ = Lagoon Systems, ‘B’ = Barrier Systems; b) Schematic configuration of the Pleistocene depositional systems in the southern CPRS (modified from Rosa, 2012); c) General stratigraphic sequence exposed along the banks showing the boundaries between depositional environments; the arrow indicates a dark sand lens formed by an erosive fluvial facies (Type 2, see explanation in the text)
138x284mm (300 x 300 DPI)



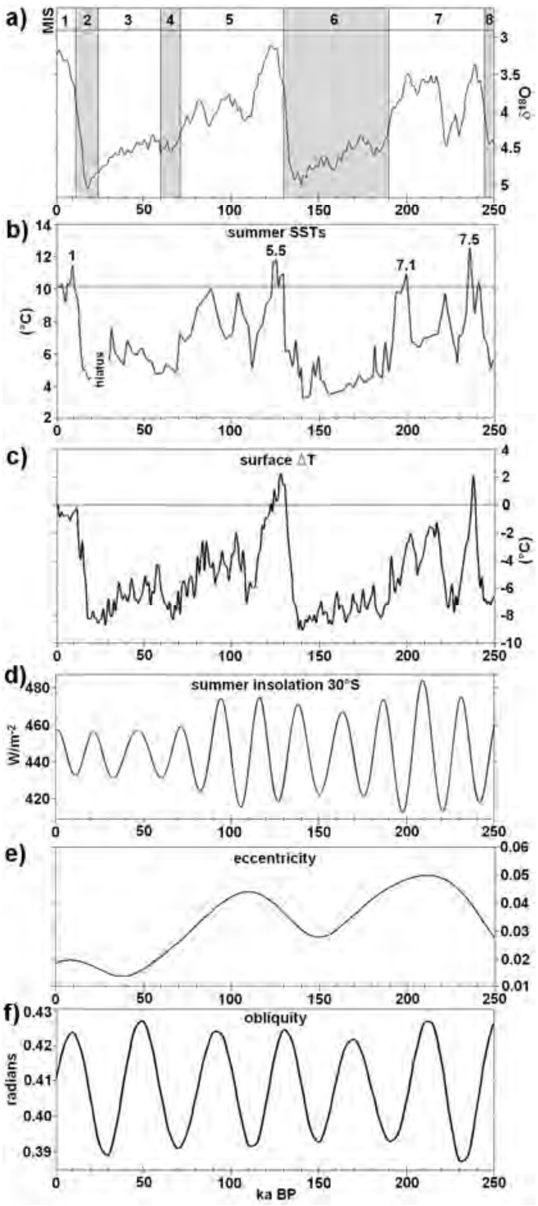
a) Aspects of the marine-terrestrial transition: paleosoils (left), fluvial concordant (Type 1, in the middle; the arrows indicate mud intraclasts, each division of the scale = 10 cm) and fluvial erosive (Type 2, on the right); b) Detail of the parallel- and cross-stratifications; c) Shallow marine sediments (Sm) truncated by aeolian sediments (Ae) on the upper part of the marine facies; d) Ichnofossil Ophiomorpha nodosa; e) Association of Rosselia sp. (Ro), O. nodosa (On) and unidentified (NI) ichnofossils. The horizontal surfaces and truncated Rosselia suggest erosion by storm events
145x195mm (300 x 300 DPI)



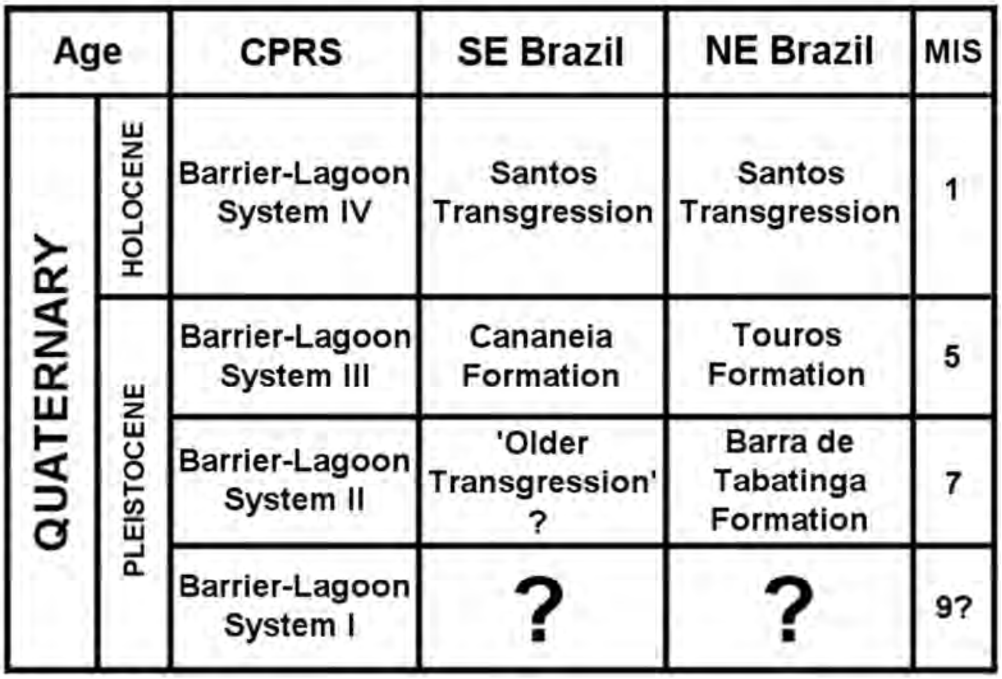
Composite stratigraphic section of the banks (on the left) showing the results of TL and ESR datings; on the right, pictures of the poits where the sediment samples were collected (indicated by letters and black circles). The horizontal arrows point the marine-terrestrial transition; vertical black arrows indicate mammalian remains, and the white one indicates an ichnofossil O. nodosa (divisions of the scale = 10 cm); the facies are shallow marine (a), aeolian (b), fluvial erosive (c) and paleosoil (d)
247x164mm (300 x 300 DPI)



Late Quaternary sea-level oscillations recorded in the CPRS, based on data from Caron (2007), Tomazelli and Dillenburg (2007), Rosa (2012) and this paper (amplitudes of the lowstands from Rohling et al., 1998). Error bars are ±1 m
148x109mm (300 x 300 DPI)



From top to bottom: a) oxygen isotope curve from Atlantic Ocean deep-sea cores (Lisiecky and Raymo, 2009) with corresponding marine isotope stages, shaded areas are glacial phases; b) summer sea-surface temperatures of the Southern Ocean (Becquey and Gersonde, 2002) with hypsithermal phases indicated; c) temperature variations at the inversion level in Antarctica from Deuterium in Vostok ice core (Petit et al., 1999); Southern Hemisphere summer insolation (d), eccentricity (e) and obliquity (f) values for the last 250 ka (from Berger, 1978)
88x198mm (300 x 300 DPI)



Age		CPRS	SE Brazil	NE Brazil	MIS
QUATERNARY	HOLOCENE	Barrier-Lagoon System IV	Santos Transgression	Santos Transgression	1
	PLEISTOCENE	Barrier-Lagoon System III	Cananeia Formation	Touros Formation	5
		Barrier-Lagoon System II	'Older Transgression' ?	Barra de Tabatinga Formation	7
		Barrier-Lagoon System I	?	?	9?

Chronostratigraphic correlation of the depositional systems of the CPRS with other Quaternary units recognized along the Brazilian coast
62x42mm (300 x 300 DPI)

Table 1 – Ampliude and timing of maximum relative sea levels (RSL) during MIS 7 from different sites around the globe.

Authors	Local	Age (ka)	MIS	RSL (m)
Li et al. (1989)	Bahamas	220-212	7c	>-10 to -15
		235-230	7e	
Pirazzoli *et al*. (1991)	Indonesia	232 ± 35	7e	-12 ± 12
Gallup *et al*. (1994)	Barbados	201-193	7a	-6 to +9
Hearty & Kindler (1995)	Bahamas, Bermuda	240-230	7e	≤ 0
	Bermuda	210-180	7a	+2.5
Roy *et al*. (1997)	Australia	261-217	7a-c	+2 to +4
Vesica *et al*. (2000)	Spain	231 ± 28	7e	+4.2
Bard *et al*. (2002)	Italy	202-190	7a	-18.5 to -9
Barreto *et al*. (2002)	NE Brazil	207 ± 4	7c	+3 to +5
		220 ± 2		
Robinson et al. (2002)	Bahamas	235	7e	-5
Murray-Wallace (2002)	Australia	230 ± 11	7e	-6.0*
		258 ± 11	7e	0.0*
Waelbroeck *et al*. (2002)	N. Atlantic / Eq. Pacific	240-235	7e	-10
		~220	7c	~-5
		~195	7a	~-10
Lea *et al*. (2002)	Pacific	~240	7e	~0
		~215	7c	~-10
		~200	7a	~0
Schellmann & Radtke (2004)	Barbados	222	7a	-16.0
		224	7c	-3.0
Goy *et al*. (2006)	Spain	237 ± 20	7e	-1
Dutton *et al*. (2009)	Italy	201.5 ± 1.7 to 189.7 ± 1.5	7a	-18
		217.2 ± 1.9 to 206.0 ± 1.9	7c	
		248.9 ± 19 to 231.0 ± 3.0	7e	
Suguio *et al*. (2011)	NE Brazil	212 ± 4	7c	>+1.7
		220 ± 22	7c	>+4
This paper	S Brazil	~230	7e	~+10 ± 1

*Assuming a paleo sea-level of +2m for MIS 5e.

REVISTA BRASILEIRA
DE PALEONTOLOGIA

São Paulo, 16 de junho de 2013.

Ilmo Sr.
RENATO PEREIRA LOPES
Programa de Pós-graduação em Geociências, UFRGS. Avenida Bento Gonçalves, 9500, Agronomia. CEP 91540-000, Porto Alegre, RS, Brasil.

Prezado Autor

Informamos que em 16 de junho p.p. recebemos o manuscrito intitulado “A PLEISTOCENE MARINE MOLLUSCAN ASSEMBLAGE FROM THE SOUTHERN COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL ", da autoria de Renato Pereira Lopes, Luiz Ricardo L. Simone, Sérgio Rebello Dillenburg, Cesar Leandro Schultz e Jamil Corrêa Pereira. A submissão do MS foi aceita e em breve ele será enviado para dois revisores ad hoc. Em tempo oportuno entraremos novamente em contato.

Cordialmente,

Dra. Juliana de Moraes Leme
Editora Adjunta RBP

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A PLEISTOCENE MARINE MOLLUSCAN ASSEMBLAGE FROM THE SOUTHERN COASTAL PLAIN OF RIO GRANDE DO SUL STATE, BRAZIL

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ABSTRACT **-** A marine molluscan assemblage is described from four fossil concentrations in the Coastal Plain of Rio Grande do Sul state, southern Brazil. The concentrations were found at the same stratigraphic interval, some 7.5 meters above present sea-level, in a layer deposited in shallow marine environment and currently exposed along the banks of Chuí Creek, located some 11 km landwards of the present coastline. The assemblage is composed of a mixture of highly fragmented, unidentifiable shells and well-preserved bivalves and gastropods. Many bivalve remains are complete, including juveniles and thin-shelled taxa, lacking signs of abrasion or bioerosion. The origin of the shell concentrations is interpreted as a short-termed depositional event, generated by storms, in shallow water settings under a marine transgressive regime. The predominant taxa in the assemblage are infaunal, stenohaline bivalves that inhabit shallow sandy bottoms, with few gastropods and epifaunal organisms. Most of the taxa have living representatives today in the southern Brazilian coast, indicating a mixture of Argentinean and Caribbean (or Brazilian) malacological provinces. The presence of taxa that indicate warm waters (*Anomalocardia brasiliana*, *Chione paphia*, *C. cancellata*, *Anadara brasiliana* and *Arcinella brasiliana*), that are not found living today in the coast of Rio Grande do Sul, suggests warmer oceanographic conditions coinciding with past sea-level highstands, also indicated by similar taxa found in fossil concentrations in the Uruguayan and Argentinean coasts. A discussion of the stratigraphic position, age and correlation of this assemblage with other outcrops is also presented.

Keywords: Chuí Creek; Barrier System II; Pleistocene; Fossil Assemblage; Paleobiogeography, Paleoenvironment

RESUMO **-** Aqui é descrita uma assembléia de moluscos marinhos a partir de quatro concentrações fossilíferas encontradas na Planície Costeira do estado do Rio Grande do Sul, Brasil. As concentrações foram encontradas na mesma posição estratigráfica, aproximadamente 7,5 metros acima do nível atual do mar, em uma camada depositada em ambiente marinho raso e atualmente exposta nas barrancas do Arroio Chuí, localizado a aproximadamente 11 km da linha de costa atual. A assembleia é composta por uma mistura de conchas altamente fragmentadas, nãoidentificáveis, bem como bivalves e gastrópodes bem preservados. Muitos bivalves são completos, incluindo juvenis e táxons de conchas finas, sem sinais de abrasão ou bioerosão. A origem dessas concentrações é interpretada como um evento deposicional de curta duração, gerado por tempestade, em águas rasas sob regime marinho transgressivo. Os táxons predominantes na assembleia são bivalves estenohalinos infaunais que habitam fundos arenosos rasos, com poucos gastrópodes e organismos epifaunais. A maioria dos táxons ainda habita a costa sul do Brasil, indicando uma mistura das províncias malacológicas Argentina e Caribenha (ou Brasileira). A presença de táxons indicativos de águas mais quentes (*Anomalocardia brasiliana*, *Chione paphia*, *C. cancellata*, *Anadara brasiliana* and *Arcinella brasiliana*), que não são encontrados vivendo atualmente na costa do Rio Grande do Sul, sugere condições oceanográficas mais quentes, coincidentes com durante máximos transgressivos marinhos no passado, também indicadas por concentrações fósseis encontradas em depósitos do Holoceno nas costas da Argentina e Uruguai. A posição estratigráfica, idade e correlação desta assembleia com outros afloramentos são discutidas.

Palavras-chave: Arroio Chuí; Sistema Barreira II; Pleistoceno, Assembléia Fóssil, Paleobiogeografia, Paleoambiente

INTRODUCTION

The southernmost portion of the Brazilian coast comprises the Coastal Plain of Rio Grande do Sul state (CPRS), a geomorphological unit formed by successive sea-level oscillations during the Neogene and Quaternary (Tomazelli *et al.*, 2000). The CPRS is known for the presence of several deposits of marine fossils, located both on the continental shelf (Figueiredo Jr, 1975) and continental areas far from the Present-day coastline. The latter were studied by several authors (Bianchi, 1969; Closs & Forti, 1971; Forti Esteves, 1974; Godolphim *et al.*, 1989), but focusing mostly on the taxonomic composition of the fossil assemblages, rather than their stratigraphy or paleoecology. From the Santa Vitória do Palmar County, in the southern CPRS, Closs & Forti (1971) described several fossil marine mollusks, found in four outcrops in continental areas, including the Chuí Creek. These fossils, however, were described without any indication of their stratigraphic origin, and probably represent material that was found out of their original depositional setting, reworked by erosive processes resulting from fluvial activity.

During recent surveys in the Chuí Creek, four concentrations of marine fossil shells were found on their original stratigraphic position, at the base of the banks of the creek. These concentrations were briefly described by Lopes & Simone (2012), but focusing mostly on new fossil records of molluscan taxa. Here is presented an expanded report on these concentrations, encompassing the systematics, taphonomy, paleoenvironmental and stratigraphic implications of these concentrations, plus a discussion regarding the fossil shells reported by Closs & Forti (1971).

Abbreviations: MZUSP: Museu de Zoologia da Universidade de São Paulo; FURG: Universidade Federal do Rio Grande.

GEOLOGICAL SETTING

The CPRS is formed by sediments accumulated in the coastal area of southern Brazil after the South America and Africa break-up, during the Late Cretaceous. These sediments filled-up the Pelotas Basin, the southernmost marginal sedimentary basin in the Brazilian coast (Closs, 1970). During the Late Pleistocene-Early Holocene, four major sea-level transgressions correlated to interglacial phases reworked the uppermost portion of the basin. Each transgression originated a long sandy barrier system on the coastline and coastal lagoons located landwards, named Barrier-Lagoon Systems I, II, III and IV, correlated to marine isotope stages 11, 9, 5 and 1, respectively, following the oxygen ($\delta^{18}O$) curves of Imbrie *et al.* (1984, in Villwock & Tomazelli, 1995).

The Chuí Creek flows subparallel to the coastline in a NE-SW direction between the Pleistocene barriers II and III, through the plain that is part of the Lagoon System III (Figure 1A, B). In its lower course, the creek makes a southeastwards turn following the Chuí faulting zone until reaching the Atlantic Ocean. The creek channel was originally shallow, but was further excavated for agricultural purposes in the early 1960s. During this, a marine sand layer was exposed, underlying sediments that contain remains of Pleistocene mammals (Figure 1C). Soliani Jr. (1973) correlated the marine layer to the “Chuí Formation” of Delaney (1965), and named the overlying fossiliferous layer as “Santa Vitória Formation”. Under the chronostratigraphic scheme proposed for the description of the geology of the CPRS by Villwock *et al.* (1986), which replaced the classical lithostratigraphic scheme of Delaney (1965), the marine sediments are identified as the shallow marine facies deposited during the sea-level highstand that originated the Barrier System II and underlies the youngest sediments of Lagoon System III (Lopes *et al.*, 2011; Rosa, 2012).

The marine sand deposit is composed of fine, well-sorted, well-rounded and mature sand, with parallel and cross stratifications. The sand is essentially composed of quartz and contains small amounts (less than 10%) of heavy minerals and carbonate fragments of biogenic origin; the uppermost centimeters of this layer are reddish due to iron oxide coating resulting from subaerial exposure. Ichnofossils *Ophiomorpha nodosa* (Lopes *et al.*, 2001), *Rosselia* sp. and other unidentified traces are commonly found, and indicate shallow coastal waters (Weimer & Hoyt, 1964; Frey *et al.*, 1978; Pollard *et al.*, 1993; Nara, 2002). Some 2 meters of this facies remain exposed above the creek bed; its total thickness is of at least 10 meters, based on direct observation of drilling activities made for building purposes near the creek.

The marine sand deposit is covered by a sediment layer containing the mammalian remains and generated in fluvial systems (Lopes *et al.*, 2009). The oldest age for a fossil mammal tooth obtained by ESR dating (226 ± 35 kyr BP) indicates that the marine facies below corresponds to the marine isotope stage (MIS) 7 (Lopes *et al.*, 2010), a conclusion

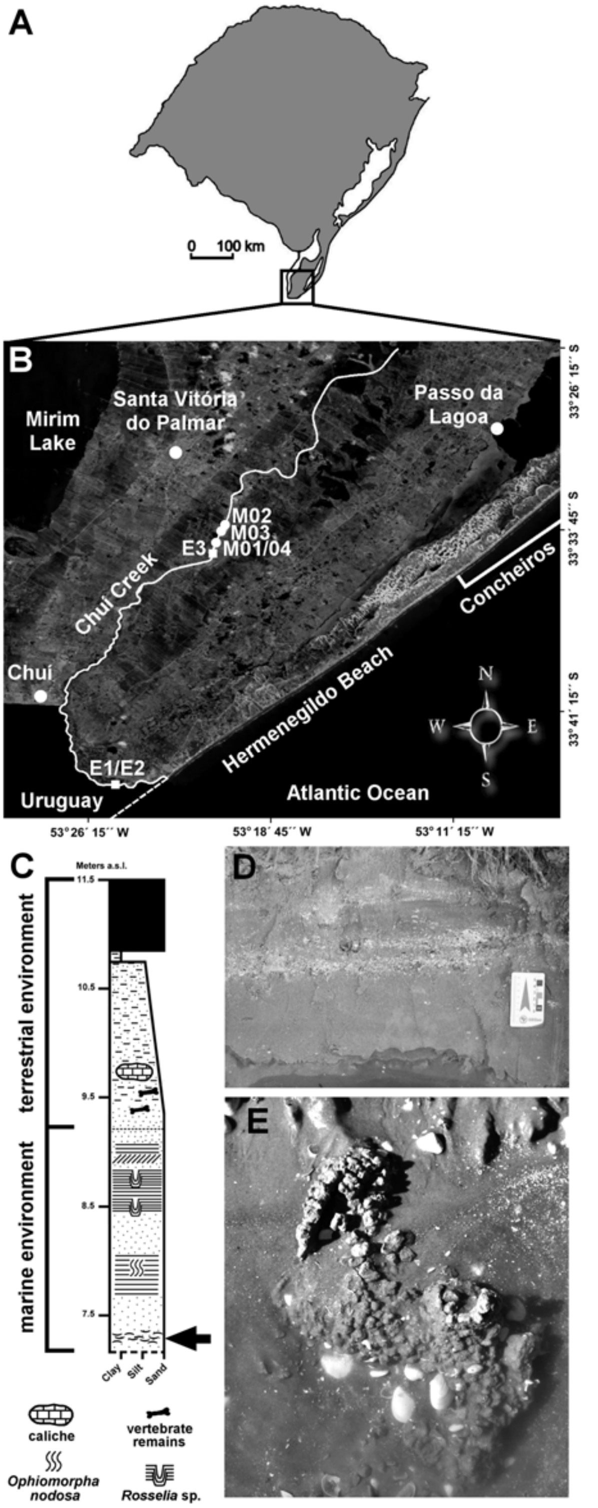

Figure 1: A – Location of Chuí Creek, in the southern part of the CPRS; B – Satellite image of Chuí Creek, showing outcrops M001, 002, 003 and 004 (the sources of the material described here), E1, E2 and E3 (sources of the shells described by Closs & Forti, 1971), and other localities with fossil shell concentrations (Passo da Lagoa and Concheiros), the lagoon (L) and Barrier (B) depositional systems are also indicated; C – Stratigraphic sequence exposed

along the banks of Chuí Creek, with the position of the shells indicated by arrow (from Lopes & Simone, 2012); D – Detail of the shell concentration exposed at the base of the banks in the outcrop M002 (scale = 50 mm); E – Gallery of a callianassid crustacean (ichnofossil *O. nodosa*) associated with the shells at the outcrop M003.

also reinforced by ESR datings on shells from this facies (Lopes et al., 2012). The layer with mammalian remains is covered by sandy silt probably of loessic origin (Lopes et al., 2011); the uppermost portion of the sedimentary sequence is composed of organic matter-rich sand and clay, containing fossil remains indicative of wetland environments and archaeological structures (Schmitz *et al.*, 1997).

MATERIALS AND METHODS

Previous descriptions of fossils of marine mollusks found in the Chuí Creek were presented by Closs & Forti (1971) and Forti Esteves (1974). The fossils described by those authors were collected in four different outcrops: on the bridge over Chuí Creek (sample E3, Figure 1B); on dredged sediments piled near the road between the town of Santa Vitória do Palmar and Hermenegildo Beach (sample E4, not shown in the figure); some 4 km to the south of the town of Chuí, in the Brazilian-Uruguayan border (samples E1 and E2), and some 50 km to the northeast of the town of Santa Vitória (sample E5, also not in the figure).

During the field work on the creek in 2010, when the water table was very low due to a drought, a concentration of fossil marine shells (M002) was found exposed at the base of the right bank of the creek (Figure 1C, D), some 2 km to the north of the bridge on the road between the town of Santa Vitória do Palmar and Hermenegildo Beach. Two other concentrations (M001 and M004) were identified in the left and right banks, respectively, at the same stratigraphic position of M002, but some 600 m to the north of the bridge. The specimens collected from these outcrops were the basis for the paper by Lopes & Simone (2012); later, a fourth concentration (M003) was found in the left bank some tens of meters to the south of M002.

The term “concentration” is used here to designate a densely-packed shell accumulation *sensu* Kidwell & Holland (1991). Each concentration is formed by a patch of densely packed (*sensu* Kidwell & Holland, 1991), decimetric thick layer (Figure 1D) of clustered and chaotically-oriented shells; smaller specimens are found nested within larger ones. Above this layer shell remains are scarce and disperse on the sandy matrix until disappearing some 15 cm upwards. A remarkable feature found in M003 is an ichnofossil *Ophiomorpha nodosa* that vertically crosses the shell concentration (Figure 1E). The total lateral extension of each concentration is yet unknown, because the adjacent banks remain covered by alluvium, but the absence of shells in portions of the creek between the outcrops M002, M003 and M001/04 suggest that each one is a single concentration rather than a laterally continuous shell bed. The physical proximity of some 20 meters between the outcrops M001 (in the left bank) and M004 (in the right bank) suggests that both may represent the same accumulation. The outcrop M001 is visible on a gully transversal to the left margin of the creek, which shows that the fossil shell concentration extends in subsurface for at least 10 meters eastwards of the creek.

The bulk samples collected from each outcrop were washed and particles smaller than 2 mm were separated by using a sieve, in order to remove fragments that are not considered bioclasts *sensu* Kidwell & Holland (1991); identifiable specimens were hand picked among the remaining fragments. Identification was based on the compendia of Brazilian seashells (Rios 1994, 2009) and comparison with reference specimens from MZUSP and FURG.

RESULTS

Taxonomic composition of the assemblage

Although most of the remains are unidentifiable fragments, a total of 708 specimens were identified at the species level (TABLE 1, Figures 2 and 3). All four concentrations are composed by the same taxa, except for those represented by a single individual. Besides the new records described by Lopes & Simone (2012), six other taxa not previously recorded from this assemblage were collected in the outcrop M003: the bivalves *Anadara brasiliana*, *A. chemnitzi* and *Erodona mactroides*, and the gastropods *Buccinanops gradatus*, *B. duartei* and *Terebra gemmulata*).

The analysis of the shells shows a predominance of bivalves (95% of the specimens) over gastropods, both in species richness and total number of individuals (TABLE 2). The remains include mostly sandy bottom dwellers that inhabit the intertidal to infralittoral zone. Most of the species are stenohaline; the only taxon that usually inhabits brackish waters is *Erodona mactroides*, represented by two individuals. The gastropods and some bivalves are epifaunal, but most bivalves are infaunal taxa. All the gastropods found in the assemblage are taxa that live today in the southern Brazilian shelf, except for *Lamniconus lemniscatus carcellesi*, a taxon that currently does inhabit Argentinean and Uruguayan waters but is not found in Brazil (Rios, 1994; 2009; Lopes & Simone, 2012). The bivalves *Chione paphia*, *C. cancellata*, *Arcinella brasiliana*, *Anadara brasiliana* and *Anomalocardia brasiliana* are not recorded among living molluscan assemblages of the coast of Rio Grande do Sul (e.g. Absalão, 1986, 1991; Borzone, 1988; Capitoli, 2002; Wigger & Veitenheimer-Mendes, 2003; Pimpão, 2004), although found living in other areas of the Brazilian coast.

Of the 35 species recorded, 10 belong to the Caribbean/Brazilian malacological province and 10 to the Argentinean; 12 occur on both Argentinean and Caribbean provinces and 3 occur on both Argentinean and Magellanic provinces (Figure 4).

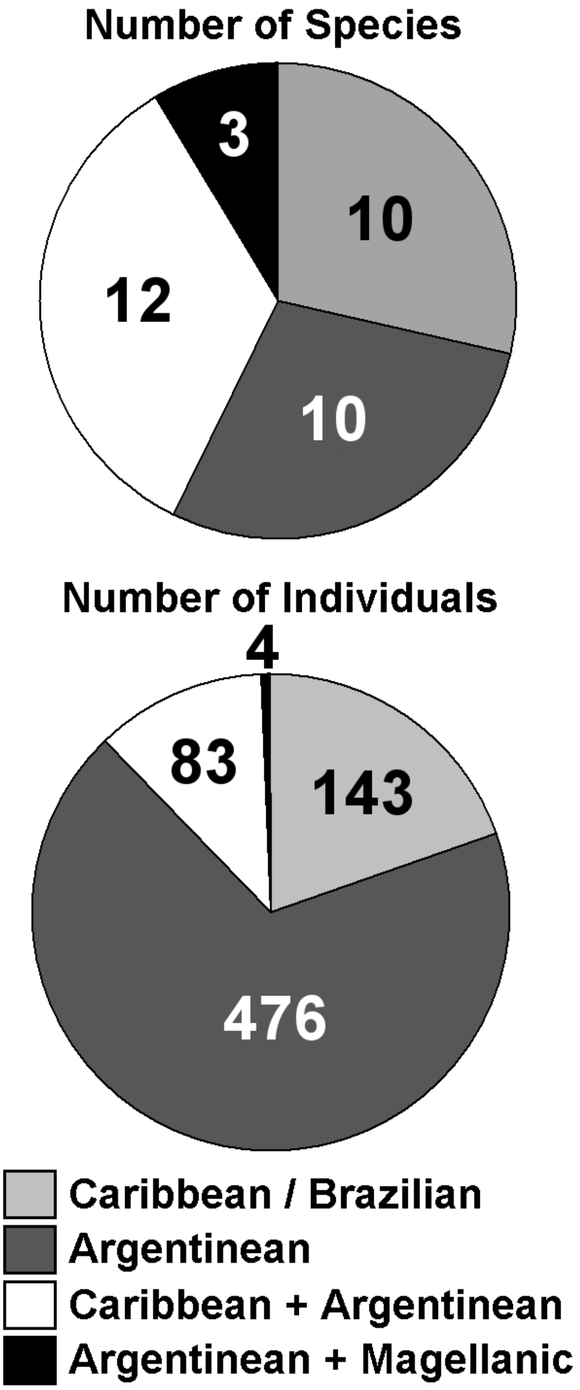

Figure 4 – Relative percentages of taxa belonging to the Caribbean/Brazilian, Argentinean and Magellanic malacological provinces.

Preservation

The shells were divided in two groups, according to their preservational state: Group I is composed of highly abraded, unidentifiable and sometimes corroded and/or bioeroded fragments, and Group II, composed of 708 specimens, either complete (85% of the total) or incomplete (15%). The term incomplete is used here to describe specimens that although broken, still have at least 50% of the shell preserved.

All specimens are, white-colored and without periostracum, except for a few *Chlamys tehuelchus* and two ostreids that exhibit traces of the original color pattern, and the *Tegula patagonica*, that exhibits traces of the original color and the pearly internal lining. The complete fossils of Group II do not exhibit signs of abrasion; the corrosion seen in 45.3% of these fossils (Figure 5A) was probably caused by exposure to acidic water. Good preservation is observed even among fragile shells, such as those of small juvenile individuals and thin-shelled taxa (e.g. *Mactra janeiroensis*).

All bivalves are represented by disarticulated valves, except for six *Corbula caribaea* that were found with valves still closed articulated. 32% of the shells exhibit signs of bioerosion; one specimen of *M. janeiroensis* exhibits a *Caulostrepsis* ichnofossil (Figure 5B) and one specimen of *Pitar rostratus* exhibits ichnofossils *Entobia* (Figure 5C). Ichnogenera *Pennatichnus* or *Maeandropolydora* have not been observed on the bivalves, although these are common in shells from other fossil concentrations. On the other hand, 8 specimens, including 5 ostreids, exhibit ichnofossils *Oichnus* (Figure 5D) that are virtually absent among fossils found in other localities of CPRS (Lopes and Buchmann, 2008; Lopes, 2012). One ostreid (Figure 5E) and one pectinid (Figure 3L) exhibit ovoid borings (cf. ichnogenus *Gastrochaenolites* isp.); another ostreid exhibit several borings of *Entobia* and *Caulostrepsis* (Figure 5F).

Most of the gastropods are poorly preserved in comparison to the bivalves. The specimens of *Zidona dufresnei* and most *Adelomelon brasiliana* are broken; both taxa also exhibit signs of corrosion and ichnofossils *Entobia* and *Caulostrepsis* (Figure 2F, G). The only other gastropod that exhibit bioerosion by *Entobia*, *Caulostrepsis* and also *Pennatichnus* is one specimen of *Olivancillaria urceus* (Figure 2J). The latter also exhibits traces tentatively assigned to the ichnogenus *Clionoides* sp. (Lopes, 2012).

DISCUSSION

Comparison with other fossil assemblages

In the southern sector of the CPRS, two other concentrations of fossil marine shells are found, one in the southwestern margin of Mangueira Lake, at the locality known as Passo da Lagoa, and the other, known as Concheiros, is found on the present shoreline, close to the Brazilian-Uruguayan border (Lopes & Buchmann, 2008). The fossils from Passo da Lagoa are found among sediments dredged from the bottom of the lake, thus their stratigraphic position is still unknown. The Concheiros are formed by fossils transported from the continental shelf to the beach by storm waves (Figueiredo Jr., 1975; Buchmann, 2002; Lopes & Buchmann, 2008), thus actually represent several storm-generated concentrations (multiple event concentrations, *sensu* Kidwell, 1991). The fossil deposits of the continental shelf, which constitute the source for the material accumulated on the beach, are likely to be lag deposits formed during past marine transgressions that are being reworked today by the erosive processes affecting the southern coast of Rio Grande do Sul (Dillenburg *et al.*, 2004).

The main taxonomic difference between the fossils from the Passo da Lagoa and Concheiros and those from Chuí Creek is the scarcity of the bivalve *Glycymeris longior* on the latter (only two specimens found), while it is common in Concheiros (72% of the specimens) and Passo da Lagoa (18%) (Lopes & Buchmann, 2008). The co-occurrence of both shallow living taxa such as *Amiantis purpuratus* and deeper dwellers such as *G. longior* indicates that the assemblages of Concheiros and Passo da Lagoa do not represent paleo-communities, but were formed by sedimentological processes related to sea-level oscillations. During a marine transgression, the rising sea-level would erode the shallow areas, removing finer sediments and leaving coarser ones (including fossils) concentrated on the ravinement surface, thus forming a transgressive lag deposit. The deeper-living taxa would also have their distribution expanded landwards following the rising sea-level, and would accumulate on top of the remains of shallow living taxa. During a sea-level lowering, such as seen today in most of the coast of Rio Grande do Sul for the last 6 ka

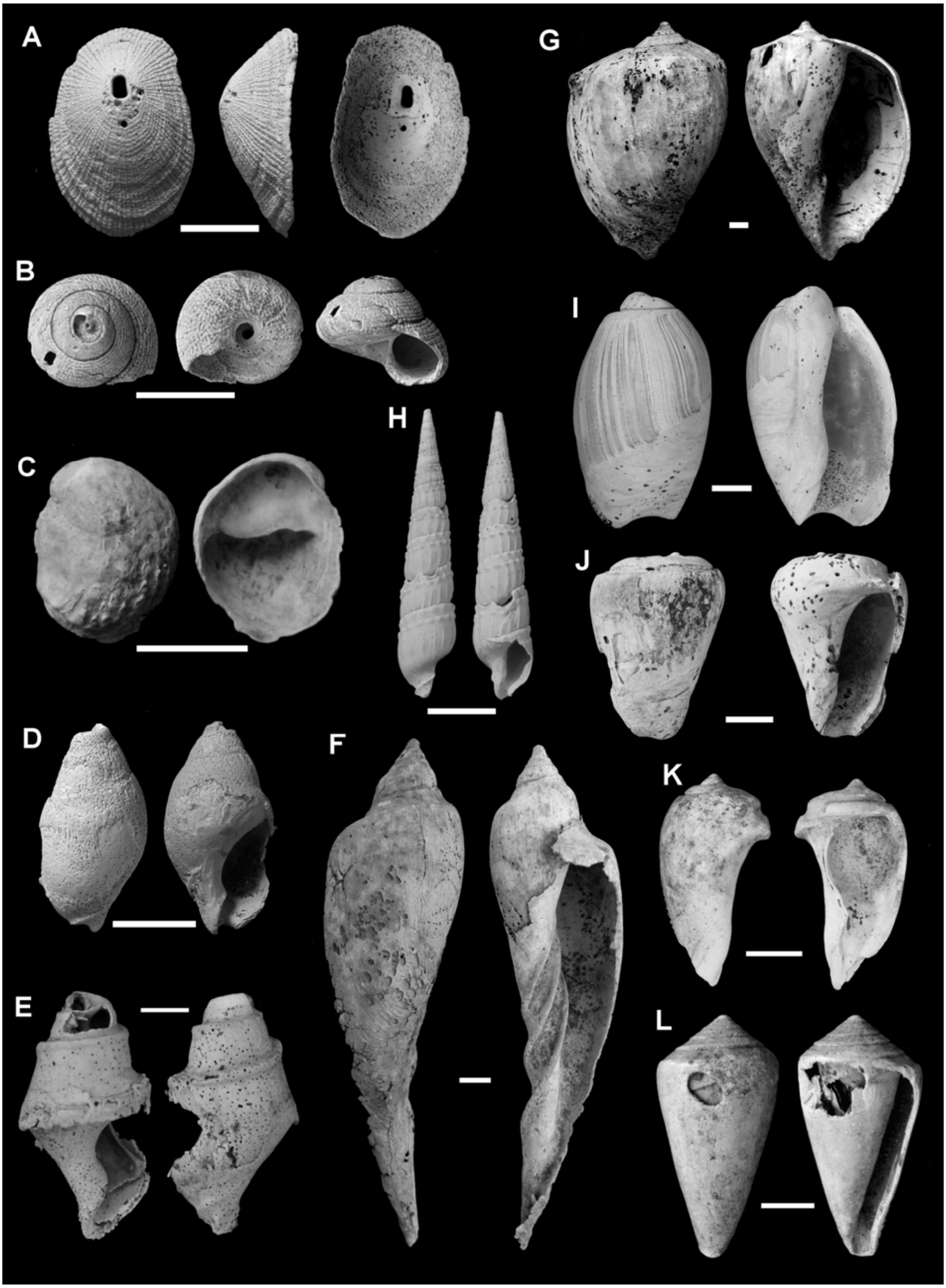

Figure 2: Gastropod taxa from Chuí Creek: A – *Diodora patagonica*; B – *Tegula patagonica*; C – *Bostrycapulus odites*; D – *Buccinanops duartei*; E – *Buccinanops gradatus*; F– *Zidona dufresnei*; G – *Adelomelon brasiliana*; H – *Terebra gemmulata*; I – *Olivancillaria carcellesi*; J – *Olivancillaria urceus*; K – *Olivancillaria deshayesiana*; L – *Lamniconus lemniscatus carcellesi* (scale bars = 10 mm).

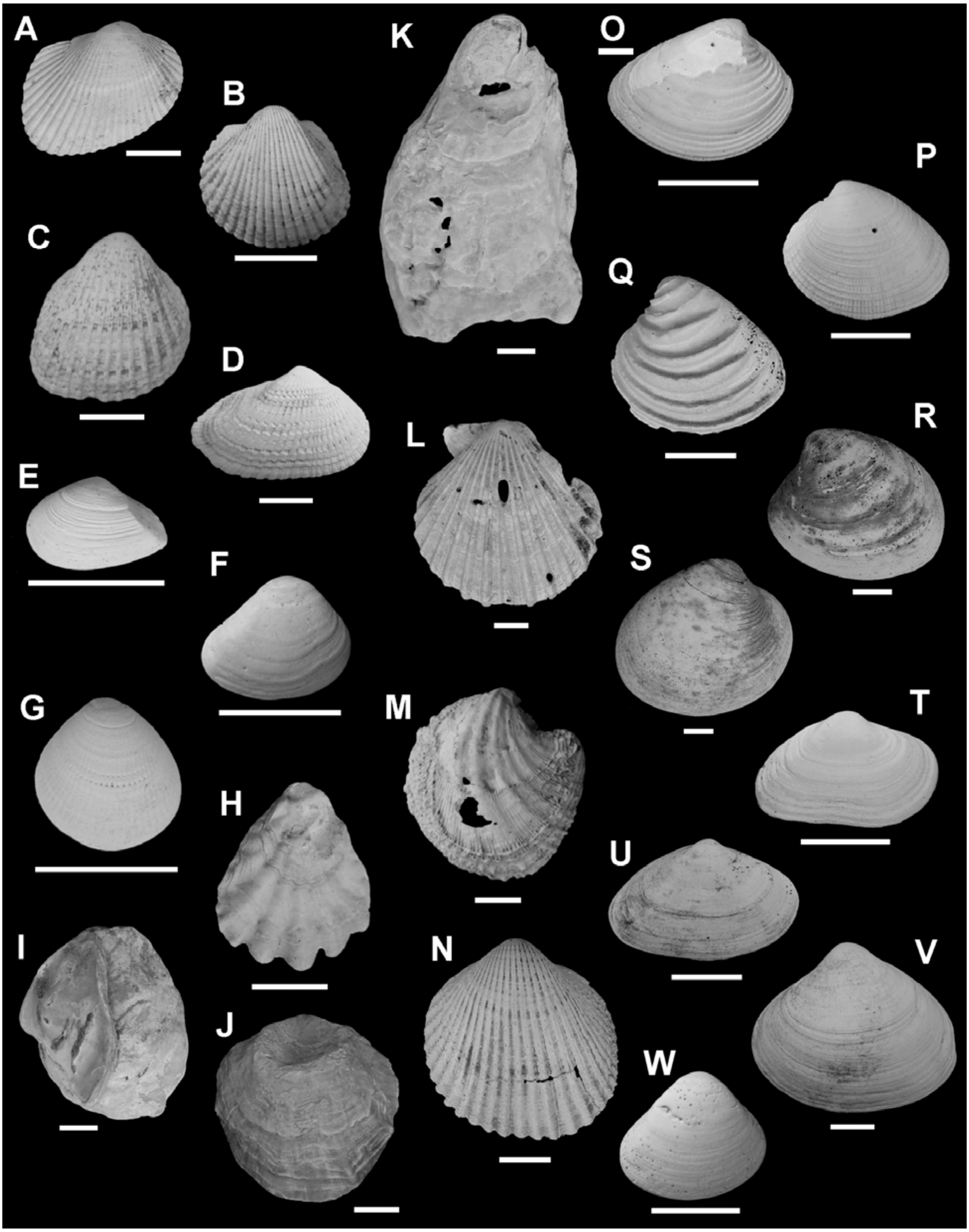

Figure 3: Bivalve taxa from Chuí Creek. A – *Lunarca ovalis*; B – *Anadara brasiliana*; C – *Anadara chemnitzi*; D – *Noetia bisulcata*; E – *Corbula caribaea*; F – *Erodona mactroides*; G – *Glycymeris longior*; H – *Plicatula gibbosa*; I – *Ostrea puelchana*; J – *Ostrea equestris*; K – *Crassostrea rhizophorae*; L – *Chlamys tehuelchus*; M – *Arcinella brasiliana*; N – *Trachycardium muricatum*; O – *Anomalocardia brasiliana*; P – *Chione cancellata*; Q – *Chione paphia*; R – *Pitar rostratus*; S – *Amiantis purpuratus*; T – *Mactra* cf. *guidoi*; U – *Mactra janeiroensis*; V – *Mactra isabelleana*; W – *Mactra marplatensis* (scale bars = 10 mm).

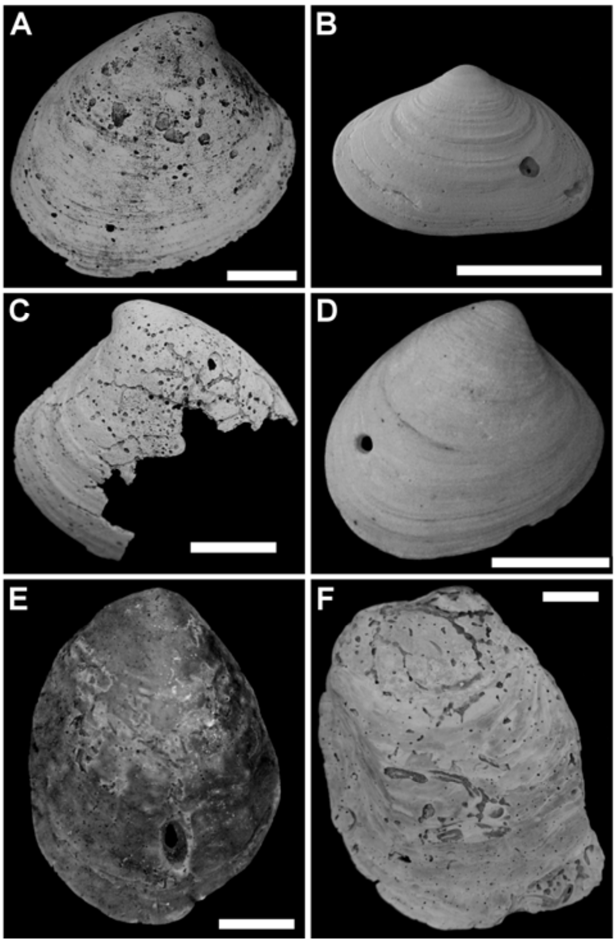

Figure 5: A – *Pitar rostratus* showing signs of corrosion; B – *Mactra janeiroensis* with borings of the ichnogenus *Caulostrepsis* sp. (on the right side of the photo); C – Incomplete specimen of *P. rostratus* with *Entobia* sp. borings; D – Juvenile of *P. rostratus* with boring made by predatory gastropod (ichnogenus *Oichnus* sp.); E – Ostreid with boring produced by myitilid bivalve (ichnogenus *Gastrochaenolites* cf. *torpedo*); F – Ostreid with *Caulostrepsis* and *Entobia* (scale bars = 10 mm).

(Dillenburg *et al.*, 2004), these lag deposits would be eroded and the fossil shells transported to the beach, mixing together fossil remains of taxa that inhabit different depths. A similar process seems to be responsible for the abundance on the coastline of fossil remains of the echinoid *Encope emarginata* that inhabits the infralittoral (Lopes, 2011a).

Taphonomy

The assemblage from Chuí Creek is composed of well-preserved remains, concentrated together with highly fragmented and abraded unidentifiable shells. Good preservation may result of less exposure time on the taphonomically active zone (TAZ, *sensu* Davies et al., 1989), while longer exposure times cause the destruction of more fragile shells, such as juveniles, small and thin-shelled taxa, and result in highly abraded and corroded specimens (Driscoll, 1970; Brandt, 1989; Davies *et al.*, 1989a, b; Kidwell, 1989). A survey among complete specimens of the most abundant bivalves (*A. purpuratus*, *P. rostratus* and *M. janeiroensis*) shows that these include elements of all ontogenetic stages (Figure 6), with predominance of juveniles. If the transport took longer time or the burial of these remains was delayed, it would be unlikely that the shells of juvenile individuals, more fragile in comparison to adults, would have been preserved. Studies have shown that shells of juveniles are more readily destroyed by currents, waves and dissolution, thus are often underrepresented in fossil concentrations (Cummins *et al.*, 1986; Kidwell, 1989; Kidwell & Bosence, 1991).

The estimated time of survival of shells in nearshore environments is shorter than in the shelf (Flessa & Kowalewski, 1994; Carroll et al., 2003; Krause et al., 2010) due to continuous mechanical reworking by waves and chemical dissolution while exposed on the water-sediment interface or buried within the zone affected by bioturbation. Because the sedimentation rates are usually lower than the rates of chemical destruction (dissolution) of the shells (Davies *et al.*, 1989b), the good preservation seen in many specimens indicates either an elevated rate of sedimentation during their final burial, or that these specimens have died shortly before burial, thus were exposed on the TAZ for a brief interval. Most of the bivalves found here are infaunal (spend most of their lives buried in the sediment), so it is likely that these could have died and remained articulated within the sediment, which prevented biogenic or mechanical reworking, until their removal and disarticulation by a storm event, after which the remains would have been buried under a thick sediment layer below the TAZ (depth of final burial, or DFB, *sensu* Olszewski, 2004). The presence of at

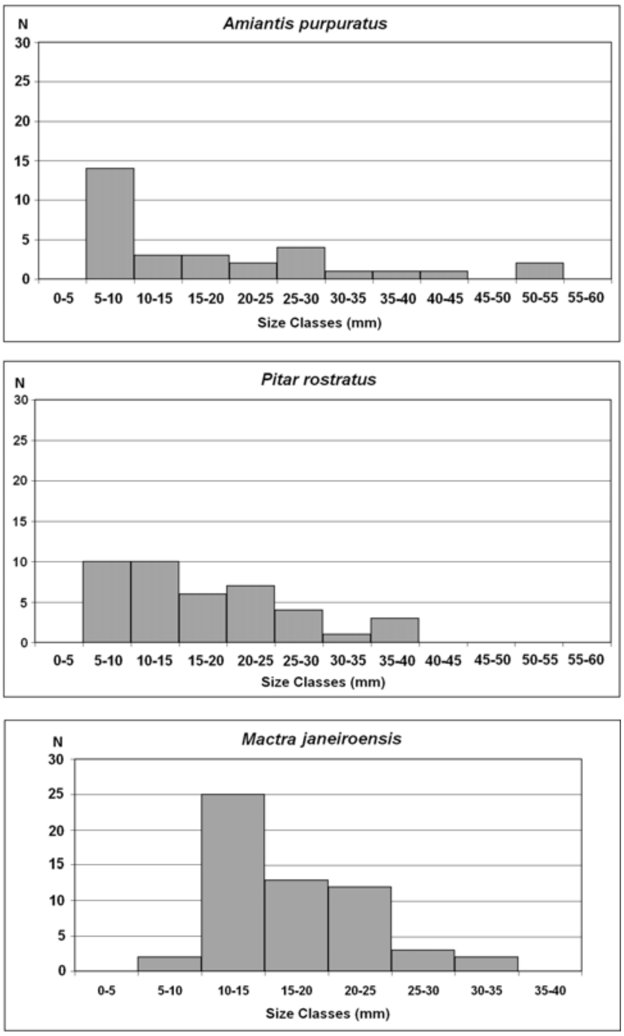

Figure 6 – Size-frequency distribution of the length of complete, well-preserved specimens of the most abundant bivalve taxa found in Chuí Creek.

least one *Ophiomorpha nodosa* preserved in association with the fossil concentration M003 (Figure 2E), plus six individuals of *C. caribaea* and several yet undescribed ostracods found with the valves still closed, reinforce the interpretation that the assemblage has not been reworked since their burial.

The specimens that are broken, bioeroded and/or corroded probably remained in the TAZ for longer periods. Among Holocene molluscan assemblages from Argentina, Aguirre & Farinatti (1999a) observed that infaunal bivalves (e.g. *Mactra isabelleana*, *Pitar rostratus*) are better preserved than epifaunal taxa. Lazo (2004) found similar results for the bivalve *Protothaca stamina*, which exhibits both infaunal and epifaunal behavior. The poor preservation among the larger gastropod shells (*A. brasiliana* and *Z. dufresnei*) could have resulted from transportation of these specimens from their living areas (between 15 and 77 m in depth according to Rios, 1994) to the shoreline. Although predation is also a possible source of breakage on shells (Cate & Evans, 1994; Alexander & Dietl, 2003; Zuschin *et al*., 2003), no conclusive evidence of such activity was identified among the specimens. It seems, however, that the high degree of bioerosion seen in some specimens was directly related to the breaking of the shell (see figure 5c).

Most of the dissolution that affects the shells occurs in the sediment-water interface and within the zone affected by bioturbation (Driscoll, 1970; Davies *et al.*, 1989a; Walker & Goldstein, 1999). Some processes related to storm events such as removal of organic matter, quick burial below the TAZ, and winnowing, that causes the shells to become densely packed, also contribute for reducing or avoiding the destruction of shells by dissolution (Cherns *et al.*, 2008). Dissolution after burial should have been minimal, considering the presence together with the shells of well-preserved foraminifer tests (Lopes & Bonetti, 2012) and ostracod carapaces. On the other hand, a single storm event could not have imprinted the taphonomic signature (corrosion and abrasion) visible in the unidentifiable fragments (Davies *et al.*, 1989a), thus the poor preservation of these remains indicates that they were continuously reworked in shallower areas within the depths affected by waves prior to their final burial together with the well-preserved shells.

The shells from Chuí Creek resemble those found in Passo da Lagoa, with white to light grey color, while those from the Concheiros are dark grey to reddish (Lopes & Buchmann, 2008). The color variation seen among the shells from submarine deposits is probably caused by incorporation of iron, manganese and other components dissolved in the seawater. Coimbra *et al*. (2009) found oxidized glauconitic coatings on Neogene foraminiferal tests from the southern Brazilian shelf, attributing it to a combination of glauconite incorporation under marine conditions and oxidization due to sea-level change. The absence of color in shells from both the Passo da Lagoa and Chuí Creek suggest that this feature is caused by a combination of less time of exposition to marine conditions after death and the influence of acidic freshwater after sea-level retreatment.

The amount of specimens affected by bioerosion is similar in the three assemblages (32% in Chuí Creek, 22% in Passo da Lagoa and 37% in the Concheiros). In soft bottom coasts such as in southern Brazil, any dead skeletal remain is a potential substrate for colonization by epi- and endoskeletozoans, and the longer these skeletons remain exposed on the water-sediment interface, higher will be the amount of bioerosion. Remarkably, the most common ichnofossil observed among the shells from Chuí Creek is *Oichnus*, virtually absent from the other two concentrations (Lopes & Buchmann, 2008; Lopes, 2012). This ichnogenus, however, indicates predatory activity by gastropods, thus it is not produced on dead remains, although cases of erroneous attacks by predators on dead shells are possible (Kelley & Hansen, 2003; Simões *et al.*, 2007). The gastropods that exhibit bioerosion (*Z. dufresnei*, *A. brasiliana* and *O. urceus*) are epifaunal taxa that inhabit depths below the influence of normal waves (some 10-12 m) and are much larger than the bivalves, thus are likely to remain exposed for a long time period and be subject to the action of bioeroders after death. Bioerosion could have been also produced while the hosts were still alive, at least concerning *Caulostrepsis*, produced by spionid polychaetes, as it was recorded in brachiopods (Rodrigues *et al.*, 2008). This trace was observed on the external surface of one *Mactra* (Figure 5b) ostreids (figure 5F) and one gastropod (figure 2J), thus it is possible that these individuals could have been infested while still alive, as is the case of fossil oysters (bioeroded mostly on the external surfaces of the valves) from the continental shelf (Lopes, 2011b; 2012). The *Entobia* observed on the external surface of *Adelomelon* and *Zidona*, which are epifaunals, could also have been produced while these were still alive.

The characteristics of this assemblage suggest that its deposition was a short-termed process. A plausible scenario would be the erosion of the lower shoreface and transportation of well-preserved shell remains to shallower zone by storm waves, followed by their final burial together with highly reworked fragments at the DBF. This process would be similar to what is seen today in the Concheiros: during autumn and winter, storm waves deposit in the upper shoreface large amounts of fossil shells transported from the lower shoreface, concentrating them together with smaller shell fragments that are continuously reworked and abraded in the surf zone, while during summer and spring, when storm surges are rare, these deposits remain above the range of waves and are covered by sand when the beach recovers the summer profile and also by sand blown from the foredunes (Lopes & Buchmann, 2008). The deposits formed in the shoreface exhibit layers of fossil shells with variable thickness, interspersed with sand layers (Figure 7).

Paleoecology and Paleobiogeography

The relative absence of articulated and / or specimens in life position, plus the mixing of unidentifiable fragments and complete specimens indicate that the concentrations are sedimentological in origin, rather than representing a paleo-community preserved *in situ*. These concentrations can be considered parautochtonous, formed by dead remains of shallow-living taxa reworked in their habitat (Kidwell *et al.*, 1986), concentrated together with allochtonous elements that were transported from their original living areas such as deep-living taxa (*Z. dufresnei* and *A. brasiliana*), hard bottom dwellers (*Bostrycapulus odites*, *Diodora patagonica*) and inhabitants of brackish-water environments (*Erodona mactroides*).

Most of the taxa found in this assemblage live today in the southern Brazilian coast (Borzone, 1988; Absalão, 1991; Gianuca, 1998; Capítoli, 1998; 2002), but some taxa (e.g. *M. guidoi*, *M. janeiroensis*) are not common among recent specimens found along the beach. Although living in most areas of the Brazilian coast, the bivalves *Anomalocardia brasiliana*,

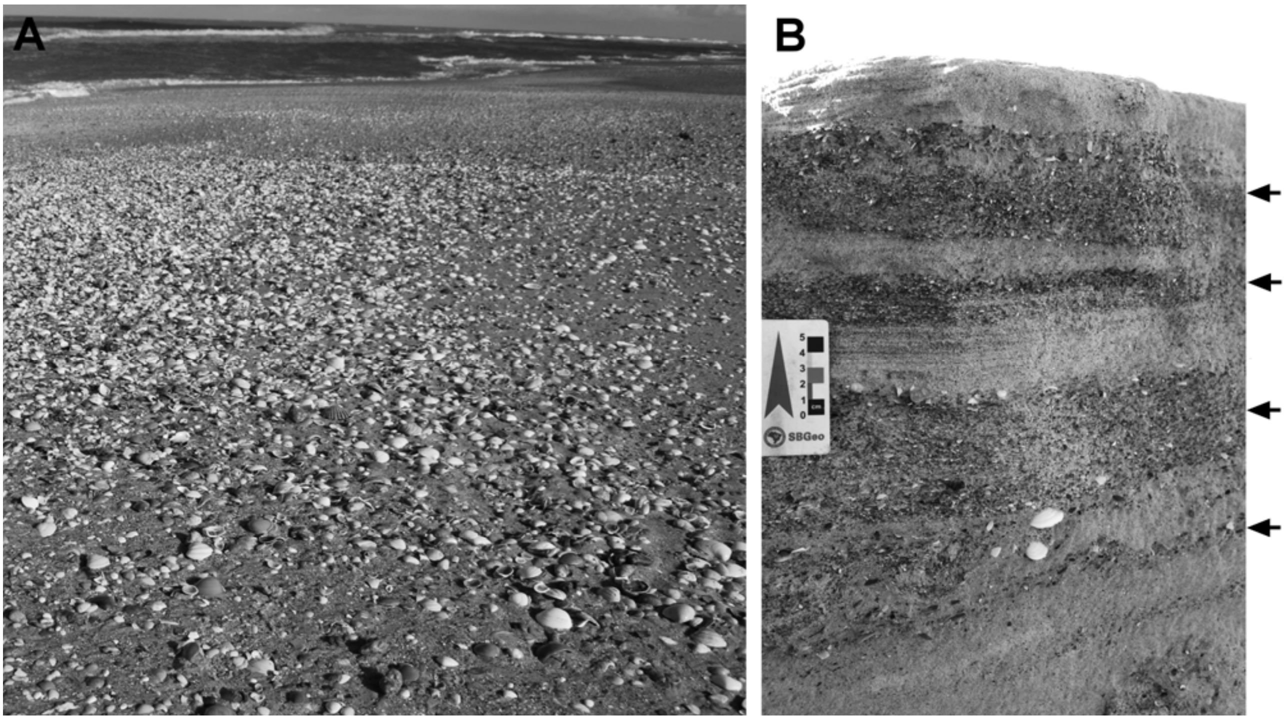

Figure 7 – A) Shell concentration formed by storm event in the foreshore at the Concheiros; B) Vertical profile of the foreshore, showing alternate layers of shells (indicated by arrows) and sand (scale bar = 5 cm).

Chione paphia, *C. cancellata*, *Anadara brasiliana* and *Arcinella brasiliana* are not found today in the coast of Rio Grande do Sul state; their southernmost distribution confirmed so far is the northern neighboring state of Santa Catarina (Figure 8; Veitenheimer-Mendes & Lopes-Pitoni, 1995; Klein *et al.*, 2001; Almeida *et al.*, 2004; Caregnato *et al.*, 2009; Rodrigues *et al.*, 2010). Although the current distribution of *Anomalocardia* has been described as reaching up to the Uruguayan coast (Rios, 1994; 2009), this taxon is not found living today in that area (Scarabino, 2003); Absalão (1986) mentioned one single specimen of *Anomalocardia* collected in the coast of Rio Grande do Sul, without specifying whether it was a living individual or just an isolated valve. Considering the presence of large concentrations of fossil and subfossil shells on the continental shelf (Figueiredo Jr., 1975; Lopes & Buchmann, 2008), containing other taxa that do not inhabit the southern Brazilian shelf today (Simões *et al.*, 2011) it seems probable that the material mentioned by that author do not represent a recent individual.

Anomalocardia and other 'Brazilian' taxa (e.g. *Anadara brasiliana*, *C. cancellata*, *Bulla striata*, among others) have been found in late Pleistocene and early-middle Holocene fossil deposits in the coastal areas of Uruguay and Argentina, at latitudes up to 38°S (Figure 10), and their presence so far to the south is considered as an indicator of conditions warmer than today around 6-4.5 kyr BP (Aguirre, 1993; Gordillo, 1998; Clavijo *et al.*, 2005; Martínez *et al.*, 2006; Aguirre *et al.*, 2011). The interval between ~10 and 5 kyr BP corresponds to the Holocene climatic optimum, (Hypsithermal) marked by warmer temperatures in high latitudes (Emiliani, 1972; Rabassa, 1987; Ciais *et al.*, 1992). Aguirre & Farinatti (1999b) found a higher proportion (35%) of warm water mollusks (of the Caribbean/Brazilian malacological province) in middle Holocene fossil deposits of the Argentinean coast than in present-day assemblages (14%). Because the distribution of the Caribbean/Brazilian province is controlled by the warm Brazilian Current (Martínez & Del Río, 2002), a higher southern influence of this current during past interglacials has been considered the factor responsible for the southwards displacement of molluscan taxa that

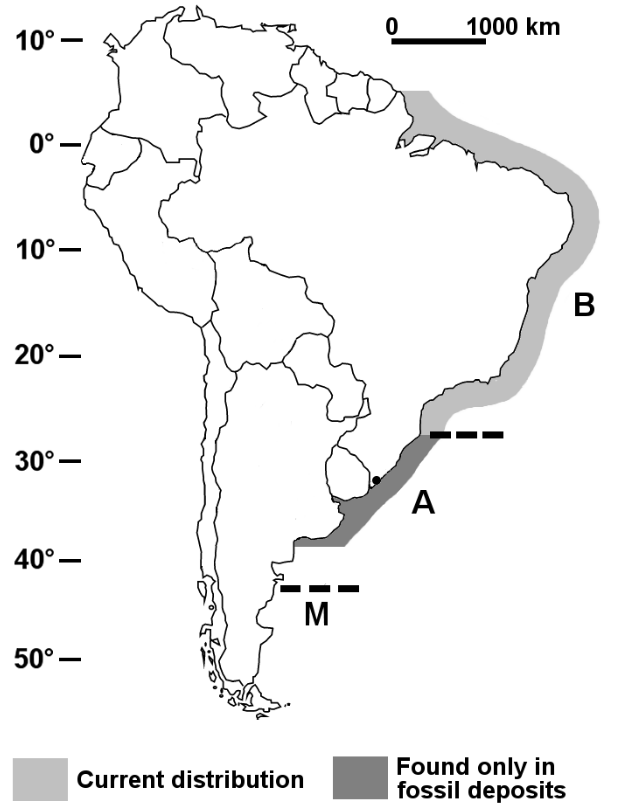

Figure 8 – Current distribution of *Anomalocardia brasiliana* along the Brazilian coast and its range during the late Pleistocene/early-middle Holocene. The distribution of *Arcinela brasiliana*, *Anadara brasiliana*, *Chione cancellata* and *C. paphia* is similar. The capital letters indicate the areas of the Caribbean/Brazilian (B), Argentinean (A) and Magellanic (M) malacological provinces; the black dot indicates the location of Chuí Creek.

today reach only up to southern Brazil (Aguirre, 1993; Martínez & Del Río, 2005).

The oceanographic conditions in the area that encompasses southern Brazil, Uruguay and the Bonaerensian coast of Argentina (up to ~41°S) are controlled basically by the interplay between the warm Brazilian Current (BC) and the cold Malvinas Current (MC), which is a branch of the Antarctic Circumpolar Current (ACC). The convergence between these two currents forms the Brazilian-Malvinas Confluence (BMC), which is subject to seasonal latitudinal shifts that characterize the Subtropical Front (STF). The southwards influence of the BC is stronger during austral summer, while during austral winter the pattern is reversed, when the ACC (and consequently the MC) are intensified; thus the intensity of the MC seems to exert control on the maximum southern reach of the BC (Matano *et al.*, 1993; Wainer *et al.*, 2000).

Several records have shown that during the Holocene hypsithermal, between ~10 and 5 kyr BP, the surface waters around Antarctica were warmer and ice-free, suggesting a polewards retreatment of the Subantarctic (SAF) and Polar (PF) fronts (Domack *et al.*, 2001; Hodell *et al.*, 2001; Lamy *et al.*, 2002). It seems likely that during past hypsithermals this retreatment resulted in weakened ACC and consequent reduction in the equatorwards influence of the MC, thus allowed the BC to reach farther south than during colder intervals. Besides, paleotemperatures obtained from foraminiferal tests found in drilling cores indicate temperatures between 1 and 5°C warmer than today for the waters surrounding Antarctica during the early phases of the last five interglacials (Becquey & Gersonde, 2003). Thus it seems possible that these warmer conditions would have allowed a southwards expansion of tropical to subtropical taxa. The age of some 235 thousand years for these shells (see below) is correlated with an hypsithermal phase of the penultimate interglacial; the foraminiferal assemblage found associated with the shells also point to warmer conditions (Lopes & Bonetti, 2012).

The current southernmost distribution (28^{o}S) of the ‘Brazilian’ taxa found here is coincident with mean sea surface temperature (SST) of 21^{o}C, while in the latitude of Chuí Creek it is of 18^{o}C (Garcia, 1998; de Castro *et al.*, 2006). If temperature was the key environmental factor controlling the distribution of those taxa, then it is reasonable to assume that mean SSTs during past hypsithermals were at least 3^{o}C warmer than today.

Anomalocardia was also recorded in fossil concentrations formed by the Holocene marine highstand around 6-5 kyr BP in the coast of Rio Grande do Sul (Closs & Forti,1971; Buchmann *et al.*, 1998; Caron, 2007; Lima, 2008), and Caron (2007) also reported the presence of *C. paphia*. This suggests that during the Holocene Hypsithermal the marine conditions were also warmer than at present. The cooler conditions during the Neoglacial stage that followed the hypsithermal, would led to the Present-day conditions of relatively increased influence of the Malvinas current, resulting in the northwards retreatment of the fauna adapted to warmer waters. Although reliable data about molluscan faunas correlated to the ~123-kyr marine transgression (MIS 5) from Southern Brazil are not available yet, Aguirre *et al.* (2011) considered that the high molluscan diversity found in deposits of this age in the Argentinean coast is also related to warmer conditions than at present. Thus, the data gathered so far points towards a cyclic pattern of southwards displacement of warmer marine conditions (and due southwards distribution of taxa adapted to warm waters) during the early phases of interglacial epochs. Conversely, the presence in the southern Brazilian continental shelf of late Pleistocene fossils of a brachiopod (*Magellania* cf. *M. venosa*) that today inhabits only the colder waters of Argentina, suggests that during glacial times the Magellanic fauna had its distribution extended northwards, following the displacement of the SAF and PF (Simões *et al*., 2011). Becquey & Gersonde (2003) estimated that these fronts suffered a northwards shift of ~5° during glacial intervals.

Comparison with previous studies

Previous works regarding fossil marine mollusks found in the Chuí Creek were presented by Closs & Forti (1971) and Forti Esteves (1974). Although those authors have not described the precise stratigraphic position of the fossils, they considered that all samples were from the “Chuí Formation”, represented by the marine sediments exposed at the base of the banks of the creek.

Delaney (1965) attributed a Pleistocene age for the “Chuí Formation”, while Closs & Forti (1971) considered it Holocene, and correlated it to the “Querandinense” transgression and the Vizcaíno Fm. of Uruguay, and to the “Belgranense” sediments of Argentina. Forti Esteves (1974) mentioned a ^{14}C age of 5,045 years for fossil shells collected 4 km to the south of the town of Chuí (outcrop E1/E2). Closs & Forti (1971) and Forti Esteves (1974) considered that all the five outcrops represented a single transgressive event, namely the Holocene transgression of some 6 kyr BP. Sprechmann (1978) also correlated marine deposits of the Vizcaíno Formation of Uruguay with those described from Santa Vitória do Palmar County, but concluded that the latter were also of late Pleistocene age.

Recent research on the outcrop from where samples E1/E2 were collected (Caron, 2007) revealed that this can be confidently considered a Holocene deposit, based on a ^{14}C age of 5,750 ± 40 years (cal. 6,260-6,080 yr BP) for an articulate bivalve (*Tagelus plebeius*). A ^{14}C age of 5,070 ± 70 years (cal. 5,073-5,541 yr BP) was found for a specimen of *M. isabelleana* from the Uruguayan bank of Chuí Creek (Martínez *et al.*, 2006), which is part of the same deposit from where the samples E1/E2 were collected. This deposit represents a Holocene estuarine environment, as indicated by the muddy sediment and abundance of the mollusks *T. plebeius* (in life position), *Erodona mactroides* and *Heleobia australis*, and is positioned some 2 meters above present sea-level (Caron, 2007). This deposit is part of of the Barrier-Lagoon System IV and represents the last marine transgression (MIS 1), that reached an estimated amplitude of 4 ± 1 meters above present sea-level in southern Brazil (Dillenburg & Hesp, 2009), thus it cannot be correlated to the fossil assemblage described here or to the samples E3, E4 and E5 of Closs & Forti (1971).

Although the fossils of the outcrop E3 of Closs & Forti (1971) are likely to be remains found scattered along the creek bed, removed from their original stratigraphic position by erosion, they probably came from the same stratigraphic level that contains the assemblage described here, because no shells were found so far in upper levels of the marine facies. The remains from E5, however, may represent fossils from different stratigraphic settings; these were collected among sediments extracted during the construction of a small dam in the late 1960s, according to verbal communication from local people. These shells are not exposed on the surface, so additional drillings are needed in order to identify their exact stratigraphic position.

The fossil assemblage described here is of Pleistocene age (see below), thus cannot be correlated to assemblages from outcrops E1 and E2 of Closs & Forti (1971).

Age and stratigraphic significance

Fifteen shells from the outcrops M001, 002 and 004 were dated using electron spin resonance (ESR), and provided a mean age close to ~235 kyr BP (Lopes et al. 2012). This result indicates a late middle Pleistocene age, and correlates this assemblage with the MIS 7, possibly representing the marine highstand during the substage 7.5. The ages are in agreement with the stratigraphic position of the shells, ESR ages of fossil mammals from the overlying sediments (Lopes *et al.*, 2010).

The presence of a ~2 meter-thick sand layer above the shells, containing ichnofossils *Ophiomorpha*, *Rosselia* and cross strata indicates the persistence of shallow marine conditions after the deposition of the shell concentrations, until sea-level gradually started to fall and sedimentation under terrestrial conditions began, as indicated by paleosoils, fluvial channels and vertebrate fossils found just above the marine facies. The absence of faciological or environmental changes above the shell concentrations indicate that although sea-level continued to rise after the deposition of the shells, the total depth did not change much. If depth was increasing, one would expected to find a greater proportion of mud, which accumulates in deeper areas (lower shoreface and offshore) below the influence of waves (Catuneanu, 2006). The sedimentary record, however, shows the persistence of shallow-marine conditions, seemingly under high rates of sedimentation, punctuated by storm events, as indicated by the shell concentrations and truncated ichnofossils *Rosselia* sp. Such a scenario of conditions of high sedimentation rates under a regime of sea-level rise is consistent with coastal aggradation followed by shoreline progradation, resulting in marine regression (Assine & Perinotto, 2001; Catuneanu, 2006).

Because of the low thickness and the same stratigraphic position of the shell concentrations along the banks of the creek, this assemblage can be used as a paleo sea-level indicator. Such indicators are scarce in the PCRS in comparison to other places of the Brazilian coast (e.g. Martin *et al.*, 2003; Angulo *et al.*, 2006). These concentrations are placed nearly 7.5 meters above present sea-level (Lopes & Simone, 2012), but are overlain by ~2 meters of marine sediments. Thus the total amplitude of this transgression was ~9.5 meters above present sea-level, higher than the transgression that formed Barrier III around ~123 kyr BP (Tomazelli & Dillenburg, 2007).

CONCLUSIONS

The fossils described by Lopes & Simone (2012) and here are the first record of body fossils from sediments of the Barrier System II. From the taxonomic composition, taphonomy, ecological aspects and stratigraphy of this assemblage, several conclusions can be drawn:

- Most of the fossil mollusks found in Chuí Creek are shallow-living taxa that inhabit sandy bottoms, mixed together with gastropods from deeper areas and a few hard substrate dwellers. This, plus the mixture of shells exhibiting very distinct taphonomic features indicate that it is a parautochtonous assemblage, probably formed by storm events.

- Most of the shell material from this assemblage is composed of unidentifiable, highly abraded shell fragments, as a result of continuous reworking by wave action in the surf zone.

- The well-preserved shells (lacking signs of abrasion, fragmentation and corrosion), including fragile juveniles, indicates that these remains were buried below the TAZ and were not subject to reworking, thus preventing further destruction by physical and chemical agents.

- The relative absence of corrosion, bioerosion or bioincrustation in most of the complete shells indicates that these fossils remained for a short period exposed in the TAZ prior to their final burial, while those that are bioeroded and/or corroded were exposed for longer periods.

- The assemblage described here is probably the source of the fossil molluscan sample E3 described by Closs and Forti (1971) and Forti Esteves (1974) as collected near the bridge over Chuí Creek. The stratigraphic position of the assemblage and ESR datings, however, indicate that these fossils are Pleistocene and not Holocene in age, as stated by those authors.

- The presence of molluscan taxa that are not found living today in the coast of Rio Grande do Sul and whose current distribution seems related to warmer conditions (*Anomalocardia brasiliana*, *Arcinella brasiliana*, *Anadara brasiliana*, *Chione cancellata* and *C. paphia*), also recorded in molluscan assemblages from Uruguay and Argentina, suggests a weakened Malvinas Current and stronger southwards influence of the Brazilian Current during this marine highstand.

- The presence of taxa that indicate warmer conditions in the deposits of late middle Pleistocene of Chuí Creek and also in middle Holocene deposits of the CPRS, suggests a cyclic pattern of warmer oceanographic conditions during the hypsithermal phases of past interglacials, coincident with marine highstands.

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TABLE 1 – Molluscan taxa found in the concentrations.

Class GASTROPODA
  Order VETIGASTROPODA
    Family FISSURELLIDAE
      Diodora patagonica (d'Orbigny, 1847) (Fig. 3A)
    Family TROCHIDAE
      Tegula patagonica (d'Orbigny, 1840) (Fig. 3B)

  Order CAENOGASTROPODA
    Family CALYPTRAEIDAE
      Bostrycapulus odites (Collin, 2005) (Fig. 3C)
    Family Nassaridae
      Buccinanops duartei (Klappenbach, 1961) (Fig. 3D)
      Buccinanops gradatus (Deshayes, 1844) (Fig. 3E)
    Family VOLUTIDAE
      Zidona dufresnei (Donovan, 1823) (Fig. 3F)
      Adelomelon brasiliana (Lamarck, 1811) (Fig. 3G)
    Family TEREBRIDAE
      Terebra gemmulata (Kiener, 1839) (Fig. 3H)
    Family OLIVIDAE
      Olivancillaria carcellesi (Klappenbach, 1965) (Fig. 3I)
      Olivancillaria urceus (Röding, 1798) (Fig. 3J)
      Olivancillaria deshayesiana (Duclos, 1857) (Fig. 3K)
    Family CONIDAE
      Lamniconus lemniscatus carcellesi (Martins, 1945) (Fig. 3L)

Class BIVALVIA
  Order ARCOIDA
    Family ARCIDAE
      Lunarca ovalis (Bruguière, 1789) (Fig. 4A)
      Anadara brasiliana (Lamarck, 1819) (Fig. 4B)
      Anadara chemnitzi (Philippi, 1851) (Fig. 4C)

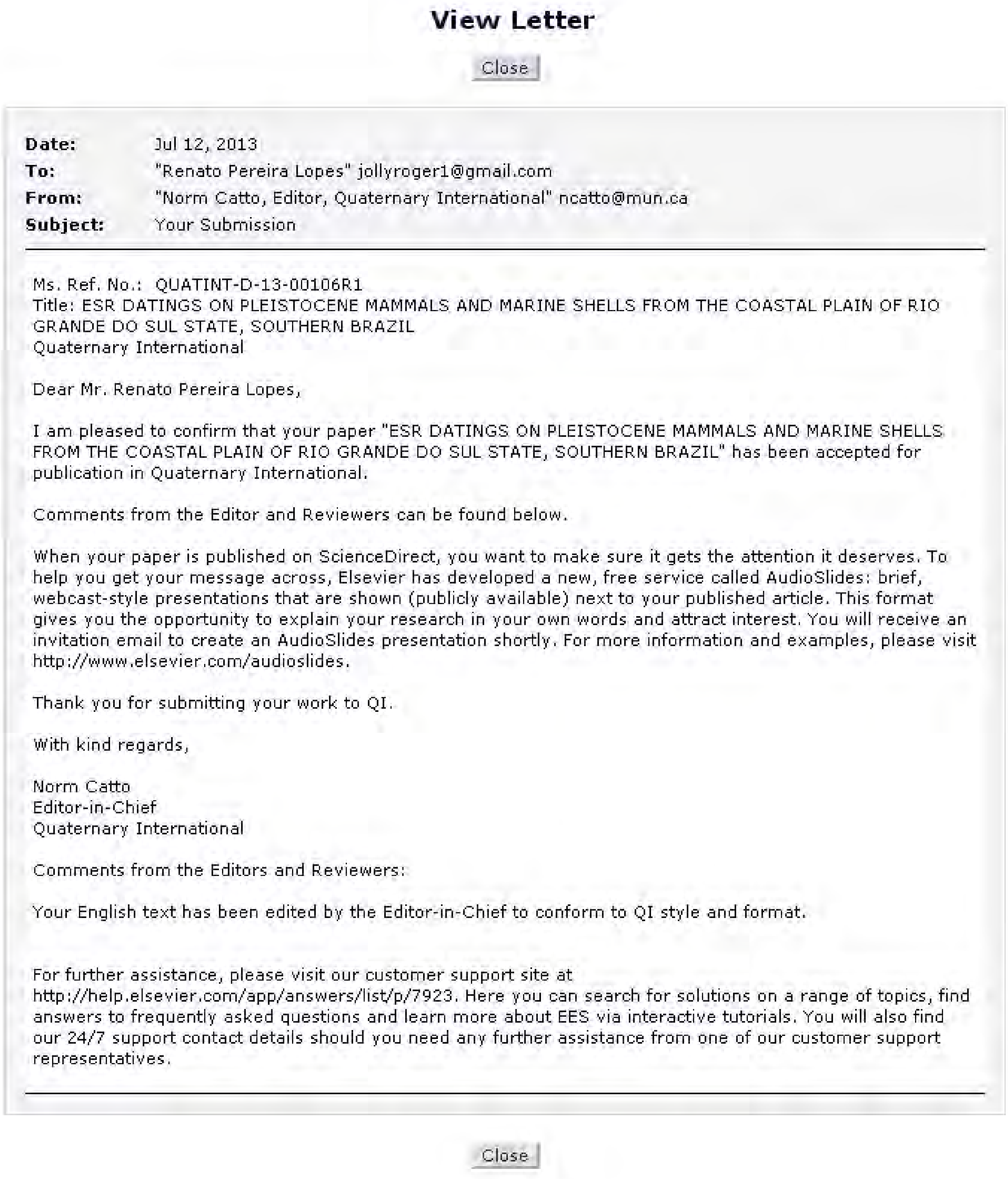
  Order MYOIDA
    Family NOETIIDAE
      Noetia bisulcata (Lamarck, 1819) (Fig. 4D)
      Corbula caribaea (d'Orbigny, 1842) (Fig. 4E)
    Family ERODONIDAE
      Erodona mactroides (Bosc, 1802) (Fig. 4F)
    Family GLYCYMERIDIDAE
      Glycymeris longior (Sowerby, 1833) (Fig. 4G)

  Order OSTREOIDA
    Family PLICATULIDAE
      Plicatula gibbosa (Lamarck, 1801) (Fig. 4H)
    Family OSTREIDAE
      Ostrea puelchana (d'Orbigny, 1841) (Fig. 4I)
      Ostrea equestris (Say, 1834) (Fig. 4J)
      Crassostrea rhizophorae (Guilding, 1828) (Fig. 4K)
    Family PECTINIDAE
      Chlamys tehuelchus (d'Orbigny, 1846) (Fig. 4L)

  Order VENEROIDA
    Family CHAMIDAE
      Arcinella brasiliana (Nicol, 1953) (Fig. 4M)
    Family CARDIIDAE
      Trachycardium muricatum (Linné, 1758) (Fig. 4N)
    Family VENERIDAE
      Anomalocardia brasiliana (Gmelin, 1791) (Fig. 4O)
      Chione cancellata (Linné, 1767) (Fig; 4P)
      Chione paphia (Linné, 1767) (Fig; 4Q)
      Pitar rostratus (Koch, 1844) (Fig. 4R)
      Amiantis purpuratus (Lamarck, 1818) (Fig. 4S)
    Family MACTRIDAE
      Mactra cf. *guidoi* (Signorelly and Scarabino, 2010) (Fig. 4T)
      Mactra janeiroensis (E.A. Smith, 1915) (Fig. 4U)
      Mactra isabelleana (d'Orbigny, 1846) (Fig. 4V)
      Mactra marplatensis (Doello-Jurado, 1949) (Fig. 4W)

TABLE 2 – Ecological data of the fossil molluscans found in Chuí Creek, compiled from Aguirre (1993); Rios (1994, 2009); Gordillo (1998); Aguirre & Farinatti (1999b); Martínez & Del Río (2005).

		ZONE			DEPTH	SUBSTRATE		SALINITY		LIFE MODE		PROVINCE		
Gastropoda	NUMBER OF SPECIMENS	SUPRALITTORAL	INTERTIDAL	INFRALITTORAL	METERS	HARD	SOFT	EURIHALINE	STENOHALINE	EPIFAUNAL	INFAUNAL	MAGELLANIC	ARGENTINEAN	CARIBBEAN
Diodora patagonica	1			■	0 to 30	■			■	■		■	■	
Tegula patagonica	1		■	■	0 to 30	■			■	■		■	■	
Bostrycapulus odites	9		■	■	0 to 30	■		■		■			■	■
Buccinanops duartei	1			■	0 to 10		■		■	■				■
Buccinanops gradatus	1			■	10 to 30		■		■	■			■	■
Zidona dufresnei	2			■	15 to 75		■		■	■			■	
Adelomelon brasiliana	9			■	25 to 77		■		■	■			■	
Olivancillaria urceus	2		■	■	0 to 30		■		■	■			■	
Olivancillaria carcellesi	3			■	10 to 15		■		■	■			■	
Olivancillaria deshayesiana	1		■	■	0 to 10		■		■	■			■	
Lamniconus lemniscatus carcellesi	1			■	10 to 30		■		■	■			■	■
Terebra gemmulata	1			■	15 to 90	■			■				■	
Bivalvia														
Mactra cf. *guidoi*	34			■	10 to 40		■		■		■		■	
Mactra isabelleana	58		■	■	0 to 10		■		■		■		■	
Mactra janeiroensis	64			■	0 to 30		■		■		■			■
Mactra marplatensis	2		■	■	0 to 30		■		■		■		■	
Pitar rostratus	195		■	■	0 to 30		■		■		■		■	
Amiantis purpuratus	157		■	■	0 to 30		■		■		■		■	
Chione cancellata	14		■	■	0 to 30		■		■		■			■
Chione paphia	7		■	■	0 to 30		■		■		■			■
Trachycardium muricatum	6		■	■	0 to 30		■		■		■		■	■
Corbula caribaea	38			■	10 to 30		■		■		■			■
Erodona mactroides	2	■	■		0 to 10		■	■			■		■	■
Ostrea puelchana	5			■	10 to 100	■			■	■			■	
Ostrea equestris	18		■	■	0 to 20	■		■		■			■	■
Crassostrea rhizophorae	4		■	■	0 to 30	■		■		■			■	■
Plicatula gibbosa	38		■	■	0 to 30	■			■	■			■	■
Chlamys tehuelchus	9			■	10 to 20		■		■	■			■	
Lunarca ovalis	6		■	■	0 to 30	■			■	■				■
Anadara brasiliana	1			■	15 to 75	■	■		■	■				■
Anadara chemnitzi	2			■	20 to 75		■		■	■				■
Glycymeris longior	2			■	10 to 75		■		■		■		■	■
Noetia bisulcata	3		■	■	0 to 10	■	■		■		■		■	■
Anomalocardia brasiliana	9		■	■	0 to 30		■		■		■			■
Arcinella brasiliana	2		■	■	0 to 10		■		■		■			■



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Date: Jul 12, 2013
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From: "Norm Catto, Editor, Quaternary International" ncatto@mun.ca
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Title: ESR DATINGS ON PLEISTOCENE MAMMALS AND MARINE SHELLS FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL
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Article Type: Late Quaternary of South America

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Abstract: The Coastal Plain of Rio Grande do Sul state (CPRS), in southern Brazil, encompasses four barrier-lagoon depositional systems formed by marine highstands during the Quaternary, but the ages of the Pleistocene systems older than ~125 ka BP are not precisely known due to the lack of absolute datings. In order to refine the chronology of these deposits, several fossils of terrestrial mammals collected in the fluvial facies of the Lagoon System III and fossil shells from the marine facies of the Barrier System II, exposed in the southern sector of the CPRS, were subject to dating by electron spin resonance (ESR). The ages of the mammalian remains range from 90 ± 10 to 43 ± 3 thousand years, thus representing the last glacial cycle (marine isotope stages, or MIS, 4 and 3). The mean EU age of the shells is 224 ± 24.6 ka, but this value is considered younger than the 'real' age because of excessive Uranium uptake observed among the younger shells. An estimated mean age of some 235 to 238 thousand years would agree with other ESR and TL ages obtained for fossils and sediments collected from beds overlying the shells, and would be consistent with the sea-level hightand at the early MIS 7 (substage 7e). The presence of bivalves and foraminifers that indicate ocean temperatures higher than at present seems to corroborate this estimate, given that MIS 7e was characterized by hypsithermal conditions.

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Rio Grande, July 6th, 2013

To the Editor of Quaternary International

We are pleased to re-submit the manuscript '**ESR DATINGS ON PLEISTOCENE MAMMALS AND MARINE SHELLS FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL**'.

All considerations and suggestions presented by the reviewers have been taken in account and reviewed in the best possible manner.

With our best regards,

Renato P. Lopes (Corresponding author)
Angela Kinoshita
Oswaldo Baffa
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ESR DATINGS ON PLEISTOCENE MAMMALS AND MARINE SHELLS FROM THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL

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ABSTRACT

The Coastal Plain of Rio Grande do Sul state (CPRS), in southern Brazil, encompasses four barrier-lagoon depositional systems formed by marine highstands during the Quaternary, but the ages of the Pleistocene systems older than ~125 ka BP are not precisely known due to the lack of absolute datings. In order to refine the chronology of these deposits, several fossils of terrestrial mammals collected in the fluvial facies of the Lagoon System III and fossil shells from the marine facies of the Barrier System II, exposed in the southern sector of the CPRS, were subject to dating by electron spin resonance (ESR). The ages of the mammalian remains range from 90 ± 10 to 43 ± 3 thousand years, thus representing the last glacial cycle (marine isotope stages, or MIS, 4 and 3). The mean EU age of the shells is 224 ± 24.6 ka, but this value is considered younger than the „real" age because of excessive Uranium uptake observed among the younger shells. An estimated mean age of some 235 to 238 thousand years would agree with other ESR and TL ages obtained for fossils and sediments collected from beds overlying the shells, and would be consistent with the sea-level hightand at the early MIS 7 (substage 7e). The presence of bivalves and foraminifers that indicate ocean temperatures higher than at present seems to corroborate this estimate, given that MIS 7e was characterized by hypsithermal conditions.

Keywords: Pleistocene; Megafauna; Paleoceanography; Electron Spin Resonance; Uranium uptake; Chronostratigraphy

Abbreviations: LGP-E – Laboratório de Geologia e Paleontologia (Notoungulata); LGP-G – Laboratório de Geologia e Paleontologia (Proboscidea).

1. INTRODUCTION

In recent years, Electron Spin Resonance (ESR) technique has been used for dating speleothems, travertines, marine organisms, terrestrial megafauna and archaeological remains (Grün, 1989; Rink, 1997; Kinoshita et al., 2008; Blackwell et al., 2010; Kerber et al., 2011). The physical basis of the ESR method is the measurement of the concentration of unpaired electrons by ESR spectroscopy. Electrons trapped in defects of the lattice of solid materials are produced by ionizing radiation emitted by radioactive elements (mainly ^{238}U, ^{232}Th and ^{40}K) present in the surrounding sediments and within the sample being dated; and from cosmic rays. The total dose of natural radiation is called equivalent dose (D_e) and is proportional to the age. By measuring the concentration of unpaired electrons trapped in the material and the dose rate from the environment and radioactive elements in the material itself, the age can be calculated The internal dose rate depends on the way in which the radioactive elements were incorporated by the sample. Thus some theoretical models for uranium uptake have been developed and implemented in a computational algorithm . In the Early uptake (EU) model it is assumed that uranium incorporation occurs in a short time relative to age and remains constant (Bischoff and Rosenbauer, 1981). This model corresponds to closed system and provides the minimum age of sample. In the Linear Uptake model, the absorption of Uranium occurs at a constant rate (Ikeya, 1993). These models were implemented in the ROSY (Brennan et al 1999) and DATA (Grün, 2009a) software for tooth dating. In the ROSY software, there is another option, the Combination Uptake model, in which, it is possible to calculate the ages with different combinations of the EU and LU for enamel and dentine. The Recent Uptake (RU) provides de maximum age since it is assumed that the Uranium present in the tissues was recently incorporated (Blackwell and Schwarcz 1993). When U-series is used coupled to ESR, the uptake history can be determined by solving the equation proposed by Grün et al (1988). This methodology has been applied successfully in several problematic dating (Grün 2009b; Falgueres et al 2010; Duval et al. 2011; Duval et al. 2012) and it becomes increasingly important as the ages increases and the difference between the ages obtained by models above mentioned are very large, thus justifying the resources needed to perform this method.

ESR has been employed for dating Quaternary fossils of mammals, human remains, mainly using tooth enamel, and shells of both marine and terrestrial mollusks (Molodkov, 1988; 1993; Engin et al., 2006; Kinoshita et al., 2006). This method is useful for Quaternary fossils because it can determine ages older than the maximum limit of ^{14}C (about 50,000 years) its upper limit is dependant on the saturation of defects and signal stability in older samples and on the thermal stability of the defects (Ikeya and Ohmura, 1981; Radtke et al., 1985; Shimokawa et al., 1992; Schellmann and Radtke, 1997).

The coastal plain of Rio Grande do Sul state (CPRS, Fig. 1), in southern Brazil, is a geomorphological unit formed by successive marine transgressions correlated to glacial cycles of the Quaternary; the exact ages of the depositional systems, however, are mostly unknown. The only ages published so far were obtained for sediments from the northern and central sectors of the CPRS using thermoluminescence (TL) (Poupeau et al., 1988; Buchmann and Tomazelli, 2003), and shells, peat and mammalian remains from the southern sector using ^{14}C and ESR (Forti Esteves, 1974; Buchmann et al., 1998; Caron, 2007; Lima et al., 2013; Lopes et al., 2010).

Two major problems concerning the ages of the Pleistocene units of the CPRS are the predominance of sandy deposits mostly reworked by aeolian activity and/or covered by younger sediments, and the absence of fossil materials with good stratigraphic control. Although Holocene shells and peat are found in or near the present-day shoreline, Pleistocene materials in their original stratigraphic setting are scarce. The only deposit known so far that contains such materials is Chuí

Creek, located in the southern sector of the CPRS. Lopes et al (2010) published seven ESR ages from mammalian remains from the continental shelf (dated between ~650 and 18 ka BP) and four from the banks of Chuí Creek, with ages between 226 and 34 ka BP. Although these ages were useful for refining the stratigraphy, paleobiogeography and paleo sea-level curves for the CPRS, additional dating on fossils from Chuí Creek are necessary in order to establish more robust interpretations. Here are presented new results on dating of other mammalian fossils from the creek and from marine shells collected from a stratigraphic interval that outcrops below the mammalian remains.

2. GEOLOGICAL SETTING

The study area encompasses the Chuí Creek, located in the southernmost portion of the CPRS (Fig. 1A); in this area only three of the four barrier-lagoon depositional systems that form the CPRS are preserved (Fig. 1B). The creek flows over a plain that is part of the Lagoon III depositional system, located between the Pleistocene barriers II and III; each barrier was formed in response to a marine transgression correlated to an interglacial epoch. While the age of the Barrier System III was found to be correlated to the ~125 ka BP marine transgression (MIS 5), according to TL datings (Poupeau et al., 1988; Buchmann and Tomazelli, 2003), the age of the Barrier System II was considered to be of some 325 thousand years, by correlation with the oxygen isotopic curves of Imbrie et al. (1984) (Villwock and Tomazelli, 1995; Tomazelli et al., 2000). The Barrier-Lagoon System IV comprises the present coastline and was formed by the marine transgression around ~6ka BP (Caron, 2007; Lima, 2013).

The Chuí Creek is the most studied Pleistocene fossiliferous locality of the CPRS. It flows parallel to the coastline in a NE-SW direction, which changes to NW-SE near the town of Chuí following the Chuí faulting zone. Prior to the 1960s, the creek was a shallow stream surrounded by wetlands, but it was further excavated in 1963 for agricultural purposes. During the excavations, a stratum containing remains of extinct mammals was exposed (Paula Couto and Cunha, 1965). The fossiliferous interval has been extensively studied in the last 10 years and has provided several new records of extinct mammals, besides information on past environments and climate conditions in the area (Lopes et al., 2009, 2011, 2013; Lopes, 2013; Pereira et al., 2012).

Closs and Forti (1971) reported the presence of several species of marine mollusks in the creek, but did not correlate these remains with any specific stratigraphic interval, thus this material probably consisted of shell remains scattered on the creek bed due to erosion of the banks, as can be seen today. Recently, four outcrops containing concentrations of marine shells were discovered in their original stratigraphic position, exposed at the base of the banks of the creek (Lopes and Simone, 2012).

The total height of the banks is of some 4.5 meters (Fig. 2A, B). The lowermost layer is composed of well-selected, quartz sand with small amounts of biogenic carbonate, heavy minerals and micas, contains ichnofossils *Ophiomorpha nodosa* and *Rosselia* sp., shell concentrations (Fig. 2C) and exhibits parallel and cross stratifications, thus indicating a shallow marine environment (upper shoreface). Some 2 meters of this layer remain above the creek bed, and although the total thickness is yet unknown, it measures more than 4 meters, based on soundings with hand auger. In the first survey of the stratigraphy of Chuí Creek, Soliani (1973) considered the marine sediments to be part of the "Chuí Formation" of Delaney (1965), while the overlying mammal-bearing stratum has been assigned to a new unit he called "Santa Vitória Formation". The reviews on the geology and stratigraphy of the CPRS in the 1980s led to the replacement of the lithostratigraphic units by chronostratigraphic units (barrier-lagoon depositional systems) formed by associations of facies (Tomazelli and Villwock, 2005). Following the new scheme, the marine sediments exposed along the banks of the creek are part of the marine facies of the Barrier System II.

After the marine highstand, sea-level retreated and the uppermost portion of the marine facies was occupied by paleosoils, fluvial systems and possibly small lakes that constitute the

Lagoon System III. The contact between the marine facies and the overlying terrestrial environment is gradual, except in places where ancient fluvial streams eroded the marine sediments. These fluvial facies contain remains of Pleistocene terrestrial mammals, mostly fragmented and isolated, indicating intense erosion and reworking after the fossilization (Lopes, 2009; Lopes et al., 2009). The fossiliferous bed measures between 1.0 and 1.5 meter in thickness, and is composed of silty sand with root traces and iron oxide concentrations; at some points of the banks a ~40cm-thick caliche horizon consisting of nodules and rhizocretions is found at its upper portion. Above the fossiliferous bed the amount of silt increases and vertebrate remains disappear. The silty layer measures some 1m in thickness, and is covered by a ~50-70 cm-thick layer of organic matter-rich sand and clay of Holocene age, indicated by the presence of paleoindian remains (Schmitz et al., 1997).

3. MATERIAL AND METHODS

3.1 Fossil Teeth

Six teeth of extinct mammals, three of the notoungulate *Toxodon* and three of the proboscidean *Notiomastodon* (= *Stegomastodon*) were selected for dating. All remains have been collected from the fossiliferous level in the banks of Chuí Creek, near the town of Santa Vitória do Palmar, and belonged to the paleontological collection of the Universidade Federal do Rio Grande (FURG). Three samples of the surrounding sedimentary matrix containing the fossils were also collected. considering that the sediments containing mammalian remains are rather homogeneous, composed mostly of siliciclastic sand deposited and reworked by fluvial systems,. Because the area is isolated from other fluvial systems since the Barrier II was formed, it is considered here that the fossil-bearing layer did not receive sediment contributions from external sources that could affect the results. The humidity of 10% was used to calculate the cosmic ray attenuation. This water content was estimated considering that the fossils are most of the time located above the water table (except during winter, when large floods can cover the fossiliferous horizon from periods of hours to a few days), and the beds above the shells are rather impermeable. The fossils are also too deep beneath the surface to be reached by plant roots, thus the only humidity that could usually affect the fossil remains comes from precipitation, but this reaches only the first few centimeters of the banks.

Between 2.2g and 5g of enamel and dentine were extracted from the specimens by mechanical drilling; enamel was separated from dentine using the thermal expansion technique. The samples were immersed in liquid nitrogen for a few minutes and then warmed to room temperature; this procedure was repeated a few times until enamel was detached from dentine due to differences in thermal expansion between these two materials. The enamel was then etched in a 1:10 HCl solution for 2 minutes to remove a thin surface layer (approximately 100μm in thickness). The etched enamel was manually powdered until obtaining a fine (about 500 μm in diameter) powder which was then divided in 200 mg samples for irradiation with additive doses using a radioactive source with known energy (^{60}Co). The final dose of each aliquot was obtained in a single step, with the same dose rate, to increase the ESR signal. ESR spectrum was recorded in a JEOL FA-200 X-band spectrometer with the following acquisition parameters: central field 344mT, scan width 10mT, scan time 1min, modulation amplitude 0.1mT, microwave power 2mW, time constant 100ms. The amplitude peak-peak at $g_{\perp}$ was used to construct the dose response curves. The dose-response curve was adjusted using an single saturation exponential function (Ikeya, 1993):

(equation 1)

where I_0 is the signal intensity of the saturation signal, D the additive dose and D_0 is the dose at saturation, using instrumental weighing ($1/I^2$) (Grün and Brumby, 1994, Skinner 2000). Neutron activation analysis (NAA) was used to obtain the concentration of ^{238}U, ^{232}Th and ^{40}K in enamel, dentin and sediments. Once the D_e was obtained, the ages of the samples were calculated using one of the softwares available. Although DATA (Grün, 2009a) has incorporated the most recent beta attenuation factor, the software ROSY (Brennan et al., 1999) allows combinations of uptake models for dentine and enamel and was used in this work. Due to differences on porosities , the combination uptake (CU) was set as EU for dentine and LU for enamel is the best choice. This option is in accordance with U-concentration maps obtained by ICPMS that show that U-migration through the external enamel surface is very small when compared to the bulk of the uranium that migrated internally through the dentine into the enamel (Grün et al., 2008).

3.2 Fossil Shells

Shells were collected from three outcrops exposed at the banks of Chuí Creek (M001, M002 and M004). The three concentrations are at the same stratigraphic horizon, and seem to have been accumulated by a storm event, thus are considered as a single assemblage. Today, the concentrations are positioned at the level of the creek, thus are permanently saturated in water. Shell remains consisted mostly of bivalves, with few gastropods (Lopes and Simone, 2012). One major concern regarding the suitability of these shells for dating is the fact that most of the bivalves are disarticulated. Schellmann and Radtke (1997) considered that only well-preserved, articulated (in living position) bivalves are useful for datings, but the only articulated specimens from Chuí Creek are six *Corbula caribaea*, a taxon that is too small to provide reliable results using ESR.

One sample of the sedimentary matrix surrounding the shells was collected from each outcrop; the sediments samples are homogeneous, consisting of well-selected, rounded mature siliciclastic sand. The presence of articulated bivalves and ostracod carapaces indicates that the shells have not undergone reworking before being collected.

The dating of reworked shells could give a wide range of ages due to time-averaging (e.g. redeposition of older shells together with much younger material). As an attempt to minimize these problems, the taxon selected for dating was the bivalve *Amiantis purpuratus*, because it is abundant in all outcrops and is a shallow-living species, thus the probability of survival of the shells of dead individuals for more than 10^3 years is low, as pointed by studies of the rate of mechanical and chemical destruction of shells in marine habitats (Flessa and Kowalewski, 1994). Because of the higher rate of shell destruction in shallow areas, it is expected that well-preserved shells of taxa that inhabit these areas represent material that was quickly buried shortly after the individuals have died. Thus, the use of *A. purpuratus* would in theory avoid large uncertainties that could result from the larger time-averaging of species that inhabit deeper areas of the continental shelf, where chemical and mechanical destruction rates are lower (Flessa and Kowalewski, 1994). Besides, considering that the assemblage seems to have been formed by a short-termed depositional event and that the shells were covered by marine sediments and were not disturbed until the creek was excavated, they are probably reliable indicators of the time of deposition of the marine facies. The use of a single taxon would also exclude variations related to interspecific physical differences, as pointed by other studies (Shimokawa et al., 1992; Brumby and Yoshida, 1994).

Five pristine, similar-sized and well-preserved (without signs of abrasion and / or bioerosion), disarticulated valves of *A. purpuratus* from each outcrop were selected for dating. The samples were subject to etching in a 1:10 HCl solution for 1 minute for removal of the surface layers of the shells (Table 1). After drying, the shells were manually powdered with agate mortar and pestle; the sediment samples were also manually disaggregated. The resulting powder (<0.5mm) was separated in subsamples and irradiated with additive doses up to 550Gy using a radioactive source with known energy (^{60}Co). Aliquots from the fifteen shells and sediment samples from each outcrop were subject to Neutron Activation Analysis (NAA) to determine ^{238}U, ^{232}Th and ^{40}K concentrations The ESR spectra of subsamples were recorded using a X-band (9.5GHz) JEOL FA-200 spectrometer. The acquisition parameters were: center field 338mT, sweep width 1.5mT, scan time 1minute, modulation frequency 100kHz, modulation width 0.025mT, time constant 100ms, microwave power 1mW. The value of the double integration signal was associated to the additive dose for obtaining the dose-response curve. As performed in the fossil teeth experiment, the dose-response curve was adjusted using the equation (1) using instrumental weighing ($1/I^2$) (Grün and Brumby, 1994; Skinner, 2000).

4. RESULTS AND DISCUSSION

4.1 Mammalian remains

In South America there are few Pleistocene fossil localities with both good stratigraphic control and absolute ages for the associated fossils. This had hampered the biostratigraphic correlations, that have been based mostly on the Stage/Ages defined from the fossil beds of the Pampean region of Argentina (Cione and Tonni, 1999; Lopes 2013). The reworked nature of most fossiliferous units of fluvial origins indicate that absolute datings on fossil remains rather than on sediments from such deposits is the most reliable way of establishing biostratigraphic correlations.

Table 2 lists concentration of ^{238}U, ^{232}Th and ^{40}K in enamel, dentin and sediments. Table 3 lists the Equivalent Dose (D_e), early uptake (EU), linear uptake (LU) and combined uptake (CU) of the fossil teeth. The value of 190 µGy / year was found for cosmic radiation after corrections of latitude and longitude, altitude (Prescott and Hunton, 1994). The water content of the sediment was considered 10%, values of $^{234}U / ^{238}U = 1.20 \pm 0.20$, $\alpha_{eff} = 0.13 \pm 0.02$

Although some obtained ages are older than most of the previously published ages, they are in agreement with others presented by Lopes et al. (2010). These CU ages are also consistent with ages obtained for large mammal fossils from the Touro Passo Formation in the western Rio Grande do Sul state (Kerber et al., 2011), thus reinforcing the biostratigraphic correlation between both areas and also with those from the Sopas Formation of Uruguay (Ubilla et al., 2009).

The new ages, together with the results previously published by Lopes et al. (2010), also help to refine the chronology of the formation of the fossil mammalian assemblage from Chuí Creek. The ages indicate that most of the fossils represent the time interval between the end of MIS 5 and MIS 3 (roughly between 90 and 30 ky BP); the only specimen dated so far older than this interval is the aforementioned 226 ka-old tooth of *Toxodon*, which represents MIS 7 (Fig. 4). These results in part fill the ~180 thousand years gap between the oldest fossil dated of 226 ± 35 ka and the next older of 42 ± 3 ka from Chuí Creek (Lopes et al., 2010). The relative absence of specimens older than 80 ka may be a result of successive reworking and destruction of the fossils from this location by fluvial action (Lopes, 2009; Lopes et al., 2009). The sedimentary record exposed along the banks of the creek shows evidences of humid and dry phases, linked to climate oscillations; it is likely that older fossils have a lower chance of being preserved because of successive reworking by episodes of fluvial reactivation. The co-occurrence in the same stratigraphic interval of fossils with such age variation corroborates the existence of several episodes of burial-exhumation-redeposition of most of the remains and associated sediments (Lopes, 2009).

The identification of the time interval during which these animals lived in southern Brazil may help to identify the causes that led to their disappearance in this area. Most of the specimens are chronocorrelated to intervals of milder climates, mostly the MIS 3 interstadial (Figure 4), a relatively warm interval marked by warm (and cold) pulses in both hemispheres caused by Dansgaard-Oeschger (and Heinrich) events (EPICA Community Members, 2006; Rabassa and Ponce, in press). This pattern suggests that the late Pleistocene climatic oscillations affected the faunal dynamics of the large mammal community that inhabited the area. Several studies have pointed that the interval between ~50 and ~18 ka BP in south and southeastern Brazil and the Argentinean Pampas was marked by intercalated dry/humid and cold/warm conditions, followed by very dry conditions during the Last Glacial Maximum (LGM), between ~25 and ~11 ka BP (Ledru, 1993; Behling and Lichte, 1997; Turcq et al., 1997; Carignano, 1999; Iriondo, 1999). Other geological records show that during the pre-LGM interval the environmental changes in southern Brazil were also influenced by insolation-driven millennial-scale oscillations that occurred in the Northern Hemisphere and affected the patterns of precipitation (Cruz et al., 2005; Wang et al., 2007).

4.2 Shells

Figure 3 shows the dose response curve for sample 1 from outcrop M001. The equivalent dose (D_e) was determined by fitting with exponential function (Ikeya, 1993) (equation 1).

Table 4 lists the concentration of ^{238}U, ^{232}Th and ^{40}K of shells and sediments that were used to convert D_e in ages using the software DATA (Grün, 2009a). The value of 116 µGy / year was found for cosmic radiation after corrections of latitude and longitude, altitude (~7 m a.s.l) and depth (~4,5 m). The water content of the sediment was considered 100%, because the water table is at the same level of the shells since the creek was excavated in the early 1960s. Also for the age calculations the values of ^{234}U / $^{238}U = 1.20 \pm 0.20$, $\alpha_{eff} = 0.10 \pm 0.02$ and density = 2.71 ± 0.02 g/cm^{-3} were adopted following the literature (Blackwell et al., 2010).

The calculated early uptake (EU) and linear uptake (LU) ages for the shells are listed in Table 5. Because the oldest dated tooth from the fluvial facies above the marine sediments was dated of 226 ± 35ka (Lopes et al., 2010), it was expected that all shells were older than this; the results however, show a wide variation. The ages obtained through the EU model range from 140 ± 40 ka to 430 ± 30 ka; the average ages are 266 ± 30 ka for the shells from M001, 222 ± 26 ka for M002, and 184 ± 18 ka for M004. The mean EU age for the fifteen specimens is of 224 ± 24.6 ka and corresponds to the average of the minimum age of shells (Ikeya, 1993; Blackwell 1995). The LU ages range from 570 ± 20 ka to 230 ± 30 ka, with a mean value of 340 ± 31 ka.

Differences of approximately 120 ka between EU and LU models due to uranium uptake modeling were also observed by Schellmann and Radtke (1999), indicating how sensitive this information can be to the age obtained, thus the results shall be considered as minimum ages, unless it is assumed that the enrichment has occurred shortly after the burial of the material (Radtke et al., 1985). Because Early Holocene shells already display uranium concentrations equivalent to those found in shells from the Last or Penultimate Interglacial, the most reliable ages are those obtained by the EU model (Schellmann and Radtke, 1997; 1999; 2000). The amount of uranium found in the fifteen shells was relatively low, ranging from 0.28 to 1.91 ppm (1.09 ppm on average), thus suggesting that the U-uptake occurred shortly after the shells were deposited; recent shells exhibit uranium concentrations around 0.2 ppm (Schellmann and Radtke, 1999). Nevertheless, the specimens with higher U-concentrations are also the ones that exhibit the younger ages (Fig. 5); as already mentioned, EU ages are the youngest possible (Blackwell, 1995). The coupled ESR-US method provides results of age independently of uranium uptake, but as in this study the US determination was not available, so the entire discussion here is based on the EU ages, taking into account that these are probably younger than the „real" ages of the samples.

The U-uptake may be related to the thickness (higher concentrations are usually found in thinner shells), the type of surrounding matrix (higher in sandy sediments) and the mobility of the interstitial water (Shimokawa et al., 1992). The sedimentary matrix in which the shells are embedded is composed of fine sand; the shells themselves were progressively buried beneath a ~4.5 meter-thick sedimentary cover, and although it is not clear how much the water table varied since their burial, it is probable that they remained below the water table until the creek was excavated in the early 1960s. Today, the shells are at the mean level of the creek, constantly saturated in water (Fig. 2D).

On the other hand, some shells exhibit very low uranium concentrations, and conversely are the ones with older ages. This pattern needs further investigation, but may indicate that these shells were reworked from older deposits or that there was some diagenetic alteration on these specimens, which interfered in the uranium uptake. Considering that the assemblage is composed mostly of shallow-living mollusks accumulated in the upper shoreface, with many specimens well-preserved, including small and fragile juveniles, it seems unlikely that the large age discrepancies represent time-averaging, because the shells would not have withstood the mechanical destruction for such a long time in this high-energy environment (Flessa and Kowalewski, 1994). Large time-averagings are expected to be found in transgressive lag deposits that are formed on the shelf during marine transgressions, as those found in the continental shelf today (Figueiredo, 1975)

The ages of the shells reinforce the interpretation that the marine facies of the Barrier II is older than 226- thousand years, based on a tooth from the overlying fossiliferous bed (Lopes et al., 2010). Despite of the large ages difference of the shells, the results seem consistent with TL ages obtained for marine sediments collected about 1 meter above the shells (Lopes, unpublished data). Given the time interval indicated by the EU (~224 ± 24.6 ka BP) and the LU (~340 ± 31 ka BP) models, and that the EU ages are the youngest possible, these shall be considered younger than the „real" ages due to excessive U-uptake. An estimated age closer to ~234-238 ka BP, therefore within the error margin of the EU model, seems reasonable and also agrees with the interglacial peak of the marine isotope substage 7e, according to oxygen isotope curves for the Atlantic (Lisiecki and Raymo, 2009; Fig. 4). The interval between ~238 and 234 ka BP, within the substage 7e, is considered a hypsithermal, marked by warmer ocean temperatures than at present in the southern Atlantic (Robinson et al., 2002; Becquey & Gersonde, 2002; 2003). The shell assemblage from Chuí Creek also points to oceanographic conditions warmer than at present, indicated by the presence of the bivalves *Anadara brasiliana*, *Anomalocardia brasiliana*, *Chione cancellata* and *C. paphia*, which today are found living only in areas of the Brazilian coast to the north of Rio Grande do Sul state, and also by foraminifers found together with the shells (Lopes & Bonetti, 2012; Lopes et al., 2012).

Kanfoush et al. (2002) and Rainer and Gersonde (2002) reconstructed past oceanographic conditions from the Atlantic sector of the Southern Ocean and concluded that the early phases of the last four interglacials were hypsithermals, characterized by higher temperatures in comparison to the present. Thus, the presence of warm-water bivalves in the coastal waters of southern Brazil around ~234-238 ka BP seems consistent with the hypsithermal recorded at the beginning of MIS 7 (substage 7e). A hypsithermal was also identified during the late MIS 7 (substage 7a) around 200 ka BP, which would fall within the lower error margin of the EU ages; nevertheless, one tooth of *Notiomastodon* from the continental shelf dated as of 207 ± 28 ka BP (Lopes et al., 2010) indicates that sea-level had already retreated around 200 ka BP.

On the other hand, a LU age around ~340 ka BP would not be consistent with a sea-level highstand, considering that at this time sea-level was more than 120 meters below the present due to the glacial maximum of MIS 10 (Rohling et al., 1998). Nevertheless, an age closer to ~325 ka BP, within the lower error margin, would be consistent with the marine transgression of MIS 9.

4.3 Stratigraphic implications

The ages presented here increase the available ages for the deposits of the CPRS (Table 6), and help refine the sea-level curves for the coast of Rio Grande do Sul state presented by Lopes et al. (2010) (Fig. 6). Because of the scarcity of datable indicators of past sea-levels, mainly for the Pleistocene deposits, the exact timing of the sea-level highstands that formed the barrier-lagoon depositional systems have been mostly unknown. Based on the oxygen curves of Imbrie et al. (1984), Villwock and Tomazelli (1995) correlated the Barrier-Lagoon System II with the marine highstand of MIS 9, while the ages presented here suggest instead that the Barrier System II was formed by the marine transgression correlated to MIS 7. That leaves open the question of whether the oldest system (Barrier-Lagoon I) is correlated to MIS 9 or if it may represent an even older marine highstand.

The ~125 ka-old marine transgression that formed the Barrier System III, correlated to MIS 5 and called Cananéia Transgression or Penultimate Transgression, is relatively well documented along the Brazilian coast (Bittencourt et al., 1983; Suguio et al., 1986), but deposits formed by older transgressions are scarce. In the northeastern Brazilian coast, several raised marine terraces of a unit called Barra de Tabatinga Formation have yielded TL and optical stimulated luminescence (OSL) ages of ~210-220 thousand years (Barreto et al., 2002; Suguio et al., 2011). The similar ages suggest that the Barrier System II and the Barra de Tabatinga Formation have been formed by the same transgressive event. The presence of chronocorrelated transgressive marine deposits in two distant areas (more than 3,000 km from each other) indicates that there are probably other similar deposits along the Brazilian coast that have not yet been identified due to lack of absolute datings..

5. CONCLUSIONS

The new ESR datings confirm a Late Pleistocene age for most of the mammalian remains found in Chuí Creek and their correlation with similar faunas found in deposits from Northern Uruguay and Western Rio Grande do Sul state. These new results help to put this assemblage in a more precise time interval, which should contribute to biostratigraphic correlations with other localities and for the assessment of the causes that led to the disappearance of the large mammals in the area. One hypothesis is that the progressive increase in aridity after ~34 ky BP, correlated to the LGM, may have played a role in their (pseudo)extinction. These ages will also help to reconstruct and understand the evolution of the terrestrial environments in the southern CPRS during the late Quaternary.

The mean EU age of ~224 ka obtained from the fossil shells seem to be in agreement with other unpublished datings and provide an estimate for the timing of the marine transgression that formed the Barrier System II. These results indicate a Late Middle Pleistocene age; considering that 224 ka is the youngest possible age, and that the younger shells are probably younger than the „real‟ age due to excessive Uranium uptake, an estimated age of ~234-238 ka BP for the shells seems closer to the „real‟ ages and would be consistent with the marine highstand during early MIS 7 (substage 7e). This time interval was characterized by higher ocean temperatures, related to the hypsithermal phase at the beginning of the interglacial; such conditions are indicated by the presence in the fossil assemblage of bivalves that today live only in warmer areas to the north of Rio Grande do Sul state. Although the LU values suggest a mean age of 340 ± 31 ka BP for the shells, the higher reliability of the EU model and the correlation with other yet unpublished ages suggest that the EU values are closer to the real ages than the LU values.

These results help to refine and improve the knowledge regarding the chronostratigraphy and sea-level variations for the Coastal Plain of Rio Grande do Sul state, showing that the maximum amplitude of the marine highstand that formed the Barrier System II was reached around 230 ka BP. The ages also indicate chronological correlation of this depositional system with other marine deposits from northeastern Brazil. This correlation among two distant areas indicates that other depositional systems formed by this marine transgression are likely to be found in other parts of the Brazilian coast.. ESR datings on shells, in conjunction with other methods and datable materials, are a potential tool for refining the chronology of the middle to late Quaternary deposits along the Brazilian coast.

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FIGURE CAPTIONS

Figure 1 – A) Location of Chuí Creek, in the southernmost Rio Grande do Sul state, a rectangle indicates the area where the fossils were collected. Dashed lines indicate boundaries

between the depositional systems: a) Lagoon II; b) Barrier II; c) Lagoon III; d) Barrier III; e) Lagoon IV and f) Barrier IV; B) West-East transect (modified from Tomazelli and Villwock, 2005) of the coastal plain in the area where Chuí Creek is located (indicated by arrow).

Figure 2 – A) panoramic view of the creek. B) stratigraphic sequence exposed along the banks of the creek, with indication of the position of the fossils. C) marine shells outcropping at the base of the left bank; on the insert, one specimen of *Amiantis purpuratus*.

Figure 3 – (A) ESR spectrum of fossil shell irradiated with dose of 400Gy. The spectrum is composed and the signal of CO_2^- radical ($g_\perp$ =2.0018 and $g_{//}$=1.9973) is present. (B) Dose response curve (DRC) built by double integration of signal OF sample no.1 from outcrop M001. The fitting parameters are D_e = 95 ± 7 Gy, I_0 = 0.77 ± 0.11 and D_0 = 770 ± 160 Gy.

Figure 4 – Correlation of the marine isotope stages (MIS) and oxygen isotope curve (= ice volume) from Atlantic Ocean core samples (Lisiecki and Raymo, 2009) with the ages of the mammalian remains (black circles) and EU / LU ages of the shells (triangles) from the Chuí Creek. Open circles indicate the ages of mammalian fossils from the continental shelf (Lopes et al., 2010).

Figure 5 – Relationships between uranium concentration and EU / LU ages of the shell samples.

Figure 6 - Simplified scheme of sea level oscillations in southern Brazil between Late Miocene and Holocene. Oscillations older than 400 ka are indicated by ostracode assemblages from drilling cores (Carreño et al., 1999), while the three last highstands are represented by

geomorphological features and fossils (Villwock and Tomazelli, 1995; Caron, 2007 and this paper). The dashed lines indicate inferred oscillations (from Rohling et al., 1998); open circles indicate mammalian fossils from the continental shelf dated by ESR (modified from Lopes et al., 2010).

Figure 1

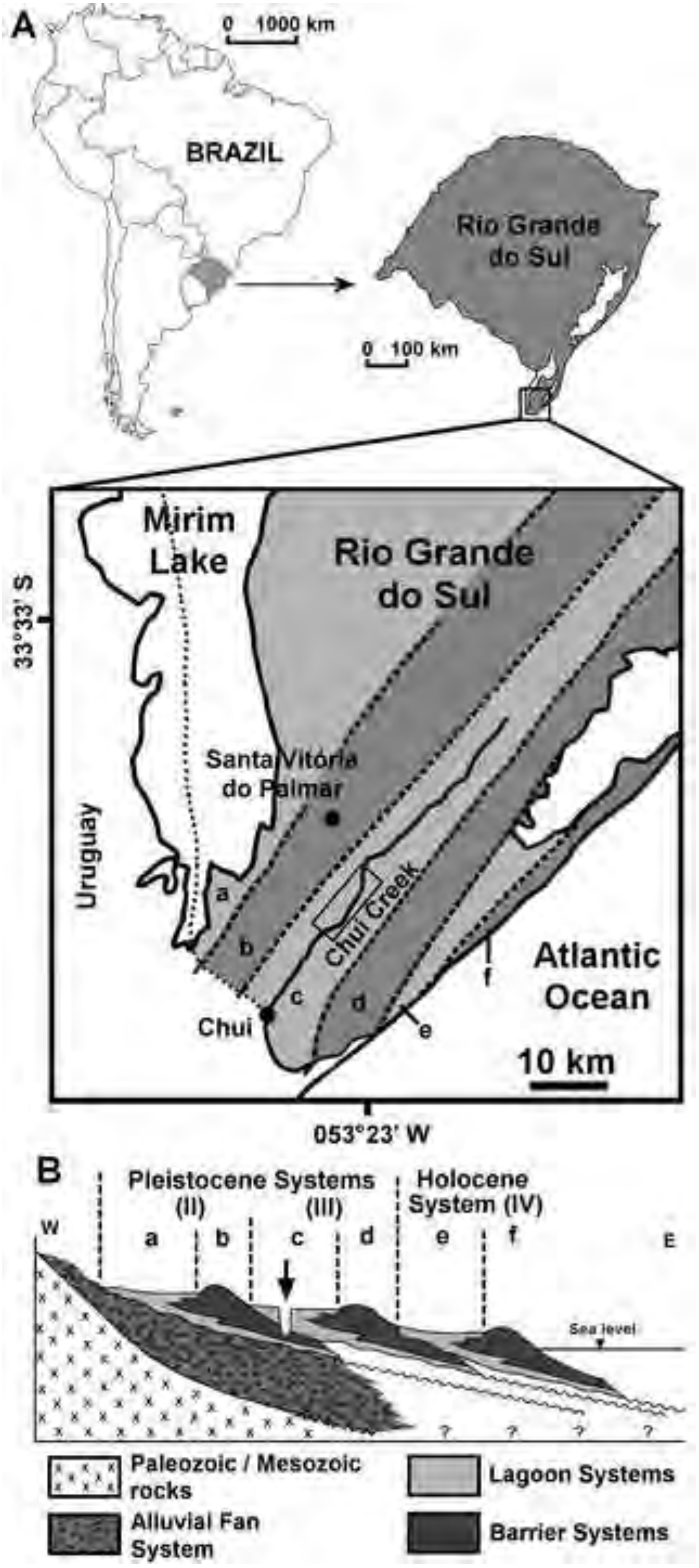
A
0 1000 km
BRAZIL
Rio Grande do Sul
0 100 km
Mirim Lake
Rio Grande do Sul
33°33' S
Santa Vitória do Palmar
Uruguay
Chui Creek
a
b
c
d
e
f
Chui
Atlantic Ocean
10 km
053°23' W
B
Pleistocene Systems
(II)
(III)
Holocene System (IV)
W
a
b
c
d
e
f
E
Sea level
?
Paleozoic / Mesozoic rocks
Alluvial Fan System
Lagoon Systems
Barrier Systems

Figure 2

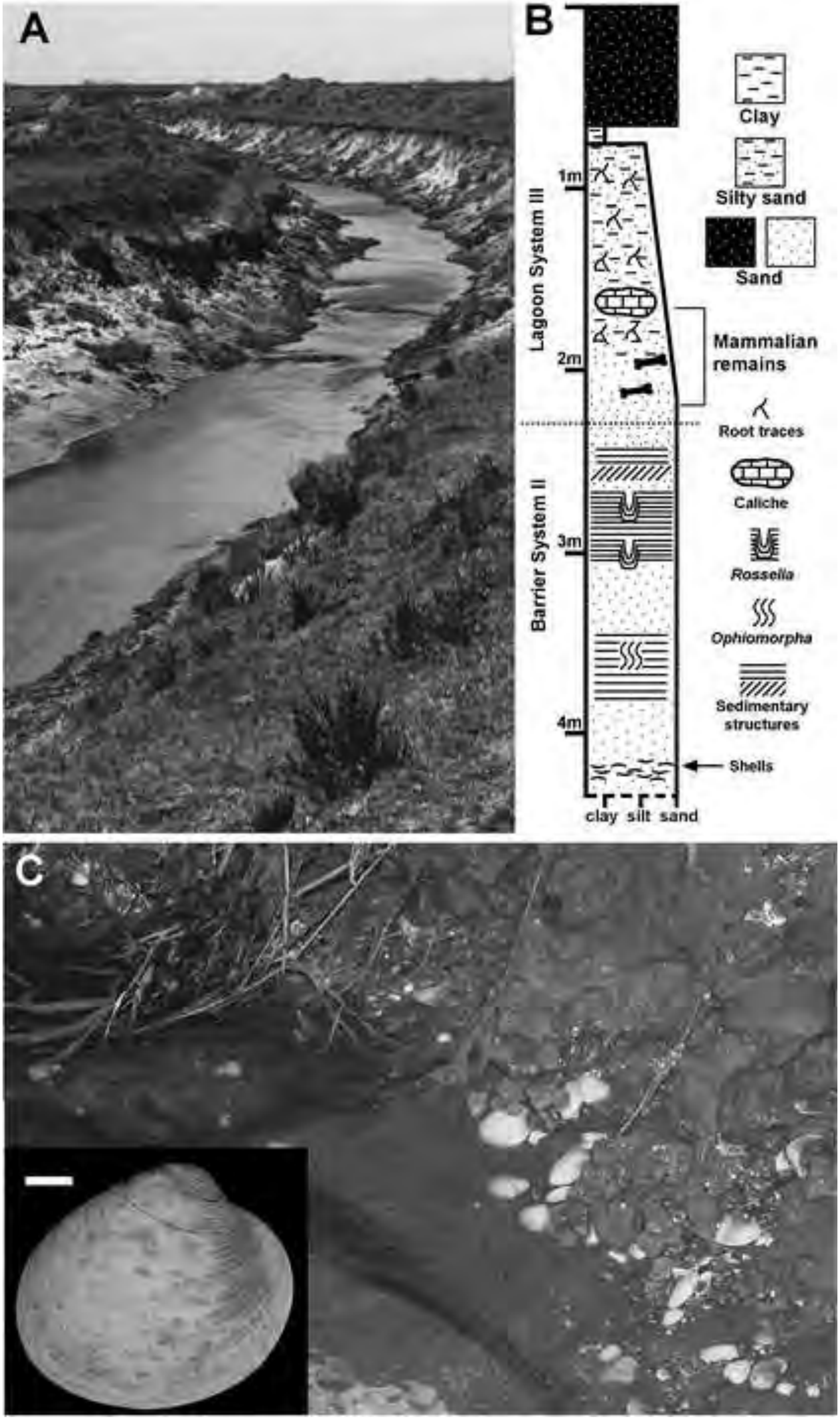
A
B
Lagoon System III
Barrier System II
1m
2m
3m
4m
Clay
Silty sand
Sand
Mammalian remains
Root traces
Caliche
Rosselia
Ophiomorpha
Sedimentary structures
Shells
clay silt sand
C

Figure 3

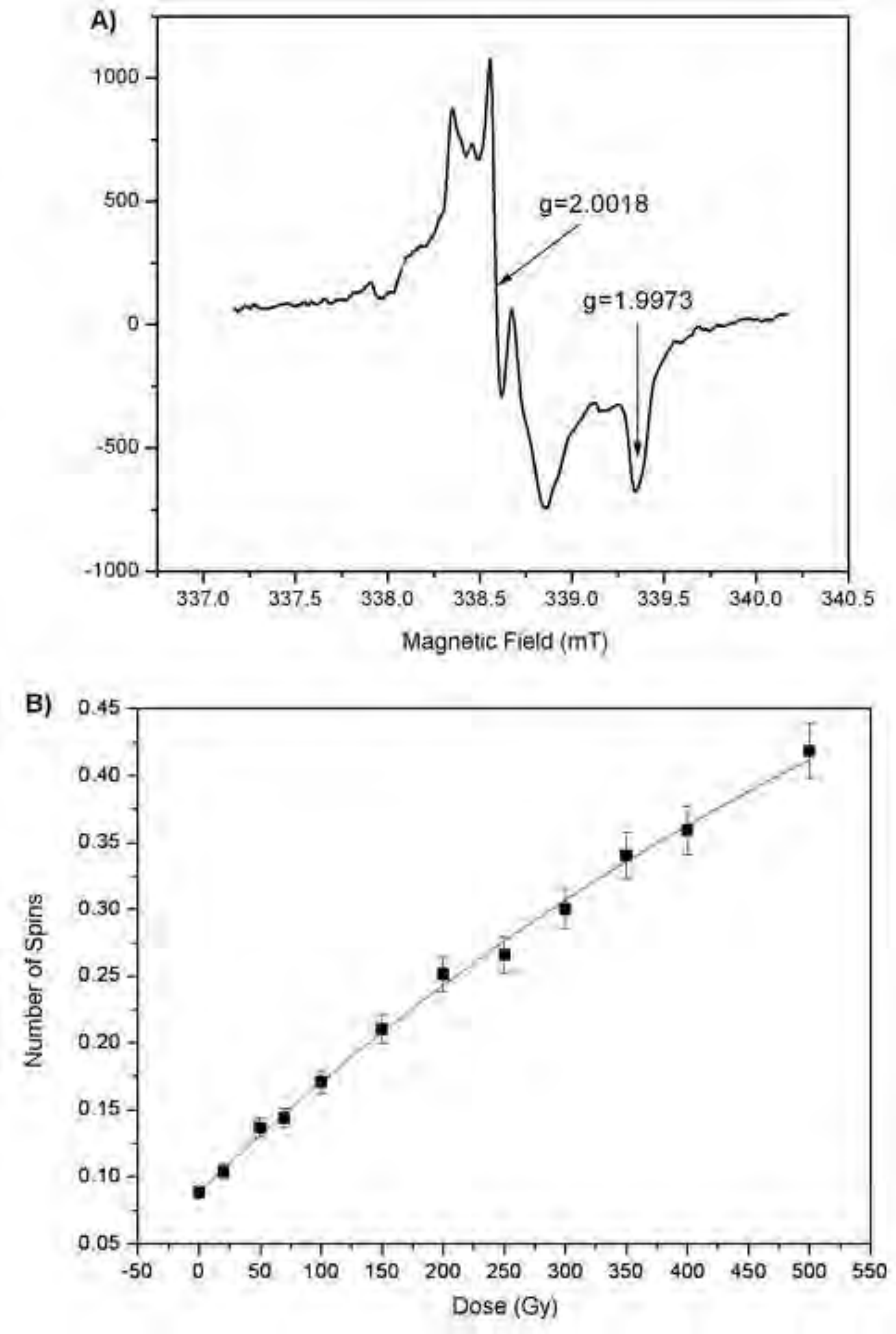
A)
1000
500
0
-500
-1000
g=2.0018
g=1.9973
337.0
337.5
338.0
338.5
339.0
339.5
340.0
340.5
Magnetic Field (mT)
B)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Number of Spins
-50
0
50
100
150
200
250
300
350
400
450
500
550
Dose (Gy)

Figure 4

Click here to download high resolution image

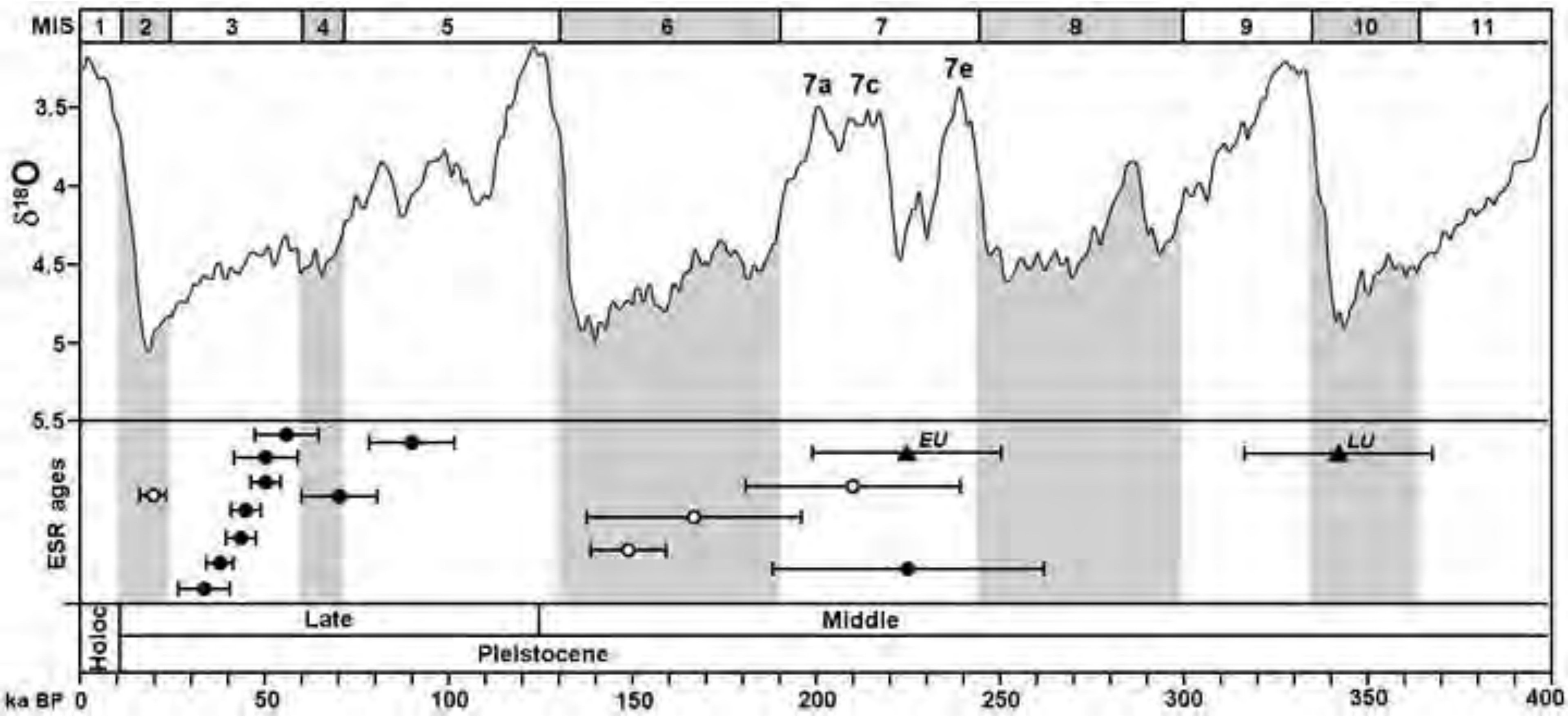

Figure 5

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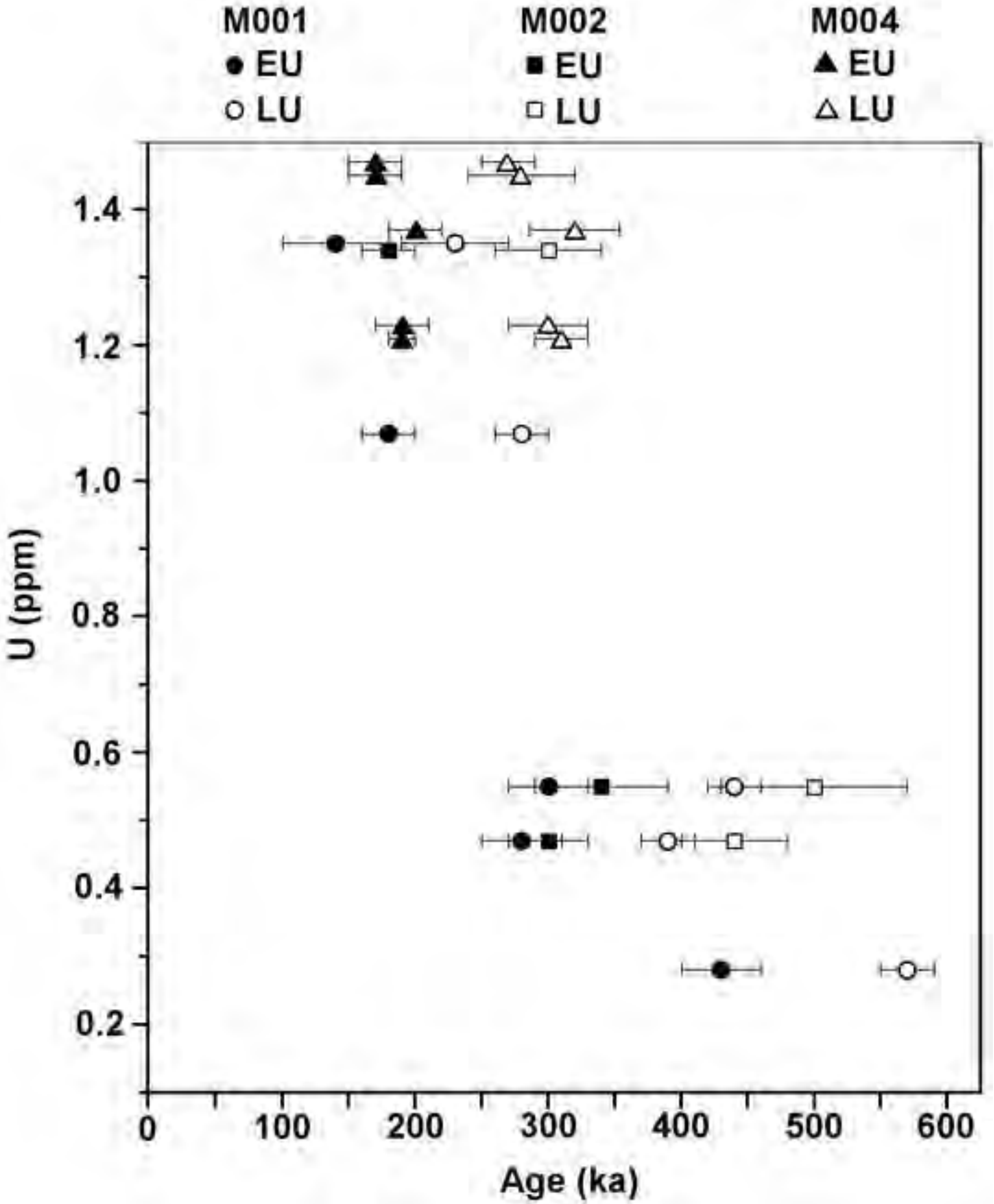

Figure 6

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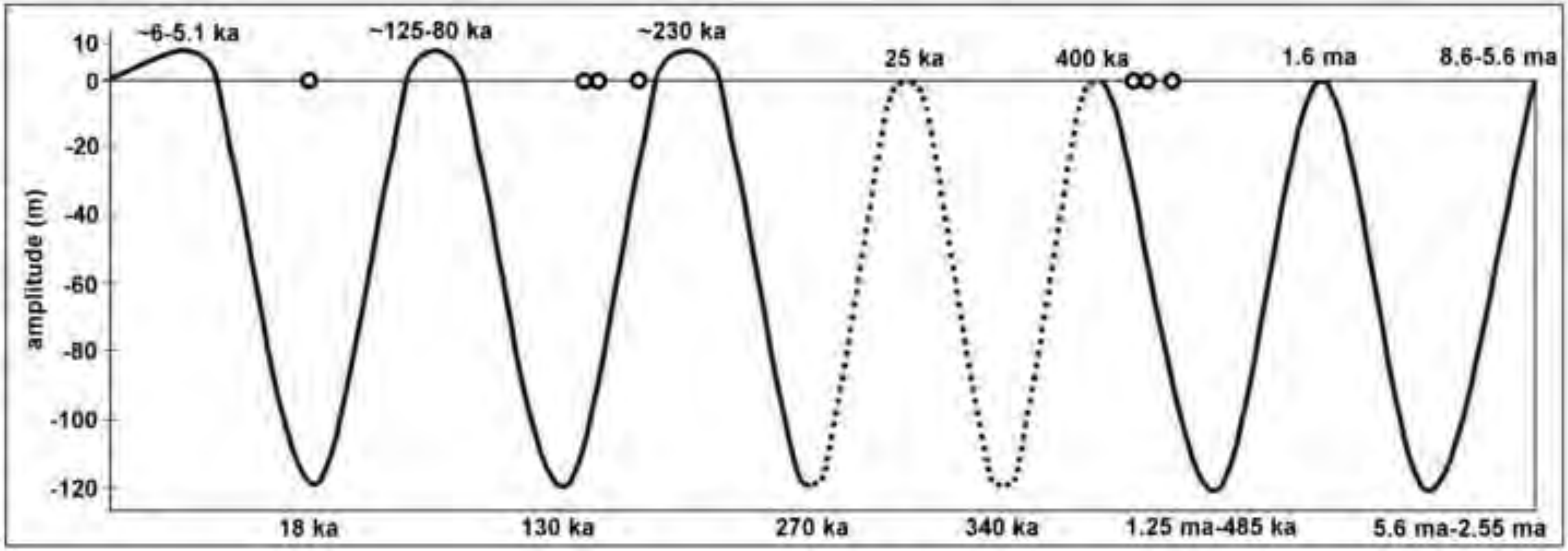

Equation 1

$$I = I_0 \left[1 - e^{\frac{(D - De)}{D_0}} \right]$$

TABLE 1 – Thickness of the shell samples before and after the acid etching.

Outcrop	Sample	Before Etching	After Etching
M001	1	2.0 mm	1.4 mm
	2	1.4 mm	1.2 mm
	3	1.4 mm	1.2 mm
	4	1.2 mm	1.0 mm
	5	1.1 mm	0.7 mm
M002	1	2.2 mm	1.6 mm
	2	1.3 mm	1.0 mm
	3	1.1 mm	0.6 mm
	4	1.0 mm	0.7 mm
	5	1.3 mm	0.7 mm
M004	1	1.4 mm	1.0 mm
	2	1.1 mm	0.9 mm
	3	2.0 mm	1.6 mm
	4	1.2 mm	0.8 mm
	5	1.5 mm	1.2 mm

Table 2

TABLE 2 – ^{238}U, ^{232}Th and ^{40}K contents (in ppm) of tooth enamel, dentin and sediments

	ENAMEL			DENTINE		
Sample	**U (ppm)**	**Th (ppm)**	**K (%)**	**U (ppm)**	**Th (ppm)**	**K (%)**
LGP-G0001	1.00 ± 0.03	n.d.	n.d.	82 ± 4	0.082 ± 0.005	<0.075
LGP-G0036	2.68 ± 0.08	n.d.	n.d.	104 ± 5	<0.01	<0.075
LGP-G0037	1.72 ± 0.05	n.d.	n.d.	150 ± 8	<0.01	<0.075
LGP-E0038	1.68 ± 0.05	n.d.	n.d.	109 ± 6	<0.01	<0.075
LGP-E0040	1.36 ± 0.04	n.d.	n.d.	118 ± 6	<0.01	<0.075
LGP-E0053	3.91 ± 0.11	n.d.	n.d.	155 ± 8	<0.01	<0.075

Sediment 1	2.2 ± 0.1	3.03 ± 0.09	0.63 ± 0.09
Sediment 2	1.70 ± 0.09	3.23 ± 0.07	0.60 ± 0.07
Sediment 3	2.2 ± 0.1	2.90 ± 0.09	0.64 ± 0.07

Table 3

TABLE 3 – Equivalent Dose (D_e), early uptake (EU), linear uptake (LU) and combined uptake (CU) ages (in thousands of years) of the fossil teeth.

Sample	D_e (Gy)	EU	LU	CU
LGP-G0001	39 ± 3	42 ± 3	50 ± 4	48 ± 4
LGP-G0036	90 ± 10	67 ± 9	90 ± 10	90 ± 10
LGP-G0037	54 ± 8	47 ± 6	60 ± 9	57 ± 8
LGP-E0038	100 ± 20	45 ± 8	70 ± 10	48 ± 9
LGP-E0040	130 ± 20	64 ± 8	90 ± 10	70 ± 10
LGP-E0053	102 ± 7	38 ± 3	59 ± 4	43 ± 3

Table 4

TABLE 4 – ^{238}U, ^{232}Th and ^{40}K content of shells and sediment samples.

Outcrop	Sample	U(ppm)	Th(ppm)	K(%)
M001	1	0.28 ± 0.02	<0.01	<0.075
	2	0.47 ± 0.02	<0.01	<0.075
	3	0.55 ± 0.03	<0.01	<0.075
	4	1.35 ± 0.03	<0.01	<0.075
	5	1.07 ± 0.03	<0.01	<0.075
	Sediment	0.39 ± 0.02	1.31 ± 0.1	0.91 ± 0.07
M002	1	1.91 ± 0.04	<0.01	<0.075
	2	0.47 ± 0.02	<0.01	<0.075
	3	1.73 ± 0.05	<0.01	<0.075
	4	1.34 ± 0.05	<0.01	<0.075
	5	0.55 ± 0.08	<0.01	<0.075
	Sediment	0.41 ± 0.04	1.60 ± 0.1	0.82 ±0.2
M004	1	1.45 ± 0.06	<0.01	<0.075
	2	1.47 ± 0.06	<0.01	<0.075
	3	1.23 ± 0.04	<0.01	<0.075
	4	1.21 ± 0.08	<0.01	<0.075
	5	1.37 ± 0.05	<0.01	<0.075
	Sediment	0.5 ± 0.1	1.4 ± 0.2	0.9 ± 0.3

Table 5

TABLE 5 – Accumulated dose, early and linear uptake ages (in thousands of years) of the fossil shells.

Outcrop	Sample	D_e	Age (E.U.)	Age (L.U.)
M001	1	95 ± 7	430 ± 30	570 ± 20
	2	75 ± 7	280 ± 30	390 ± 20
	3	90 ± 10	300 ± 30	440 ± 20
	4	67 ± 17	140 ± 40	230 ± 40
	5	73 ± 9	180 ± 20	280 ± 20
Mean			**266 ± 30**	**296 ± 24**
M002	1	97 ± 8	150 ± 10	250 ± 20
	2	84 ± 9	300 ± 30	440 ± 40
	3	79 ± 12	140 ± 20	230 ± 30
	4	90 ± 11	180 ± 20	300 ± 40
	5	104 ± 14	340 ± 50	500 ± 70
Mean			**222 ± 26**	**344 ± 40**
M004	1	92 ± 13	170 ± 20	280 ± 40
	2	87 ± 8	170 ± 20	270 ± 20
	3	89 ± 10	190 ± 20	300 ± 30
	4	91 ± 5	190 ± 10	310 ± 20
	5	104 ± 11	200 ± 20	320 ± 34
Mean			**184 ± 18**	**382 ± 28.8**
TOTAL MEAN AGE			**224 ± 24.6**	**340 ± 31.0**

TABLE 6 – Available ages for the Pleistocene-Holocene depositional systems of the CPRS.

Ages (years BP)	Material	Method	Unit	Author
960	Sediments	TL	Barrier IV	Poupeau et al., 1988
1,222	Sediments	TL	Barrier IV	Poupeau et al., 1989
2,470 ± 60	Peat	^{14}C	Lagoon IV	Buchmann et al., 1998
2,567	Sediments	TL	Barrier IV	Poupeau et al., 1988
2,667	Sediments	TL	Barrier IV	Poupeau et al., 1988
3,250	Sediments	TL	Barrier IV	Poupeau et al., 1988
3,833	Sediments	TL	Barrier IV	Poupeau et al., 1988
4,330 ± 60	Shells	^{14}C	Lagoon IV	Buchmann et al., 1998
4,920 ± 110	Shells	^{14}C	Lagoon IV	Buchmann et al., 1999
5,045	Shells	^{14}C	Lagoon IV	Forti Esteves, 1974
5,750 ± 750	Shells	^{14}C	Lagoon IV	Caron, 2007
6,820	Shells	^{14}C	Lagoon IV	Lima, 2008
6,870	Shells	^{14}C	Lagoon IV	Lima, 2008
10,160	Peat	^{14}C	Barrier III	Lima, 2008
16,250 ± 1,670	Shells	^{14}C	continental shelf	Figueiredo, 1975
17,000 ± 340	Shells	^{14}C	continental shelf	Figueiredo, 1975
18,000 ± 3,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010
>30,000	Shells	^{14}C	continental shelf	Figueiredo, 1975
34,000 ± 7,000	Mammalian Fossils	ESR	Lagoon III	Lopes et al., 2010
38,000 ± 2,000	Mammalian Fossils	ESR	Lagoon III	Lopes et al., 2010
>38,000	Peat	^{14}C	Lagoon III?	Buchmann et al., 1998
42,000 ± 3,000	Mammalian Fossils	ESR	Lagoon III	Lopes et al., 2010
42,260 ± 1,400	Shells	^{14}C	Lagoon IV	Lima, 2008
43,000 ± 3,000	Mammalian Fossils	ESR	Lagoon III	This paper
48,000 ± 4,000	Mammalian Fossils	ESR	Lagoon III	This paper
48,000 ± 9,000	Mammalian Fossils	ESR	Lagoon III	This paper
57,000 ± 8,000	Mammalian Fossils	ESR	Lagoon III	This paper
70,000 ± 10,000	Mammalian Fossils	ESR	Lagoon III	This paper
90,000 ± 10,000	Mammalian Fossils	ESR	Lagoon III	This paper
74,840	Sediments	TL	Barrier III	Poupeau et al., 1988
85,075	Sediments	TL	Barrier III	Poupeau et al., 1988
86,440	Sediments	TL	Barrier III	Poupeau et al., 1988
109,000 ± 7,5	Sediments	TL	Barrier III	Buchmann & Tomazelli, 2003
146,000 ± 9,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010
165,000 ± 28,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010
207,000 ± 28,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010
224 ± 24.6	Shells	ESR	Barrier II	This paper
226,000 ± 35,000	Mammalian Fossils	ESR	Lagoon III	Lopes et al., 2010
428,000 ± 30,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010
464,000 ± 65,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010
650,000 ± 100,000	Mammalian Fossils	ESR	continental shelf	Lopes et al., 2010

Lopes et al, "ESR datings on Pleistocene mammals and marine shells from the coastal plain of Rio Grande do sul State, Southern Brazil"

REFEREE 1:

All the considerations were taken into account in the new version of the article. An introduction about the parametric and non-parametric models for Uranium uptake for ESR dating were included in the text as well as the rationale for use of parametric model, used in the absence of data from the U-series. All discussion of the chronology of the CPRS area respect the limitations imposed by the models and are described in the text. Unfortunately the *in situ* dosimetry site was not possible but we adjusted cosmic radiation dose rate through well established model described in the literature. Other text and typing corrections were also included.

REFEREE 2:

The discussion on shells must make clear what 'younger' means. The phrasing should be something like "Calculated ages are probably younger than true ages due to uranium uptake" and should be repeated every time 'younger' appears. However, there seems to be some inconsistency in interpretation here. On the one hand, the authors insist that 224 ka can only be a minimum age, implying that there is little confidence in it. The 'true' age could be 250 ka or it could be 550 ka. They cite an older tooth age as evidence that 224 ka is an underestimate. Then they correlate 224 ka with a high seastand at 230 ka, implying that they do believe the EU values, although there is a nod to a possible earlier high seastand. Clearly there has been uptake of U since the fossil samples contain on average about five times the modern. That does not tell us, unfortunately, whether it occurred early or more linearly. It is also possible, of course, that the actual model is neither of these, something in between, perhaps. Additionally, the M001 and M002 assemblages strongly suggest two populations, as the distribution of ages is not continuous (especially for M002). Incidentally, the quoted averages for M001 and M003 are reversed in Table 5. In the end, it seems as if the ages of the shells are deduced from the seastand rather than from the ESR measurements. With respect to those, the correlation between uranium concentration and age is hardly surprising. All samples have very similar AD's. The internal dose is determined by the uranium concentration. If the uranium concentration is high, the internal dose is high, and for the same AD you will get a younger age than you will get with a low uranium concentration.

The best reason to believe that a 'real' age between ~235 and 240 is the result of two luminescence datings that provided ages of 235 ka (middle height of the exposed marine facies) and 214 ka (Aeolian sediments at the lower part of the terrestrial sequence). Unfortunately, these ages have not been published yet. Besides the age, the bivalves that indicate warmer oceanographic conditions are consistent with the hypsithermal recorded around 235-238 ka BP.

The results for the teeth are much more consistent. Here we note that the dentinal uranium concentration is very much higher than that in the enamel. Most teeth show a difference of a factor of 10-20. In fact the absolute amount of uranium in the dentine borders on dangerous exposures. This is characteristic of fossils from a saline environment, such as these. The issue then is whether 'normal' uptake models hold. There are examples where recent uptake (RU) modeling gives ages in better agreement with other methods. This is not to say that the actual model is RU. Rather, apparently uranium concentration and mobility in saline environments may be considerably higher than in fresh water. The authors might try RU modeling (with a relatively small p-value), not only because others have done so, but also because the quoted ages seem, again, younger than would be expected. Lagoon III lies between Barriers II and III. While there are no good ages for Barrier II except the shell ages in this manuscript, there are several ages for Barrier III that suggest the teeth in this study should exceed 85 ka in age. This is not discussed in the manuscript, but should be. If the explanation is that the teeth washed into the lagoon at a later date rather than when the lagoon was formed, then they do not date the lagoon. If there is another explanation, what is it?

In fact, the mammalian fossils are preserved in fluvial rather than lagoon facies. Stratigraphy shows different fluvial systems represented along the banks. We believe that most of the fossils should be younger than the ~125 ka-old Barrier III, because prior to the formation of this barrier, the fluvial systems flowed eastwards until discharging into the sea, thus many wouldn't be preserved close to the area where the creek is located. The formation of the Barrier III created the conditions for preservation of all the fossils between the barriers.

The following additional specific comments should be addressed.

1. Introduction 6th line: ".emitted by radioactive elements (PRIMARILY 238U." Other elements are always possible. **OK**

2. Fossil shells section: Could the authors consider including a figure showing the type of shell? **OK**

3. Fossil shells section: A sample ESR spectrum for the shells, showing both natural and dosed values, should be included as molluscan spectra are more variable than those for teeth. **OK**

4. Section 4.1: It is a serious stretch to go from these results to the migration of mammals to and from the area. This section should be shortened.

5. Caption to Figure 6: The dots are not black but empty. **OK**

6. Figure 5 should be removed for reasons noted above.

7. Table 2: Why are the concentrations not in ppm as in Table 3?

8. Table 5: As noted, the means for M001 and M003 are reversed. Also the caption should read 'linear' uptake, not late uptake. **OK**

9. Table 6 would be more interesting if rearranged to show the different dates for each unit, rather than arranged by author. **OK**

CAPITULO II - O PALEO-AMBIENTE TERRESTRE

Parte 1 - Artigo “BIOSTRATIGRAPHY OF THE PLEISTOCENE FOSSILIFEROUS DEPOSITS OF THE SOUTHERN BRAZILIAN COASTAL AREA”, publicado no **Journal of Mammalian Evolution**, n° 20, páginas 69 a 82.

Parte 2 – Artigo “LATE MIDDLE TO LATE PLEISTOCENE PALEOECOLOGY AND PALEOENVIRONMENTS IN THE COASTAL PLAIN OF RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL, FROM STABLE ISOTOPES IN FOSSILS OF *TOXODON* AND *STEGOMASTODON*” publicado na **Palaeogeography, Palaeoclimatology, Palaeoecology**, n° 369, páginas 385 a 394.

Parte 3 – Resumo expandido “GEOLOGICAL AND ENVIRONMENTAL EVOLUTION OF LAGOON SYSTEM III IN THE SOUTHERNMOST COASTAL PLAIN OF RIO GRANDE DO SUL STATE”, apresentado no VIII Congresso da ABEQUA.

Biostratigraphy of the Pleistocene Fossiliferous Deposits of the Southern Brazilian Coastal Area

Renato Pereira Lopes

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ORIGINAL PAPER

Biostratigraphy of the Pleistocene Fossiliferous Deposits of the Southern Brazilian Coastal Area

Renato Pereira Lopes

Abstract Fossils of Pleistocene mammals have been discovered in the southern Brazilian coastal area since the late XIX century, in two main places: the continental shelf and the Chuí Creek. Although the taxonomic composition of fossil assemblages from these areas has been the focus of most studies during the late XX century, research concerning the ages, stratigraphic position, and biostratigraphy of such assemblages remains scarce. This is due to the lack of suitable materials for age determination and the reworked nature of the fossiliferous deposits in the continental shelf. Only in recent years have new data shed light on these subjects. Taxonomic revisions, ESR ages, and biostratigraphic correlations confirm a late Pleistocene age for the fossil assemblages, although those from the shelf represent a significant time averaging, while fossils from the Chuí Creek exhibit a narrower age range. The fossil mammals found in southern Brazil represent a mixture of Brazilian and Pampean taxa, including forms that disappeared much earlier from the Argentinean pampas. Gaining an understanding of the biostratigraphic context of such assemblages in comparison to similar assemblages from Argentina and Uruguay, in conjunction with stratigraphic, geomorphological, and paleoclimatic data should provide additional tools with which to reconstruct the environmental and climatic dynamics of this portion of South America during the late Pleistocene—early Holocene and its effects on the fauna, and possibly to help address the problem of the disappearance of megamammals in the area.

Keywords Quaternary · Pleistocene · Biostratigraphy · Paleoclimate · Megafauna · Brazil

Introduction

Fossils of Pleistocene mammals were first reported from southern Brazil (coastal area of Rio Grande do Sul state) in the late XIX century, by the German naturalist Hermann Von Ihering (Von Ihering 1891). The first discoveries consisted of disarticulated, mostly fragmented specimens of extinct megamammals found scattered along the beach after storms. In the late 1960s, excavations for agricultural purposes revealed a fossiliferous level in Chuí Creek, located some 14 km landwards of the coastline and containing essentially the same extinct groups found in the marine deposits. During most of the past century, these fossils have been the object of several taxonomic studies (e.g., Cunha 1959; Paula Couto and Cunha 1965; Oliveira 1992, 1996; Rodrigues and Ferigolo 2004; Rodrigues et al. 2004; Scherer 2005; Marcon 2008), which led to a detailed understanding of the extinct fauna that inhabited the area. Few studies were aimed at understanding the stratigraphy, geology (Soliani 1973), and biostratigraphy (Bombin 1975) of these fossil assemblages. These studies, however, have been hampered by the lack of suitable materials for age determination and the view of the fossiliferous deposits of the continental shelf and Chuí Creek as chrono-correlated lithostratigraphic units (Paula Couto and Cunha 1965; Soliani 1973). Recent studies using new dating methods, a new geological framework, and revision of collections have led to updates of the nature, ages, faunal composition, biostratigraphy, and taphonomy of the fossil assemblages (Lopes et al. 2001, 2005, 2008, 2010; Pereira et al. 2009; Aires et al. 2010; Lopes and Buchmann 2010; Lopes and Pereira 2010a, b; Lopes et al. 2011; Pereira et al.

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2011). New fossiliferous outcrops in the southern coastal area of Rio Grande do Sul have also been identified, but these are still in need of detailed studies (Lima and Buchmann 2005; Lopes and Pereira 2010a, b).

Geological Setting

The best known fossiliferous deposits in the southernmost portion of the Brazilian coast, the continental shelf and the Chuí Creek area, are located in the area encompassed by the Coastal Plain of Rio Grande do Sul state (CPRS, Fig. 1). The CPRS measures some 620 km in length and 100 km in width; it is located between the latitudes 29°18′31″S and 33°43′17″S, and corresponds to the uppermost portion of the Pelotas Basin that remains above sea level. This marginal sedimentary basin has a maximum thickness of 10 km and was formed by the accumulation of sediments eroded from Paleozoic and Mesozoic rocks of the continental geological units after the split between South America and Africa in the Late Cretaceous (Closs 1970; Bueno et al. 2007; Barboza et al. 2008). During the Quaternary, sea-level oscillations correlated to glacial cycles reworked the uppermost sediments of the Pelotas Basin, as evidenced by facies changes and microfossil assemblages recovered from drilling holes (Closs 1970; Carreño et al. 1999). As a result of these oscillations, two major depositional systems were formed parallel to the coastline: the Tertiary Alluvial Fans System and the Quaternary Complex Multiple Barrier system (Villwock 1984; Villwock et al. 1986). The Complex Multiple Barrier System is subdivided into four major barrier-lagoon depositional systems and associated features. Each system was formed in response to a major sea-level transgression during interglacial episodes, and although the exact ages have not yet been determined, they have been correlated to the interglacial episodes at 400 ky (Barrier-Lagoon System I), 325 ky, (Barrier-Lagoon System II), 123 ky (Barrier-Lagoon System III), and 6 ky (Barrier-Lagoon System IV) (Villwock and Tomazelli 1995; Tomazelli et al. 2000). The sediments that constitute these systems are essentially terrigenous siliciclastic, well-sorted and mature, with small fractions of organic matter, biogenic carbonate and diagenetic clays, with some concentrations of heavy minerals (Villwock and Tomazelli 1995).

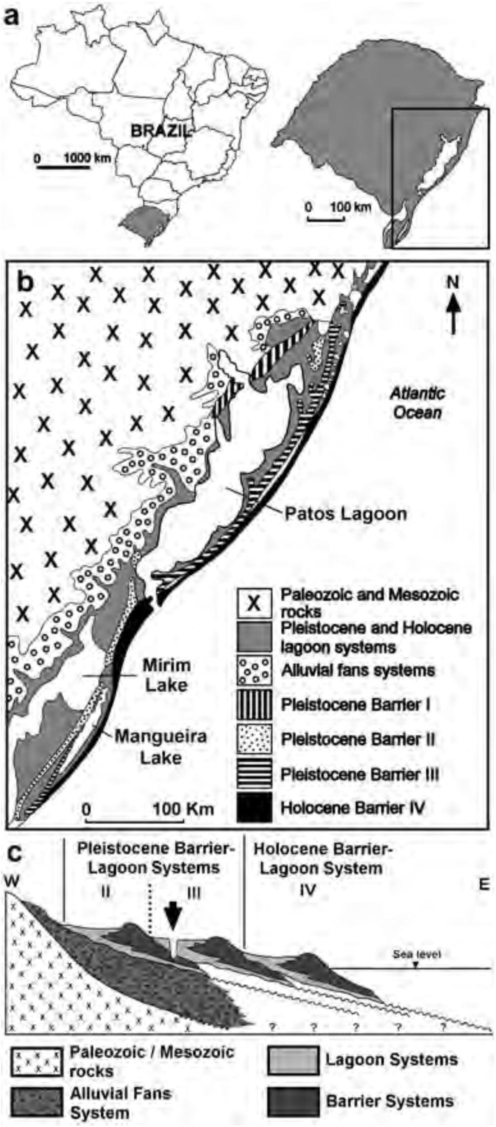

Fig. 1 **a** location map of Rio Grande do Sul; **b** geomorphological subdivisions of the Coastal Plain of Rio Grande do Sul state (CPRS); **c** transversal profile of the southernmost portion of the CPRS; Chuí Creek is indicated by arrow, associated with the Lagoon System III between Pleistocene barriers II and III (modified from Lopes and Buchmann 2010)

Fossiliferous Deposits of the Continental Shelf

The southern Brazilian continental shelf has a low topographic gradient (a 1:1.000 average ratio), with the shelf break located at depths between 80 and 170 m. The shelf is broad, contains submerged paleofluvial channels and sand banks (Corrêa et al. 1996; Weschenfelder et al. 2008). During the Holocene sea-level transgression, around 6 ky BP, variations in the rates of sea-level rise resulted in the reworking and concentration of terrigenous clastic sediments of the shelf, and erosive terraces were formed in response to episodes of sea-level stabilization (Kowsmann and Costa 1974; Martins et al. 1996). Sediments that constitute the upper portion of the shelf are nonmarine clastics that originated from erosion of the older geomorphologic units, and were deposited by several fluvial systems during the sea-level lowstands, including the La Plata River (Tomazelli 1978; Martins 1983).

The fossils of megamammals are found in two distinct areas of the shelf: the inner shelf (from the surf zone up to depths of 10 m, roughly the zone affected by wave action), and the outer shelf (at depths of 20 m and more, where the action of waves does not reach the ocean bottom, as indicated by extensive bioincrustation in vertebrate remains collected in deeper areas of the shelf; Lopes and Buchmann 2010). Although the presence of fossils of terrestrial mammals has been recorded all along the coastline of Rio Grande do Sul, such fossils are more conspicuous in the southernmost portion (Buchmann 1994). These are found associated with large concentrations of fossil marine shells and other marine organisms on the inner continental shelf (Figueiredo 1975). During autumn and winter, storm waves erode these deposits, removing the fossils and throwing them onto the beach, forming large *konzentrat-lagerstätte* called "Concheiros" (Buchmann et al. 2009; Fig. 2). Virtually all knowledge about the fossils from the shelf is based on those from the inner shelf, collected along the beach; fossils from the outer shelf are scarce and only recently have been described in the literature (Lopes and Buchmann 2010). The presence of terrestrial mammalian elements in deeper areas of the shelf, several kilometers far from the present coastline, does indicate that the fossiliferous area of the shelf is much larger than previously imagined.

The fossils of terrestrial mammals found in the shelf comprise extinct and extant taxa. Fossils found scattered along the beach are mostly fragmented and much abraded, but sometimes complete specimens can be found (Lopes et al. 2008). The fossils from the outer shelf are incomplete, but lack signs of abrasion, and are partially covered by encrusting and boring organisms. The available data indicate that the mammalian fossils found in the shelf come from ancient fossiliferous deposits formed on areas of the shelf that remained above sea level during marine regressions and were subsequently eroded and exposed to marine environments by sea-level transgressions; this process occurred several times during the Quaternary, in response to glacial-interglacial episodes (Lopes and Buchmann 2010).

Fig. 2 A fossil concentration on the beach, known as "concheiros". In the center, an osteoderm of *Glyptodon*

Chuí Creek

The Chuí Creek is a fluvial system located some 14 km landwards of the present coastline. It flows parallel to the coastline for most of its course, and its southernmost part marks the boundary between Brazil and Uruguay. The fossiliferous layer was exposed in the late 1960s, when the creek was further excavated for agricultural purposes. The first mention of these fossils was presented by Paula Couto and Cunha (1965); later, Soliani (1973) described the stratigraphy of the Chuí Creek, correlating the fossiliferous level to a new lithostratigraphic unit that he proposed and named "Santa Vitória Formation," presumably representing an ancient lagoon environment. Following the revisions of the geology of the CPRS during the 1980s and 1990s, the lithostratigraphic scheme was abandoned and replaced by the concept of depositional systems. Under this new scheme, the Chuí Creek flows over a large plain associated with the Lagoon III System, positioned between two Pleistocene barriers: the ~325 ka Barrier II located landwards and the ~123 ka Barrier III. Additionally, new geological surveys and taphonomic analysis on the remains indicate that the fossils were preserved in a meandering fluvial system instead of a lagoon (Lopes et al. 2001, 2005).

The stratigraphic sequence exposed above the creek bed measures some 4.5 meters (Fig. 3). The basal layer is composed of well-sorted, fine sand and represents a marine environment developed during a Pleistocene sea-level transgression (Buchmann et al. 2001; Lopes 2010). This layer is correlated to the "Chuí Formation" (Delaney 1965; Soliani 1973) and contains galleries of calianassid crustaceans (ichnofossils *Ophiomorpha nodosa*), fossils of shallow-living mollusks, and parallel and crossed stratifications (Fig. 4a, b), indicating a shallow marine environment. The layer above represents continental environments and is composed of fine sand and exhibits an upwards increase in silt-sized sediments. Paleosols with root traces and dark sand lenses are visible at the base of this layer (Fig. 4c); the latter are interpreted as oxbow lakes formed by abandoned fluvial meanders (Lopes et al. 2005). This layer also contains fossils of large terrestrial mammals, preserved and re-worked in a paleo-fluvial system (Fig. 3). This layer also bears a ~40 cm-thick horizon of caliche

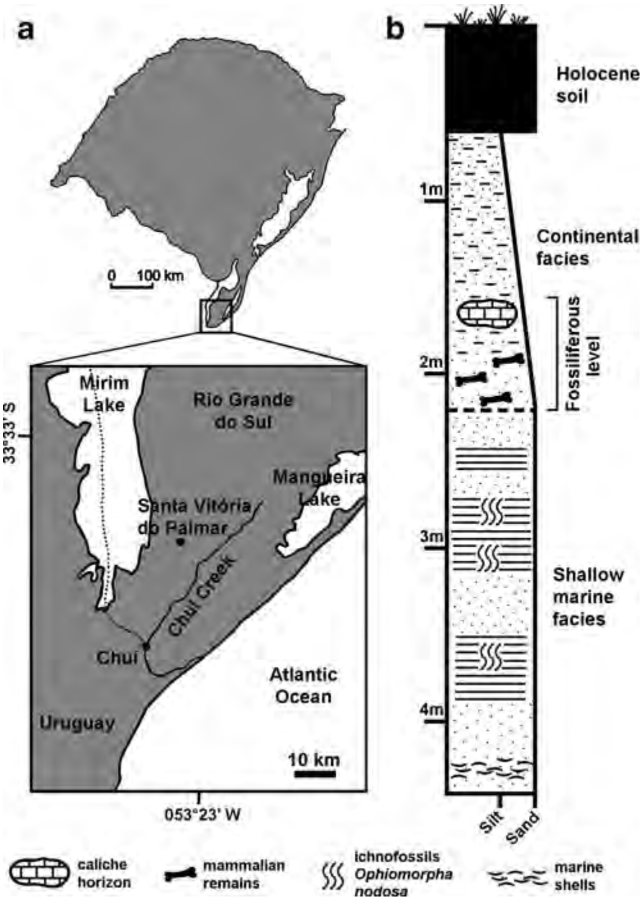

Fig. 3 **a** location map of Chuí Creek; **b** stratigraphic sequence exposed along the banks of the creek

nodules and rhizoliths (the "Caliche Cordão" of Delaney 1965) and vegetal remains in the form of rhizoliths and root traces (Fig. 4d). The caliche level is not continuous, and its longest exposure measured so far is some 460 m in length; until now, no fossils have been recovered from this horizon. The mammalian remains are mostly disarticulated and fragmented due to fluvial dynamics, but sometimes complete and even articulated remains can be found, indicating that this is a parautochtonous assemblage. Although most of the specimens found in the fossiliferous layer exposed along Chuí Creek comprise the same taxa found on the continental shelf, there are some differences and the former represent a narrower time span, according to recent age determinations (see below).

Stratigraphic Position of the Fossils

The exact biostratigraphic context of the fossil mammalian assemblages from southern Brazil was subject to some misconceptions, due to the reworked nature of the specimens found along the coast, to geological interpretations, the lack of materials suitable for dating techniques, and lack of information on the exact taxonomic composition of the fossil assemblages. In the first systematic geological mapping of the coast of Rio Grande do Sul, Delaney (1965) attributed a Tertiary age to the fossils found along the beach and correlated them to deposits of the "Graxaim Formation" (now recognized as the Alluvial Fans Systems) that presumably extended in the subsurface from the continent to the continental shelf. Paula Couto and Cunha (1965) challenged this assumption because no vertebrate fossil was ever recovered from the "Graxaim Formation." The major problem with the stratigraphic origin of the fossils from the continental shelf is the fact that these specimens are all removed from their original context. The coastal area of Rio Grande do Sul has been subject to erosive processes (Esteves et al. 2002; Dillenburg et al. 2004), which are removing the Holocene sediment cover and exposing the underlying Pleistocene substrate and fossils along the coast. Additionally, the four major sea-level transgressions that are recorded in Rio Grande do Sul

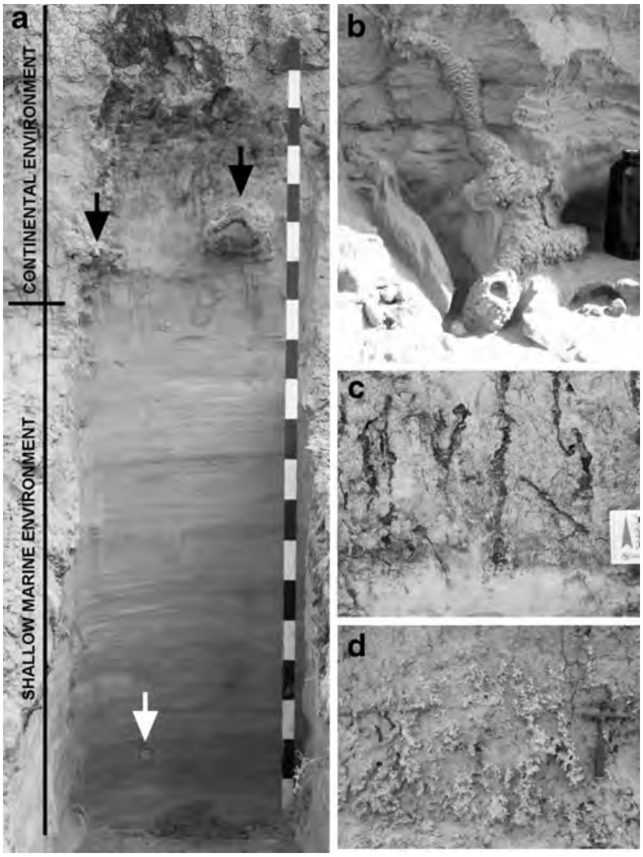

Fig. 4 **a** detail of the sedimentary sequence exposed along the banks of Chuí Creek, showing the gradual transition from shallow marine to continental environment; white arrow indicates a *Ophiomorpha nodosa* gallery, black arrows indicate mammalian fossil remains (each subdivision of the scale measures 10 cm): **b** portion of an *O. nodosa* gallery exposed at the base of the banks; **c** paleosoil with root traces above the marine facies; **d** detail of the caliche nodules and rhizocretions

also contributed to the erosion of the deposits now located on the continental shelf; Dillenburg (1994) estimated that each transgression would erode at least 10 m of the sedimentary cover, thus exposing and mixing together fossils of different ages. This assumption is corroborated by the large age span observed among the fossils from the shelf (see below).

The Chuí Creek so far represents the best fossiliferous area of the CPRS in terms of stratigraphic relations. The fossils are found in the ~1.5 m-thick layer just above the marine facies. The fossils are mostly fragmented and disarticulated, but complete and even articulated remains can be also found, suggesting that this level represents a fluvial facies, which is reinforced by the presence of some organic matter-rich sand lenses that seem to represent oxbow lakes formed by abandoned channels in a meandering fluvial system. Many fossil specimens can be found removed from the fossiliferous layer due to erosion of the banks, but those found in situ seem to occur all in the same level, except for a much older upper incisor of a *Toxodon* sp., found in the stratigraphic level below the fossiliferous layer, and one dentary of a vizcacha (*Lagostomus* sp.; Kerber et al. 2010), found above the fossiliferous level. The presence of a caliche layer (Fig. 3) above the fossiliferous level does indicate a drier climate period, which probably affected the distribution of the large mammals in the area. The uppermost portion of the sequence, representing the Holocene, is a dark, carbon-rich muddy sand, marked by the presence of specimens of *Blastocerus dichotomus*, *Myocastor coypus*, *Caiman latirostris*, and fishes, indicating a humid environment (wetland), plus several "cerritos," low mounds built by paleoindians and containing archaeological artifacts (Schmitz et al. 1997).

In his description of the stratigraphy of Chuí Creek, Soliani (1973) considered that the fossils from the creek and those from the continental shelf came from coeval lagoon facies of the "Santa Vitória Formation," after the interpretations of Paula Couto and Cunha (1965). Following the re-interpretations of the regional geology proposed during the 1980s (e.g., Villwock 1984; Villwock et al. 1986), the lithostratigraphic scheme was abandoned in favor of a chronostratigraphic framework that recognizes the geomorphological units of the CPRS as depositional systems formed at distinct times. Under this framework, the fossiliferous layer containing vertebrates exposed along the banks of Chuí Creek is now correlated with the fluvial facies of Lagoon System III, younger than most of the fossils from the continental shelf. Thus, the new data obtained by geological surveys and ages of fossils from the Chuí Creek and continental shelf indicated that these deposits constitute distinct units, and led to a better understanding of the stratigraphy of this portion of the coastal plain (Fig. 5).

Ages

The only previous ages reported in the literature for the fossils of CPRS are found in Soliani (1973), who estimated an age of 15,000 years for the material from Chuí Creek, and Bombin and Klamt (1976), who mentioned ages of 7,000 and 9,000 years for specimens found in "lacustrine deposits below recent soils," without any additional details. As an attempt to establish conclusive ages, several fossil teeth (seven from the continental shelf and four from Chuí Creek) were selected for dating using Electron Spin Resonance (ESR). The results revealed that the mammalian fossils from the shelf represent a large time range (Table 1), with their ages coinciding with marine isotope stages (MIS) 16, 12, 8, 6, 4 and 2, and indicating that the organisms occupied the area during periods of sea-level regressions related to glacial maxima (Lopes et al. 2010).

The ages obtained so far for specimens from the fossiliferous level in Chuí Creek represent a narrower time span, except for the incisor of *Toxodon* (Table 1) found in a stratigraphic level below, which probably represents the transition from marine to continental environments. Chronologically, the fossiliferous fluvial facies exposed along Chuí Creek is correlated to the Luján, Tezanos Pinto, Arroyo Feliciano and Toropí formations of Argentina (Kröhling 1999; Zurita and Lutz 2002; Zurita et al. 2007; Ferrero and Noriega 2009; Tonni 2009) and the Touro Passo Formation of western Rio Grande do Sul, which bears fossils with ages ranging between 34 and 19 thousand years at least (Kerber et al. in press).

Faunal Composition of the Assemblages

Another problem regarding the biostratigraphy of the fossil assemblages from the coastal area of Rio Grande do Sul is related to its faunal content. Throughout the years, several taxa such as *Equus*, *Hippidion*, *Ozotocerus*, *Smilodon*, *Blastocerus*, *Antifer*, *Tayassu, Macrauchenia*, *Megatherium*, *Hydrochoerus*, and *Tapirus* have been cited as occurring in Chuí Creek (e.g., Oliveira et al. 2005; Oliveira and Pereira 2009), although no report or formal description has been presented in the literature. The problem seems to date back to the work by Paula Couto and Cunha (1965), which presented a taxonomic list of fossils collected both on the beach and the Chuí Creek, without specifying what came from each deposit. Their original taxonomic list was accepted and cited by different authors, who added new taxa but didn't review the original specimens. The reason why Paula Couto and Cunha did not specify the exact provenance of the fossils was probably because they considered that Chuí Creek and the fossiliferous deposits

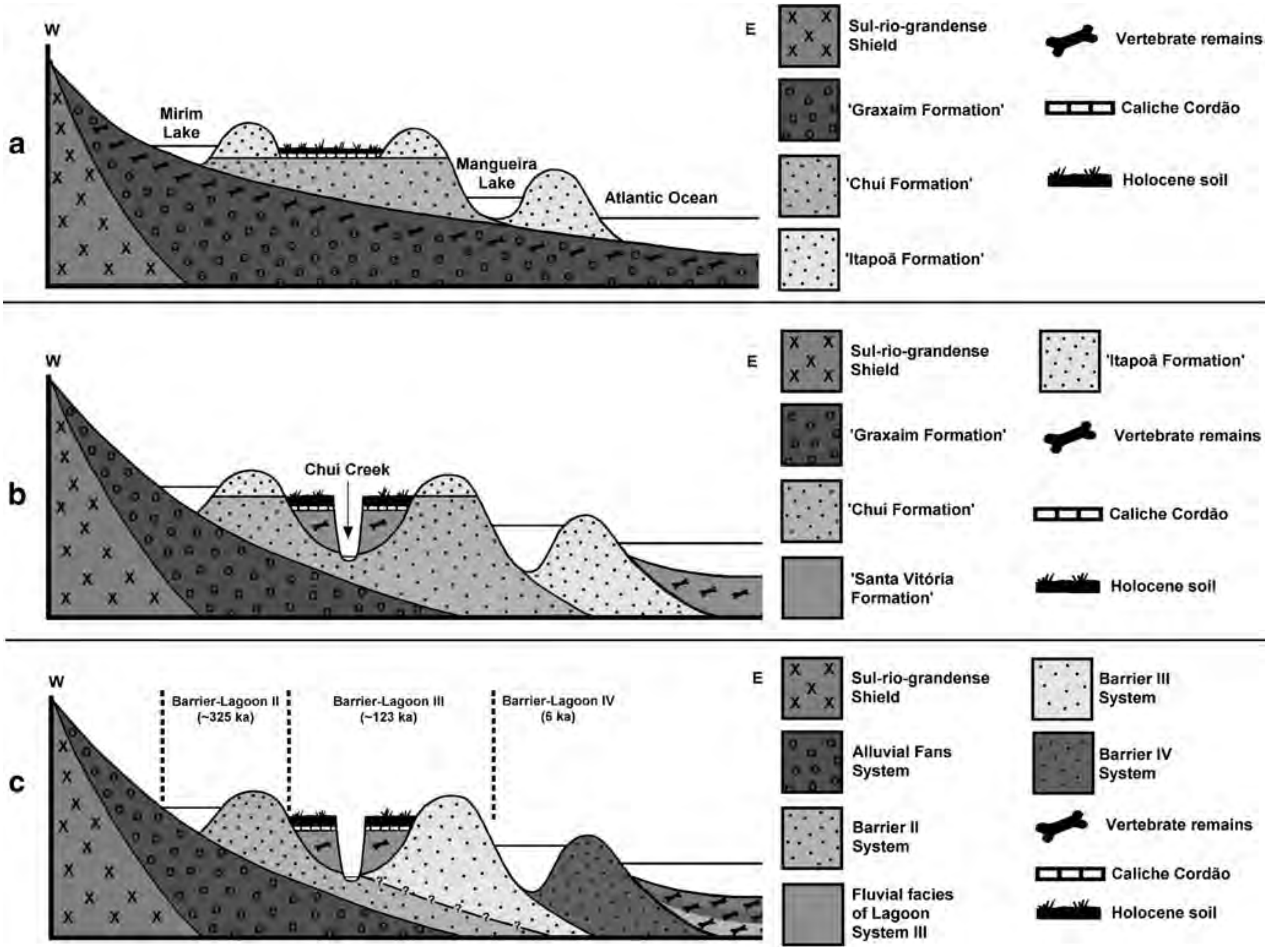

Fig. 5 Schematic views of the stratigraphic position of the fossiliferous deposits of the southern CPRS, according to interpretations of: **a** Delaney (1965), **b** Soliani (1973), and **c** this paper

in the continental shelf were part of the same lithostratigraphic unit, the "Santa Vitória Formation." The fossils collected by those authors were taken to the paleontological collection of Museu Nacional, in Rio de Janeiro, and a recent survey of the collection revealed that none of the specimens from Chuí Creek included the taxa mentioned above. Nevertheless, specimens of *Antifer*, *Macrauchenia*, *Equus, Hippidion*, and *Smilodon* have been recently described from this location (Lopes and Pereira 2009; Scherer et al. 2009; Pereira et al. 2009; Aires et al. 2010).

Table 1 Ages obtained from fossil teeth using Electron Spin Resonance (from Lopes et al. 2010)

Specimen	Location	Taxon	Age (YRS BP)
LGP-P0001	Continental shelf	*Stegomastodon waringi*	18,000±3,000
MOT0056	Continental shelf	*Hippidion* sp.	146,000±9,000
LGP-P0002	Continental shelf	*Stegomastodon waringi*	165,000±18,000
LGP-T0001	Continental shelf	*Toxodon* sp.	207,000±28,000
MOT0027	Continental shelf	*Toxodon* sp.	397,000±10,000
LGP-P0003	Continental shelf	*Stegomastodon waringi*	464,000±65,000
MOT0035	Continental shelf	*Toxodon* sp.	650,000±105,000
LGP-E0001	Chuí Creek	*Hippidion* sp.	33,500±8,000
LGP-P0004	Chuí Creek	*Stegomastodon waringi*	38,000±2,000
MOT0054	Chuí Creek	*Toxodon* sp.	42,000±3,000
MOT0050	Chuí Creek	*Toxodon* sp.	226,000±35,000

The most common taxa from the continental shelf assemblage are glyptodonts, represented mostly by isolated osteoderms, followed by cervids, toxodontids, ground sloths, pampatheriids, and equids. Until now, carnivorans, tayassuids, and tapirids are known from only a few specimens. In Chuí Creek, glyptodonts, *Toxodon*, and *Stegomastodon* are the most common, while cervids, equids, and dasypodids are scarce. The only confirmed record of Camelidae is a molar attributed to *Hemiauchenia* described by Oliveira (1992). In both assemblages the most abundant taxa are those adapted to open environments, while remains of camelids, carnivorans, and rodents are rare. The last seems mostly absent probably due to taphonomic processes (Lopes et al. 2008), while carnivorans were a group with low specific richness in South America (Prevosti and Vizcaíno 2006); thus their low proportion in the samples is expected. The differences in abundance among the two assemblages are probably the result of the large time-averaging observed among the remains from the continental shelf, but can also include environmental and/or climatic conditions (see below).

Among the specimens from the continental shelf, there are few problematic taxa, such as a Toxodontidae indet. (Cunha 1959) and a Haplodontheriinae indet. (Oliveira 1992), represented by a fragmentary femur and tooth, respectively. Given the wide time span encompassed by material found on the shelf, it is possible that the Toxodontidae indet. may represent another species of *Toxodon*, because several Bonaeran and Ensenadan species are known from Argentina (Bond 1999). The haplodonteriine toxodontids seem to have become extinct during the Pliocene; thus their record in younger sediments of southern Brazil is problematic and needs to be revised. The presence of *Megatherium* in both assemblages is also debatable. Throughout the years, several fragmentary specimens of megatheriids have been regarded as belonging to this genus, but lacked precise descriptions or comparisons. Until now, the only megatheriid formally recognized among the material from Chuí Creek is *Eremotherium*, represented by a dentary of a juvenile (Pereira et al. 2009). Nevertheless, the co-occurrence of *Eremotherium* and *Megatherium* cannot be discarded, because both taxa have been found in the same deposit, located in the central area of Rio Grande do Sul (Toledo 1986; Oliveira 1999).

Some remarkable taxa found in the continental shelf include *Pachyarmatherium* (Ribeiro et al. 2008; Bostelmann 2008) and *Neolicaphrium* (Scherer et al. 2009). The former is a Plio-Pleistocene taxon found until recently only in northeastern Brazil, Venezuela, and southeastern USA, and the latter is a taxon that disappeared in the Pampean Region of Argentina during the late Pliocene, but has also been found in the Pleistocene Sopas Formation of northeastern Uruguay (Bond et al. 2001). In Table 2 an updated list is presented of taxa known so far from the continental shelf and Chuí Creek.

Biostratigraphy

In their review of the mammalian fossils from the CPRS, Paula Couto and Cunha (1965) correlated the fossils to the “Pampeano Superior” (Bonaerean) of Argentina, according to the biostratigraphic scale of Ameghino. Bombin (1975), based on the presence of fossils of *Equus* (*Amerhippus*) *neogaeus*, correlated the fossil mammals of Rio Grande do Sul to the Lujanian “Land-Mammal Age” of the Pampean Region of Argentina, following the biostratigraphic scheme proposed by Pascual et al. (1966), and this has been accepted throughout the years. Pascual et al. (1966) proposed a homogenous distribution for this Pampean fauna, encompassing southern Brazil, Uruguay, and Argentina; however, recent fossil records have shown that this concept is incorrect (Noriega et al. 2004; Carlini et al. 2004; Ubilla 2004). The concept of South American Land-Mammal Ages (SALMAs) has been changed throughout the years, with several revisions and corrections, reflecting new fossil finds, and the instability of this concept. More recently, Cione and Tonni (1995, 1999) proposed the replacement of the concept of SALMAs by the more stable biostratigraphically-based chronostratigraphic Stage/Age scheme, defining the Lujanian Stage/Age as the biozone of *Equus* (*Amerhippus*) *neogaeus*, encompassing the time interval between 130 and 8.5 ka AP. Following this new scheme, the ages obtained so far for remains from the fossiliferous layer in Chuí Creek confirm a Lujanian Stage/Age, while the older *Toxodon* tooth is Bonaeran. Among the specimens from the shelf, however, the ESR ages indicate that they encompass not only the Lujanian, but also the Ensenadan and Bonaeran Stage/Ages (Lopes et al. 2010; Fig. 6).

The presence of *Antifer* in Chuí Creek (Lopes and Pereira 2009) is also significant, because in the Pampean region, this taxon is restricted to the Ensenadan (*A. ensenadensis*) and Bonaeran (*A. ultra*) (Cione and Tonni 1999; Cione et al. 1999), but fossils of this genus have been found in Lujanian deposits of northern Chile (Quebrada Quereo Formation, Labarca and López 2006), Mesopotamian region of Argentina (Toropí Formation, Alcaraz and Zurita 2004), Uruguay (Sopas Formation, Ubilla 2004), and western Rio Grande do Sul (Touro Passo Formation, Kerber and Oliveira 2008). Although common among fossils from the shelf (Scherer et al. 2007), specimens of *Antifer* cannot be conclusively regarded as Lujanian, due to the large time-averaging of this deposit.

Table 2 Terrestrial mammals found in fossiliferous deposits of the CPRS (following the classification of McKenna and Bell 1997)

CONTINENTAL SHELF	CHUÍ CREEK
Phyllum CHORDATA Bateson, 1885	Superorder XENARTHRA Cope, 1889
Class MAMMALIA Linnaeus, 1758	Order PILOSA Flower, 1883
Superorder XENARTHRA Cope, 1889	Family MEGATHERIIDAE Owen, 1843
Order PILOSA Flower, 1883	*Eremotherium* Spillmann, 1948
Family MEGATHERIIDAE Owen, 1843	Family MYLODONTIDAE Gill, 1872
Megatherium Cuvier, 1796	*Glossotherium* Gervais, 1855
Family MYLODONTIDAE Gill, 1872	*Lestodon* Gervais, 1855
Glossotherium Gervais, 1855	*Mylodon* Owen, 1839
Lestodon Gervais, 1855	*Catonyx* Ameghino, 1891
Mylodon Owen, 1839	
Catonyx Ameghino, 1891	Order CINGULATA Illiger, 1881
	Family DASYPODIDAE Bonaparte, 1838
Order CINGULATA Illiger, 1881	*Propraopus* Ameghino, 1881
Family DASYPODIDAE Bonaparte, 1838	*Dasypus* Linnaeus, 1758
Propraopus Ameghino, 1881	Family PAMPATHERIIDAE Paula Couto, 1954
Family PAMPATHERIIDAE Paula Couto, 1954	*Holmesina* Simpson, 1930
Holmesina Simpson, 1930	*Pampatherium* Ameghino, 1875
Pampatherium Ameghino, 1875	Family GLYPTODONTIDAE Burmeister, 1879
Family GLYPTODONTIDAE Burmeister, 1879	*Doedicurus* Burmeister, 1874
Doedicurus Burmeister, 1874	*Glyptodon* Owen, 1845
Glyptodon Owen, 1845	*Panochthus* Burmeister, 1872
Panochthus Burmeister, 1872	*Neuryurus* Ameghino, 1889
Neuryurus Ameghino, 1889	
Pachyarmatherium Downing & White, 1995	Order LITOPTERNA Ameghino, 1889
	Family MACRAUCHENIIDAE Gervais, 1855
Order LITOPTERNA Ameghino, 1889	*Macrauchenia* Owen, 1838
Family MACRAUCHENIIDAE Gervais, 1855	
Macrauchenia Owen, 1838	Order NOTOUNGULATA Roth, 1903
Family Proterotheriidae Ameghino, 1887	Family TOXODONTIDAE Owen, 1845
Neolicaphrium Frenguelli, 1921	*Toxodon* Owen, 1838
Order NOTOUNGULATA Roth, 1903	Order CARNIVORA Bowdich, 1821
Family TOXODONTIDAE Owen, 1845	Family FELIDAE Gray, 1821
Toxodon Owen, 1838	*Smilodon* Lund, 1842
	Felidae indet.
Order CARNIVORA Bowdich, 1821	Family CANIDAE Fischer de Waldheim, 1817
Family FELIDAE Gray, 1821	*Protocyon* Lund, 1842
Smilodon Lund, 1842	*Dusicyon* Hamilton-Smith, 1839
Family CANIDAE Fischer de Waldheim, 1817	Family URSIDAE
Protocyon Lund, 1842	cf. *Arctotherium*
Dusicyon Hamilton-Smith, 1839	
Theriodictis Mercerat, 1891	Order RODENTIA Bowdich, 1821
	Family CAVIIDAE Fischer de Waldheim, 1817
Order RODENTIA Bowdich, 1821	Dolichotinae (indet.) Pocock, 1922
Family CAVIIDAE Fischer de Waldheim, 1817	Family ECHIMIYDAE Gray, 1825
Cavia Pallas, 1766	*Myocastor* Kerr, 1792
Dolichotinae (indet.) Pocock, 1922	*Microcavia* Gervais & Ameghino, 1880
Family HYDROCHOERIIDAE Brisson, 1762	*Lagostomus* Brookes, 1828
Hydrochoerus Brisson, 1762	

Table 2 (continued)

CONTINENTAL SHELF	CHUÍ CREEK
Family OCTODONTIDAE Waterhouse, 1839	Order URANOTHERIA McKenna & Bell, 1997
Ctenomys Blainville, 1826	Family GOMPHOTHERIIDAE Hay, 1922
Family MURIDAE (=CRICETIDAE) Illiger, 1811	*Stegomastodon* Pohlig, 1912
Reithrodon Waterhouse, 1837	
Family ECHIMIYDAE Gray, 1825	Order PERISSODACTYLA Owen, 1848
Myocastor Kerr, 1792	Family EQUIDAE Gray, 1821
Heteromysopinae (indet.) Anthony, 1917	*Equus* Linnaeus, 1758
	Hippidion Owen, 1869
Order URANOTHERIA McKenna & Bell, 1997	
Family GOMPHOTHERIIDAE Hay, 1922	Order ARTIODACTYLA Owen, 1848
Stegomastodon Pohlig, 1912	Family CAMELIDAE Gray, 1821
	Hemiauchenia Gervais & Ameghino, 1880
Order PERISSODACTYLA Owen, 1848	Family CERVIDAE Goldfuss, 1820
Family EQUIDAE Gray, 1821	*Antifer* Ameghino, 1889
Equus Linnaeus, 1758	*Morenelaphus* Carette, 1922
Hippidion Owen, 1869	Family TAYASSUIDAE Palmer, 1897
Family TAPIRIDAE Gray, 1821	*Catagonus* Ameghino, 1889
Tapirus Brunnich, 1772	
Order ARTIODACTYLA Owen, 1848	
Family CAMELIDAE Gray, 1821	
Lama Cuvier, 1800	
Hemiauchenia Gervais & Ameghino, 1880	
Family CERVIDAE Goldfuss, 1820	
Antifer Ameghino, 1889	
Morenelaphus Carette, 1922	
Family TAYASSUIDAE Palmer, 1897	
Tayassuidae indet.	

The faunal shifts observed in the region located between southern Brazil, northern Argentina, northern Uruguay, and the Argentinean Pampas seems to be correlated to climatic variations and resulting environmental changes that affected this area during the Quaternary. Several researchers have pointed to the similarities between the faunas from Rio Grande do Sul and those from northwestern Uruguay and the Mesopotamian region of Argentina (Carlini et al. 2004; Noriega et al. 2004; Oliveira and Kerber 2009; Oliveira and Pereira 2009; Tonni 2009; Ubilla et al. 2009). The taxa found in the fossil assemblages of CPRS include mostly Pampean forms, such as ground sloths, glyptodonts, *Toxodon*, *Antifer*, and *Morenelaphus*, but also include Brazilian taxa such as *Hydrochoerus hydrochaeris* and *Tapirus* (in the continental shelf), *Protocyon troglodytes* and *Eremotherium laurillardi* (in Chuí Creek), and *Catonyx cuvieri*, *Holmesina paulacoutoi*, and *Pampatherium typum* in both assemblages (Table 3). The faunal content of these assemblages includes mostly large-bodied taxa, presumably adapted to open environments (grasslands) (Oliveira 1999).

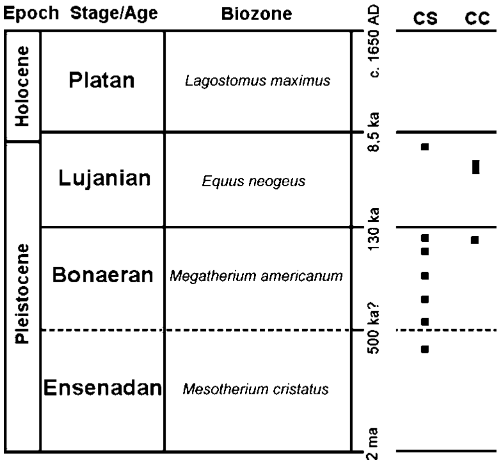

Fig. 6 Stage/Ages and corresponding biozones recognized for the Quaternary of South America, according to Tonni (2009), and ages of the mammalian remains from RSCP according to Lopes et al. (2010) (CS=Continental Shelf, CC=Chuí Creek)

Good correlation between the faunal content and paleoclimate/paleoenvironment can be observed in the vertical faunal and sedimentological variations found in

Table 3 Comparison between faunas of the fossil assemblages from CPRS (Continental Shelf=CS; Chuí Creek=CC) and different Lujanian localities in Rio Grande do Sul (TPF=Touro Passo Fm., Kerber and Oliveira 2008), Uruguay (SF=Sopas Fm., Ubilla et al. 2009) and Argentina (TF=Toropí Fm., Zurita and Lutz 2002; AF=Arroyo Feliciano Fm., Noriega et al. 2004; LF=Luján Formation, Cione and Tonni 1999; CP=Córdoba Province, Tezanos Pinto Fm?, Zurita et al. 2007; B=Barranqueras, Zurita et al. 2004). Shaded taxa indicates Brazilian (intertropical) affinity; question mark indicates taxon with uncertain occurrence; taxa marked with underlined "X̲" represent those recognized only at generic level or with affinities to the species listed here

	CS	**CC**	**TP**	**SF**	**TF**	**AF**	**LF**	**CP**	**B**
Megatherium americanum	X	?		X		X	X		
Eremotherium laurillardi		X							
Glossotherium robustum	X	X		X		X̲	X		
Lestodon armatus	X	X		X	X	X̲			
Mylodon darwinii	X	X							
Catonyx cuvieri	X	X							
Propraopus grandis	X	X		X		X̲			
Propraopus sulcatus		X	X̲						
Holmesina paulacoutoi	X	X	X			X			
Pampatherium typum	X	X	X	X	X	X̲			
Pampatherium humboldti	X	X							
Dasypus sp.		X		X					
Doedicurus clavicaudatus	X	X				X̲	X		
Glyptodon reticulatus	X	X	X̲	X	X	X		X̲	X̲
Panochthus tuberculatus	X	X	X̲	X		X̲			X
Neuryurus rudis	X	X		X					
Macrauchenia patachonica	X	X	X	X			X		
Neolicaphrium recens	X			X					
Toxodon platensis	X	X	X̲	X	X	X	X	X̲	X̲
Smilodon populator	X	X		X				X	X
Protocyon troglodytes		X							
Dusicyon avus	X̲	X						X̲	
Theriodictis sp.	X								
Arctotherium sp.		X					X		
Microcavia sp.		X		X			X		
Dolichotinae	X	X		X			X		
Hydrochoerus hydrochaeris	X		X̲						
Reithrodon auritus	X			X					
Myocastor coypus	X	X		X					
Lagostomus maximus		X					X		
Stegomastodon waringi	X	X			X̲				X̲
Equus neogaeus	X	X	X	X			X	X̲	X
Hippidion sp.	X	X	X̲	X		X̲			
Tapirus sp.	X		X	X		X̲			
Lama guanicoe			X̲			X	X		
Lama gracilis	X		X̲	X		X	X		
Hemiauchenia paradoxa	X	X	X	X		X̲	X	X	
Antifer sp.	X	X	X̲	X	X	X̲			
Morenelaphus sp.	X	X	X̲	X		X̲			X̲
Catagonus stenocephalus		X	X	X					

the Luján Formation of Argentina (Prado and Alberdi 1999; Tonni et al. 1999). The lowermost La Chumbiada Member indicates a temperate climate around 30 ka AP, while the Guerrero Member above was formed under cold and arid climates correlated to the LGM (between ~21 and 10 ka AP, Tonni et al. 2003), and there is a definite faunal turnover between both units. A similar variation seems to be recorded in the stratigraphic sequence exposed along Chuí Creek: the fossiliferous layer is a muddy sandstone deposited in fluvial environments that exhibits an upward gradual increase in silt-sized sediments and the disappearance of large-bodied taxa. This sequence suggests a humid environment at the base of the sequence, represented by the reworked mammalian fossils and organic matter-rich sand lenses, progressively replaced by a drier environment, represented by the caliche level above and the increase in silt, probably reflecting the deposition of wind-blown loess from periglacial areas of the Andes under progressively semiarid conditions, as suggested by Soliani (1973). The ages obtained for the fossils from this layer suggest that the humid interval took place between 30 and 40 ka AP. This interval could also have been warmer, which would enable the incursion of the Brazilian (intertropical) taxa. Until now the only fossil recovered from an upper level is a dentary of *Lagostomus* (Kerber et al. 2010), a rodent that may be associated with arid environments. Other fossil indicators of arid environments found in Chuí Creek are *Microcavia* (Ubilla et al. 2008) and Dolichotinae (Pereira et al. 2009). Unfortunately, the material cannot be assigned to a particular stratigraphic level, because the former was collected without exact determination of its stratigraphic position, and the latter was collected in sediments dredged from the creek.

The sea-level lowstands correlated with glacial advances probably influenced the distribution of the mammalian fauna as well, by affecting the regional climate regimes due to increased continentality. While in Chuí Creek and the continental shelf the record of camelids is scarce, in Touro Passo Formation, located some 500 km landwards, camelids are common fossils (Ribeiro and Scherer 2009) and specimens of *Catagonus* have also been found in this unit (Gasparini et al. 2009). The former is adapted to drier and colder climate, thus is considered good environmental indicators (Scherer 2005), and *Catagonus* is associated with semiarid environments. It seems probable that during sea-level regressions the westernmost Rio Grande do Sul, northwestern Uruguay, Mesopotamian, and western Pampean areas have experienced drier climates, with increased seasonality, while the CPRS would have milder climates due to its proximity to Atlantic Ocean, despite the fact that the coastline was located some 100 km eastwards in relation to the present. It seems that temperature was not a major factor affecting the faunal dynamics in southern Brazil, northern Uruguay, and the Mesopotamian region, because several taxa, such as glyptodontids, pampatherids, ground sloths, toxodontids, macraucheniids, and mastodonts, have a wide latitudinal distribution, reaching even equatorial areas. Instead, it seems that humidity played a major role in this pattern, by affecting the distribution of vegetation that was the food source for these organisms, but additional studies are needed to evaluate this hypothesis.

In both the continental shelf and Chuí Creek, the fossil assemblages contain disharmonious or non-analogs faunal elements sensu Lundelius (1989), such as taxa adapted to arid environments (Dolichotinae, *Microcavia*, *Lagostomus*, *Catagonus*) together with taxa adapted to humid environments (*Hydrochoerus*, *Myocastor*), a pattern similar to that observed in the fossil assemblage of the Sopas Formation (Ubilla 2004; Ubilla et al. 2004). An explanation for this pattern could be the existence in the Pleistocene of climatic regimes without analogs today, which would allow the coexistence of such different taxa. Nevertheless, other causes may be responsible for this pattern in the fossil assemblages of CPRS. In the case of the continental shelf, this mixture may be a result of the large time interval represented by the fossils, which include material from several different assemblages developed through time under different climatic conditions. In Chuí Creek, which spans a narrower time interval, there are three possible scenarios to explain this faunal mixture:

1) The fluvial system was active during some ten thousand years, as indicated by the ages of the fossils (Lopes et al. 2010); thus, the presence of both Brazilian and Pampean taxa may represent either a true mixture of both faunas during this interval or the gradual replacement of one by the other, but the reworking of the older deposits by the fluvial dynamics prevents the identification of this stratigraphic succession.
2) During a humid and/or warmer interval after 33 ka BP, the Brazilian taxa migrated to the south, and the fluvial system reworked older deposits, mixing the specimens of the Brazilian fauna with the older Pampean taxa.
3) The climatic regime that allowed the entrance of the Brazilian fauna occurred before 42 ka BP, and was replaced by a colder/humid climate that led to the retreat of this fauna and the readvance of the Pampean one. Fluvial dynamics between 42 and ~30 ka BP reworked and deposited together the remains of both faunas.

The mixture of both Pampean (temperate to cold) and Brazilian (intertropical) taxa suggests a northwards-southwards migration of climatic belts, related to glacial cycles. According to Rabassa et al. (2005), during glacial maxima the Pampean fauna would migrate farther to the north, following the northward displacement of the climatic belt, while Brazilian fauna would migrate southwards during interglacials, reaching the Pampean region. It can be difficult to evaluate this pattern on fossil assemblages, due to erosion and reworking of the sediments, and ages of the sediments using TL/OSL might be inconclusive due to the possibility of older fossils being re-deposited on younger sediments. Ages obtained on the fossils themselves, however, using ^{14}C or ESR, can provide direct correlation between the ages of the remains and paleoclimatic patterns recorded on sediments and palynomorph assemblages.

In southeastern Brazil, several studies have shown that the interval between ~45 and ~25 ka AP was marked by cold and/or humid climates, followed by drier ones in some areas until the beginning of the Holocene (Ledru 1993; Ledru et al. 1996; Behling and Lichte 1997; Salgado-Laboriau 1997; Turcq et al. 1997), a pattern that seems to be represented in the geological and fossil records of Chuí Creek, as evidenced by ESR ages of the fossils and the co-occurrence of taxa indicative of distinct environmental conditions. These data, correlated with the ages obtained in the fossils from Chuí Creek, seem to corroborate the statement by Oliveira (1999) proposing a cold and humid environment in this area during the late Pleistocene, based on the presence of *Mylodon darwini*, *Holmesina paulacoutoi*, and *Stegomastodon waringi*. However, southern Brazil was also probably influenced by drier climatic conditions seen in Uruguay and Pampean region, because during glacial maxima the colder/drier Patagonian climatic belt would have been displaced up to 750 km northeastern of its present position (Iriondo 1999; Behling 2002), thus reaching southernmost Brazil, resulting in vegetation changes, loess deposition and faunal migration. These conflicting climatic influences were most probably the main factor responsible for the faunal mixture of Pampean and Brazilian taxa found at this latitude.

Final Remarks

While both fossil assemblages from the southern Brazilian coastal area contain specimens of terrestrial mammals correlated to Lujanian Stage/Age, the assemblage from the continental shelf also contain fossils chronologically correlated to older Stage/Ages (Ensenadan and Bonaeran). In Chuí Creek, however, the fauna found in the fossiliferous level is Lujanian, encompassing an interval of some ten thousand years, between 42 and 33 ka BP. Nevertheless, older specimens have also been found, but in other stratigraphic levels. While there seems to be a correlation between the stratigraphic position of the fauna from Chuí Creek and the progressively drier climate of latest Pleistocene, this has yet to be compared with additional data in order to confirm or deny this correlation.

These data support the biostratigraphic correlation of this fossil assemblage with other localities in southern Brazil, Uruguay, and Argentina. Such a correlation can improve the understanding about the latest Pleistocene faunal dynamics, its distribution, extinction, and relation to climatic variations, when combined with geomorphological, sedimentological and palynological data.

The information presented here is a synthesis of the current knowledge regarding the biostratigraphy of the fossil assemblages from the CPRS. The ongoing research on the Chuí Creek should provide further information on the subject, in addition to increasing our knowledge of the stratigraphy, geologic evolution, paleoclimate, chronology and faunal dynamics in southern Brazil during the latest Pleistocene-early Holocene.

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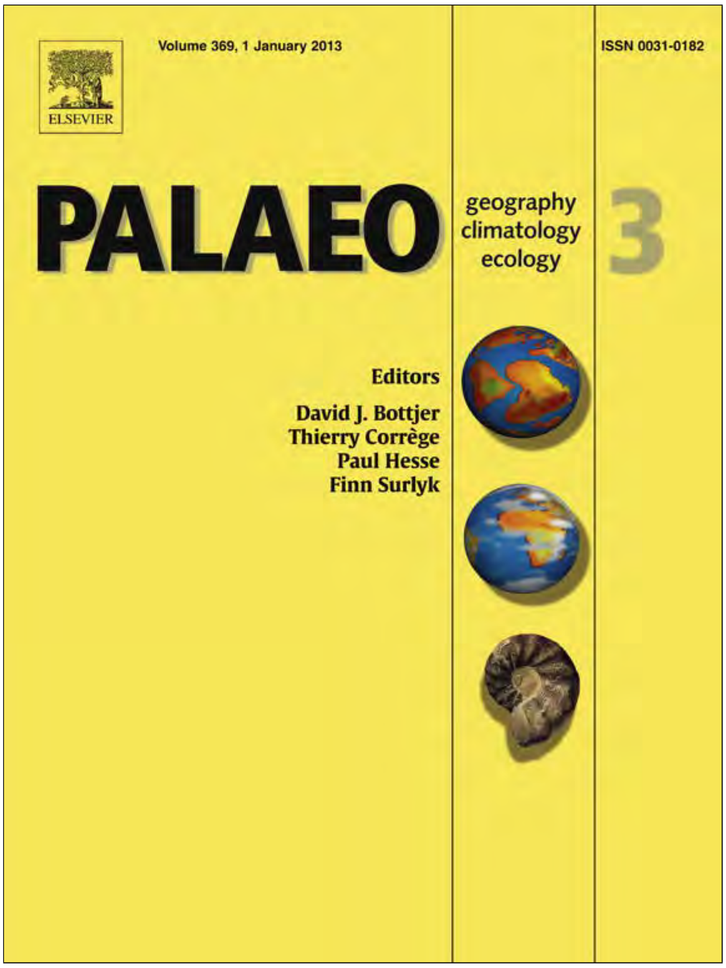
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Late middle to late Pleistocene paleoecology and paleoenvironments in the coastal plain of Rio Grande do Sul State, Southern Brazil, from stable isotopes in fossils of *Toxodon* and *Stegomastodon*

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ABSTRACT

Stable isotopes ($\delta^{13}C$, $\delta^{18}O$) in teeth of extinct mammals have been used as indicators of diets and climate conditions, which in turn are used for paleoenvironmental reconstructions. The first analysis of stable isotopes in Pleistocene mammals from Southern Brazil is reported here. The analyzed taxa were the notoungulate *Toxodon* and the proboscidean *Stegomastodon* from Late Middle to Late Pleistocene fossiliferous beds exposed along Chuí Creek, in the coastal plain of Rio Grande do Sul State. The $\delta^{13}C$ isotopes indicate that *Toxodon* was a mixed-feeder that fed mostly on C4 plants, while *Stegomastodon* was a browser to mixed-feeder with preference for C3 plants, with less C4 plants in the diet compared to modern African elephants. Comparison with carbon isotopic values in fossils of these taxa from other Late Quaternary localities in South America shows an increased proportion of C3 plants in the diets of both *Toxodon* and *Stegomastodon* in higher latitudes. The values of $\delta^{18}O$ in both taxa seem to reflect the isotopic composition of the ingested water rather than the isotopic content in the plants of which they fed on, and the observed variations are likely to mirror variations of the patterns of precipitation. Paleoclimatic inferences and possible causes for the (pseudo)extinction of these taxa in southern Brazil are also discussed.

1. Introduction

The Coastal Plain of Rio Grande do Sul State (CPRS), in southern Brazil, contains fossiliferous assemblages of Pleistocene age. The most important and studied is the one found in Chuí Creek (Fig. 1). The fossil assemblage is found in a sedimentary layer exposed along the banks of the creek, and includes mostly large-bodied extinct mammals correlated to the Lujanian Stage/Age from the Pampean region of Argentina (e.g. Paula Couto and Cunha, 1965; Soliani, 1973; Lopes et al., 2009). This assemblage is a mixture of Pampean taxa (e.g. *Doedicurus* sp., *Lestodon armatus* and *Mylodon darwinii*) and taxa with Brazilian affinities (*Eremotherium laurillardi*, *Protocyon troglodytes*, *Holmesina paulacoutoi*). Besides these, there are taxa indicative of humid (*Myocastor coypus*, *Holochilus brasiliensis*) and dry/semiarid environments (Dolichotinae sp.; *Microcavia* sp., *Catagonus stenocephalus*) (Oliveira et al., 2005; Ubilla et al., 2008; Kerber et al., 2011; Lopes, in press). The taphonomy of the fossils indicates that the assemblage is parautochthonous, composed of remains reworked and mixed by fluvial dynamics (Lopes et al., 2009). ESR ages obtained from fossil teeth show that the fossil assemblage from the Chuí Creek encompasses a time interval between Late Middle (~226 ka BP) and Late (~34 ka BP) Pleistocene at least (Lopes et al., 2010).

The mixing of organisms related to different environments, the large time interval represented by this assemblage, and the reworking by fluvial dynamics, indicate that paleoenvironmental reconstructions based solely on the faunal composition of the fossil assemblage can be difficult (Lopes, in press). The climate of the South America during the Middle to Late Pleistocene was highly variable, driven by Milankovitch cycles and millennial-scale oscillations (Clapperton, 1993; Salgado-Laboriau et al., 1998; Rabassa et al., 2005; Whitney et al., 2011). Such variation is likely to have influenced the range of habitats and the distribution (and possible the extinctions) of large terrestrial mammals, but paleoenvironmental data from southern Brazil are so far based on pollen records (Behling and Lichte, 1997; Behling, 2002) and speleothems (Cruz et al., 2005, 2006; Wang et al., 2007). The results of the first analyses of stable isotopes in fossil mammals from Chuí Creek, as an attempt to understand their paleoecology and make inferences about the climate and environments in southern Brazil during the Late Middle to Late Pleistocene are presented here.

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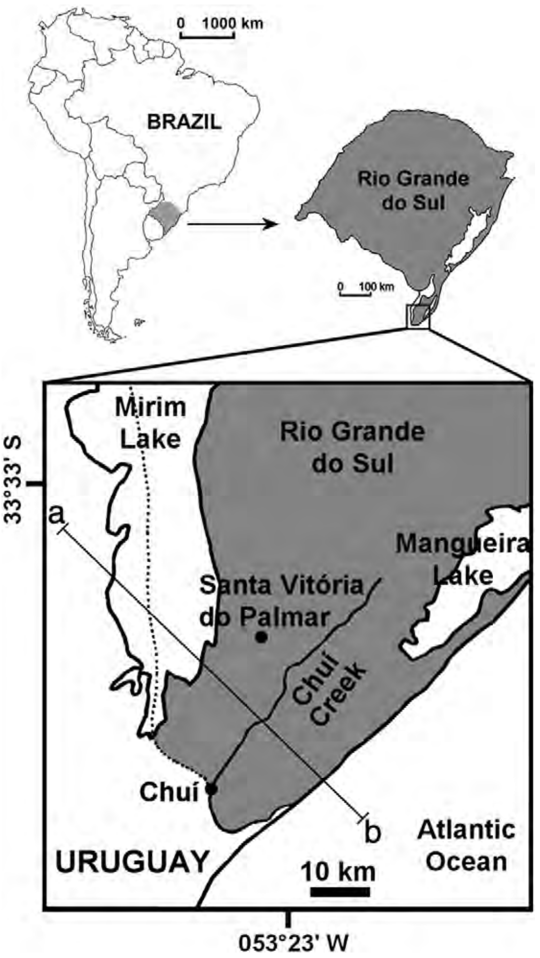

Fig. 1. Location of Chuí Creek, in Rio Grande do Sul State, southern Brazil; the a–b transect is explained in Fig. 2.

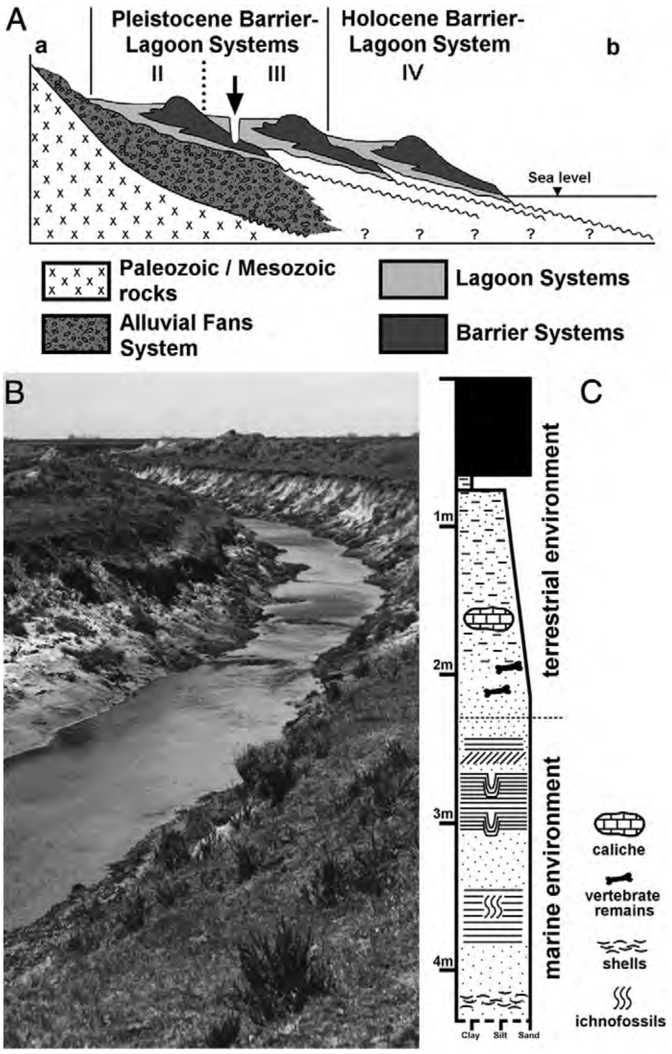

Fig. 2. A) The a–b transect of the southernmost portion of CPRS of Fig. 1, showing the position of Chuí Creek (indicated by arrow) between the Pleistocene Barriers II and III; B) panoramic view of Chuí Creek; C) stratigraphic sequence exposed along the banks of Chuí Creek.

LGP: Laboratory of Geology and Paleontology, Universidade Federal do Rio Grande, Rio Grande do Sul, Brazil.

2. Geological setting

Chuí Creek is a small fluvial system located in the coastal area of southernmost Brazil, near the town of Santa Vitória do Palmar (Fig. 1). It flows over a plain located some 11 m above sea level, between two Pleistocene coastal barriers (Fig. 2), each one formed by a marine highstand during interglacial epochs (Villwock and Tomazelli, 1995). The creek was originally a shallow stream, but in the early 1960s it was further excavated for agricultural purposes, exposing a layer containing fossils of Pleistocene mammals (Paula Couto and Cunha, 1965). The fossiliferous layer overlies shallow marine sediments and is composed of muddy sand, with organic matter-rich sand lenses that contain palynomorphs indicative of lentic environments, interpreted as oxbow lakes formed by abandoned meanders, an interpretation reinforced by the taphonomic features observed on the fossils (Lopes et al., 2009).

All fossils found so far have been collected from the lower portion of the ~1 m-thick muddy sand layer; its uppermost portion exhibits an ~40 cm-thick discontinuous horizon of caliche nodules and rhizoliths, and it is overlain by an ~1.0 m-thick silty sand layer that seems to represent loessic deposition, suggesting a drier climate regime. No vertebrate fossils have been recovered so far from the silty sand, but plant roots and some possible burrows made by small vertebrates are found. The uppermost portion of the sequence is composed of organic matter-rich clay and sand that also contains archeological remains.

Although fossils of different ages come from the same stratigraphic interval, due to fluvial reworking, the association of different faunal elements such as indicators of humid and dry environments, and also taxa with Pampean and Brazilian (intertropical) affinities indicates that southern Brazil (together with northern Uruguay and the Mesopotamian region of Argentina) was under the influence of different climate and environmental conditions between the Pleistocene and Holocene (Lopes, in press).

3. Methods

In recent years, stable isotopes in organic remains have been used as tools for paleoecological and paleoenvironmental reconstructions in continental environments of the Paleogene and Neogene (Koch et al., 1995; MacFadden and Cerling, 1996; MacFadden et al., 1996; Koch, 1998; Kohn and Cerling, 2002; Palmqvist et al., 2003). Among terrestrial mammals, the main object of the studies has been tooth enamel, that has a mineral phase composed of hydroxylapatite ($Ca_{10}[PO_4, CO_3]_6[OH, CO_3]_2$) and records dietary and environmental informations in the form of carbon and oxygen isotopes in the phosphate (PO_4^{3-}) and carbonate (CO_3) components. Several studies have demonstrated that isotopic values from enamel carbonate can be preserved with minimal or no significant diagenetic alteration (Wang and Cerling, 1994; Bocherens et al., 1996; Cerling et al., 1997; Sánchez et al., 2004).

The isotopic abundances are expressed in parts permil (‰), using the notation δ:

$$\delta = \left[\left(R_{Sample}/R_{Standard}\right) - 1\right] \times 1000$$

where R is the ratio between the heavier and the lighter isotope ($^{13}C/^{12}C$; $^{18}O/^{16}O$) and represents deviations in the isotopic ratio in relation to a standard. The standard used for carbonate is Vienna Pee Dee Belemnite (VPDB), while oxygen values are usually compared to the Standard Mean Ocean Water (SMOW). More positive values of δ indicate enrichment of the heavier isotope in relation to the lighter one.

The oxygen isotopic ratios in enamel are derived from the isotopic content of ingested water ($^{18}O_w$), either by drinking or from food, which in turn is related to climatic conditions such as mean annual temperature (MAT) and local precipitation (Dansgaard, 1964; Fricke et al., 1998). Another factor that influences the $\delta^{18}O$ content of organisms is the loss of body water through transpiration, respiration and excretion (Luz and Kolodny, 1985). Large mammals obtain most of their water by drinking, thus are more reliable paleoclimatic indicators (Bryant and Froelich, 1995; Fricke and O'Neil, 1996).

The carbon isotopic content ($\delta^{13}C$) in herbivores' tooth enamel indicates preference for plants that use C3 or C4 photosynthetic pathways, thus it can be used as tools for reconstructing the diet, which can indicate in what type of environment the animals lived (De Niro and Epstein, 1978; Ehleringer et al., 1997; MacFadden, et al., 1999). The plants that use C3 photosynthetic pathway (dicotyledonous such as trees, shrubs, herbs and cool growing season grasses) exhibit $\delta^{13}C$ values between −22‰ and −35‰ (mean = −27‰), while those that use C4 pathway (monocotyledonous such as warm growing season grasses and CAM plants) exhibit $\delta^{13}C$ values between −19‰ and −9‰ (mean = −13‰) (Koch, 1998). In large herbivore mammals (body mass ≥ 100 kg), the $\delta^{13}C$ values are between 12 and 14‰ more positive in relation to the plants they eat, because of fractioning conditioned by stable body temperature of 37 °C (Cerling and Harris, 1999; Palmqvist et al., 2003; MacFadden, 2005). The ^{13}C values among different species, however, can differ by values up to ~5‰ because of different physiologies and metabolic rates (Passey et al., 2005). Herbivores that eat only C3 plants will exhibit mean $\delta^{13}C$ values of ~−13‰, while those feeding on C4 plants only will exhibit mean values of +1‰. Herbivores that eat both C3 and C4 plants (mixed feeders) will exhibit intermediate $\delta^{13}C$ values.

Sixteen fossil teeth from Chuí Creek were selected among specimens from the paleontological collection of Universidade Federal do Rio Grande (FURG). All remains have been collected in the fossiliferous layer exposed on the banks of Chuí Creek in the last 10 years. The selected taxa were two common elements of the Pleistocene megafauna found in Chuí Creek, the toxodont *Toxodon* (ten specimens) and the mastodont *Stegomastodon* (six specimens). Because the teeth of *Toxodon* are euhypsodont and all specimens were fragments, there was no preferential portion of the teeth for enamel extraction; in *Stegomastodon* the teeth are brachydont, so the enamel was extracted from the lingual or labial side of the crown. Besides, the teeth of the latter have a thick enamel layer, so provide more material for the analyses.

The chosen specimens did not have carbonate or iron crusts, and were mostly teeth fragments. Between 0.4 and 2.3 g of enamel from each specimen were mechanically drilled and manually powdered. The enamel samples were then treated with 2% NaOCl during three days under local temperature for the removal of any organic contaminants, and treated with 0.1 M acetic for one day to remove any diagenetic carbonates and bicarbonates (Koch et al., 1997). The samples were then treated with 85% H_3PO_4 at 25 °C for 3 days to release the CO_2 (McCrea, 1950). The $\delta^{13}C$ and $\delta^{18}O$ values were measured on cryogenically cleaned CO_2, according to the method described by Craig (1957) in a double inlet, triple collector mass spectrometer (VG Isotech SIRA II) at NEG-LABISE, Universidade de Pernambuco, Brazil. The C and O isotopic data are presented as standard ‰ deviation with reference to the standards VPDB and SMOW for $\delta^{13}C$ and $\delta^{18}O$, respectively. The statistical analysis of the results consisted of normality test (Kolmogorov–Smirnov), *t*-test and coefficient of variation following Zar (1999) and were performed using the software Bioestat 5.0. Estimates of percentages of C4 plants in diet were calculated following Koch et al. (1998).

4. Results

4.1. Carbon isotopes

The results of the ^{13}C and ^{18}O analyses of both taxa, with the ages of the dated specimens (Lopes et al., 2010; unpublished data) are listed in Table 1. Isotopic data from African elephants (*Loxodonta africana*) from Bocherens et al. (1996) are also presented for comparison.

Nine samples of *Toxodon* exhibit $\delta^{13}C$ values between −4.0‰ and −5.5‰, except for one sample (LGP-E0011) that exhibits value of −8.8‰; the standard score (*z*) shows that it is an outlier (Hair et al., 2005). The mean value of $\delta^{13}C$ (excluding the outlier) is −4.6‰ (s = 0.554). These values indicate a mixed diet, with predominance of C4 plants (between 53 and 64% excluding the outlier, Fig. 3) and are similar to those obtained by MacFadden (2005) for fossils of *Toxodon* from northern Argentina, which exhibit $\delta^{13}C$ values between −1.5 and −7.2‰.

The teeth of *Stegomastodon* provided $\delta^{13}C$ values between −7.3‰ and −10.2‰ (mean = −8.5‰, s = 0.934), indicating browsing to mixed feeding habit with predominance of C3 plants in the diet (with 20 to 40% of C4 plants, Fig. 3). Five teeth exhibit values between ~−7‰ and −8‰; although one specimen (LGP-G0002) exhibits value of −10.2‰, comparable to values found in extinct *Stegomastodon* from the late Pleistocene of the Pampean region of Argentina (Sánchez

Table 1
Results of the isotope analyses of the specimens of *Toxodon* and *Stegomastodon*; the ages are from Lopes et al. (2010) and Lopes (unpublished data). The $\delta^{13}C$ values of modern elephants (*Loxodonta africana*) from Amboseli Park, Kenya (Bocherens et al., 1996) shown here are ~1.5‰ more depleted after correction for the Suess effect.

Taxon	Sample	$\delta^{13}C_{VPDB}$	$\delta^{18}O_{SMOW}$	% of C4 plants in diet	Age (ky)
Toxodon	LGP-E0010	−4.5	31.0	60	–
Toxodon	LGP-E0011	−8.8	30.3	30	–
Toxodon	LGP-E0012	−4.9	30.3	57	–
Toxodon	LGP-E0013	−5.3	30.1	54	–
Toxodon	LGP-E0038	−4.5	30.2	60	46 ± 8
Toxodon	LGP-E0040	−4.0	29.2	64	66 ± 9
Toxodon	LGP-E0053	−4.4	29.7	61	42 ± 3
Toxodon	LGP-E0054	−4.1	28.0	62	–
Toxodon	LGP-E0058	−5.5	30.1	53	–
Toxodon	MOT0050	−4.0	29.8	64	226 ± 35
	Mean	−5.0	29.9		
Stegomastodon	LGP-G0001	−8.2	27.9	33	44 ± 3
Stegomastodon	LGP-G0002	−10.2	28.5	20	–
Stegomastodon	LGP-G0034	−7.3	30.1	40	–
Stegomastodon	LGP-G0036	−8.5	29.3	32	80 ± 10
Stegomastodon	LGP-G0037	−8.2	29.1	34	52 ± 7
Stegomastodon	LGP-G0038	−8.4	29.6	32	–
	Mean	−8.5	29.1		
L. africana	Harriet	−5.8	30.4		
L. africana	M178	−4.2	29.3		
L. africana	Teresia	−8.7	28.3		
L. africana	Zach	−9.2	30.0		
L. africana	Zoe	−5.1	31.0		
L. africana	21–5/90–25	−8.5	29.8		
	Mean	−6.9	29.8		

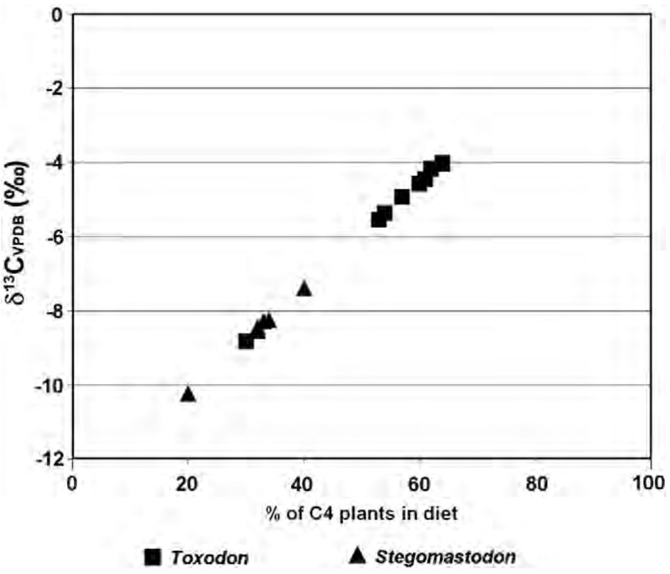

Fig. 3. Estimated percentages of C4 plants in the diet of the analyzed specimens.

et al., 2004) and values found in modern African elephants (Table 1) (Bocherens et al., 1996; Cerling et al., 1999). Although the independent *t*-test shows that the carbon values of *Stegomastodon* do not differ statistically from those found in *L. africana* ($p > 0.05$), analysis of the coefficient of variation shows that the latter exhibits a wider range of $\delta^{13}C$ values (30.9%) in comparison to *Stegomastodon* (11.2%).

4.2. Oxygen isotopes

The values of $\delta^{18}O$ for *Toxodon* teeth range between 31.0‰ and 28.5‰ (mean = 29.9‰, s = 0.80); while in *Stegomastodon* range from 27.9‰ to 29.6‰ (mean = 29.1‰, s = 0.78). Although direct comparison between different regions may be hampered by variable hydrologic conditions, $\delta^{18}O$ values for *Toxodon* are similar to those observed in fossils from northeastern Brazil, Bolivia (Chaco), northern Argentina and Buenos Aires Province of Argentina (MacFadden, 2005). The values obtained for *Stegomastodon* are similar to those found in teeth of modern *L. africana* from Amboseli Park (Bocherens et al., 1996) and *Stegomastodon* from Argentina and northeastern Brazil (Sánchez et al., 2004).

The correlation between $\delta^{18}O$ and $\delta^{13}C$ in both taxa is weak (Fig. 4), indicating that the isotopic content of the plants that these animals fed on didn't contribute for the isotopic composition of their body water.

5. Discussion

5.1. Carbon isotopes

The $\delta^{13}C$ values obtained for both taxa indicate a browsing to mixed-feeding habit based mostly on C3 plants for *Stegomastodon*, and indicate a mixed diet for *Toxodon*, composed of C3 and C4 plants (Fig. 5). The values obtained for *Stegomastodon* are very close to those found in modern African elephants, but the higher coefficient of variation seen in the latter indicates a wider range of dietary preferences that include large amounts of C4 plants, related to the seasonal feeding pattern. Most of their diet is composed of C3 plants, but during a few weeks after the beginning of the rainy season, up to 60% of their diet includes C4 grasses (Cerling et al., 2004), while in Asian elephants (*Elephas maximus*) the amount of C4 grasses in the diet during the rainy season can reach up to 90% (Sukumar and Ramesh, 1992). The $\delta^{13}C$ values in *Stegomastodon* from southern Brazil indicate that their diet included a lower proportion of C4 plants in comparison.

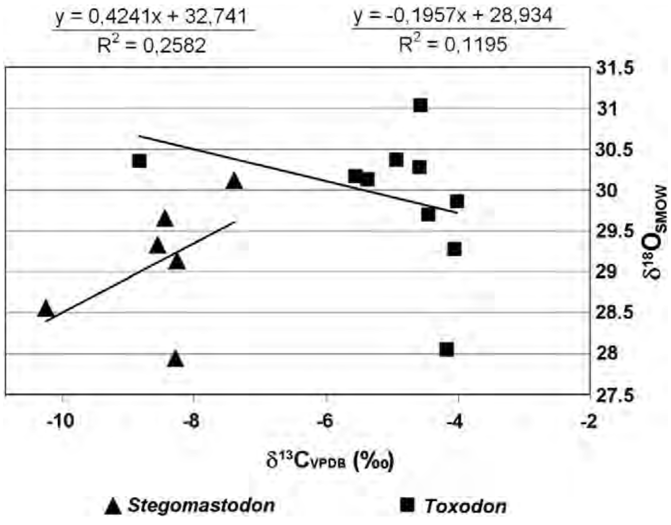

Fig. 4. Relationships between $\delta^{13}C$ and $\delta^{18}O$ of *Toxodon* and *Stegomastodon*.

The values found in *Toxodon* teeth clearly indicate the presence of both C3 and C4 plants in its diet (Fig. 5). The value of −8.8‰ found in the specimen E0011, lower than in the other specimens, suggests that it had a higher proportion of C3 plants in its diet (about 70%); similar values have been found in *Toxodon* from the Buenos Aires Province,

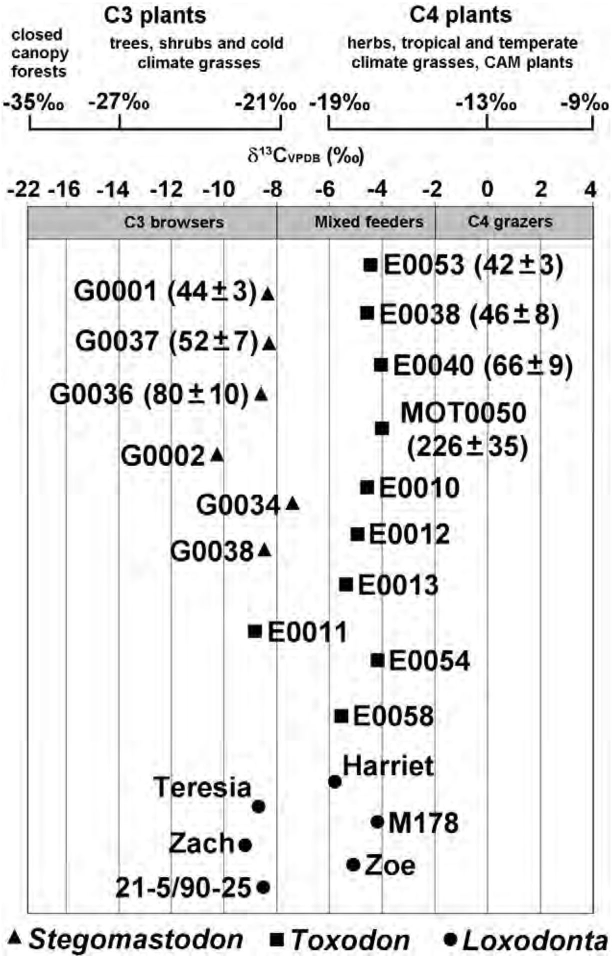

Fig. 5. Comparison between the $\delta^{13}C$ values of *Stegomastodon* and *Toxodon* from Chuí Creek and modern *Loxodonta africana* (from Bocherens et al., 1996); in parentheses are the ages of the dated specimens (Lopes et al., 2010; unpublished data).

Argentina (MacFadden et al., 1996; MacFadden, 2005). It is possible that this individual had migrated from an area with a different pattern of vegetation, or it inhabited the region during a time when the vegetation pattern was different. Another possible explanation is that this specimen may represent a young individual that was still feeding mostly on mother's milk. Studies have demonstrated that sucklings may exhibit a 3–4‰ depletion of ^{13}C values in comparison to adults as a result of the carbon isotopic content of the milk (Witt and Ayliffe, 2001).

C4 plants are less digestible and exhibit lower proteic values in comparison to C3 plants (Ehleringer et al., 2002), thus the high content of C4 plants in the diet of *Toxodon* from southern Brazil may be one cause of the widespread occurrence of enamel hypoplasy in the form of pits and sulci in the teeth of this taxon, that indicates a pathological condition related to nutritional stress (Ferigolo, 2007; Braunn et al., 2011).

5.2. Oxygen isotopes

The range of variation of the δ^{18}O values of *Stegomastodon* and *Toxodon* are 2.2 and 2.9‰, respectively (Fig. 6). In African elephants from Amboseli the range of variation is similar; because the migratory habits of elephants (in some cases reaching some 500 km) result in differences of up to 1‰ in δ^{18}O (Ayliffe et al., 1992), only migrations cannot account for such variation. Although an important part of the diet of modern elephants consists of C4 grasses, that are enriched in ^{18}O due to evaporation, the oxygen content of their body water mirrors the isotopic composition of the meteoric (local) water, because they obtain at least 1/3 of their ingested water from parts of C3 plants (stems, twigs and fruits) that are ^{18}O-depleted in comparison to leaves. Besides, trees and shrubs that constitute most of the C3 diet of elephants also have deeper roots that reach less-enriched underground water, while C4 grasses have shallow roots and can only absorb the surface, ^{18}O-enriched water (Kohn et al., 1996; Sponheimer and Lee-Thorp, 1999). If this pattern was similar for *Stegomastodon*, then the variations in oxygen values may be explained by different isotopic compositions of the ingested water. The relatively large variation of δ^{18}O values of *L. africana* (Fig. 6) is likely to represent seasonal variations of local precipitation, possibly enhanced by the migration of these animals in search of other water sources during dry seasons.

Grazers tend to exhibit higher δ^{18}O values compared to browsers and mixed-feeders because of the enriched ^{18}O content of C4 grasses in comparison to C3 plants, probably related to anatomical differences (Helliker and Ehleringer, 2000), thus, the higher ^{18}O content of the teeth of *Toxodon* could be related to the ingestion of C4 grasses. Nevertheless, as in *Stegomastodon*, there is poor correlation between the diet and oxygen content of body water (Fig. 4), suggesting that *Toxodon* also obtained most of its water from drinking rather than from food. Because there is no overlapping among the ages of the dated specimens, then the variations found in the oxygen values of *Toxodon* teeth (mostly enriched in comparison to *Stegomastodon*) probably reflect variations in the isotopic composition of meteoric water through time. Because of the incompleteness of the teeth, the possibility that such variations could reflect seasonal patterns of precipitation (causing different parts along the tooth to exhibit distinct δ^{18}O values) was not addressed here, but may be explored in the future.

It has been proposed that *Toxodon* had a semiaquatic lifestyle similar to that of hippopotamuses, based mostly on its skull morphology (Darwin, 1839; Paula Couto, 1979; Anderson, 1984). In modern African hippos, the δ^{18}O values are lower in comparison to other large herbivores living in the same area. This pattern seems to be related to the semiaquatic habit of these animals that causes the depletion of the δ^{18}O content of body water by preventing the loss of water by transpiration (Cerling et al., 2008; Clementz et al., 2008).

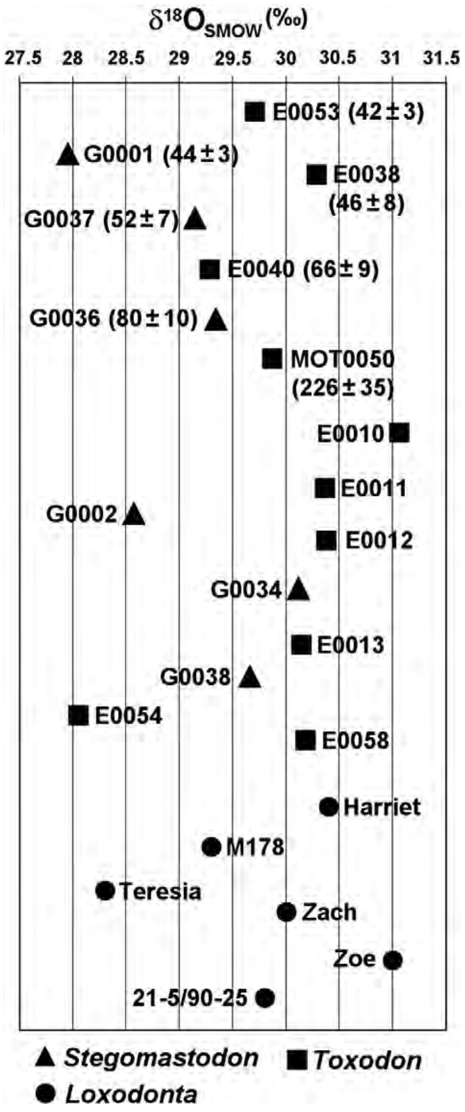

Fig. 6. Comparison between the δ^{18}O values of *Stegomastodon* and *Toxodon* from Chuí Creek and modern *Loxodonta africana* (from Bocherens et al., 1996).

If *Toxodon* was also a semiaquatic animal, it would be expected to find average low δ^{18}O values, similar as to those found for hippos. The values reported by Bocherens et al. (1996) for hippos from Amboseli Park, however, are about 2.9‰ lower (mean = 26.9‰) in comparison to elephants living in the same area. The δ^{18}O values in *Toxodon* teeth are in fact more enriched than those found in hippos and do not differ much than those found in *Stegomastodon*. Thus, the oxygen isotopes in *Toxodon* do not seem to support a semiaquatic habit. A similar conclusion was reached by analysis of the postcranial anatomy of *Toxodon* (Shockey, 2001).

5.3. Comparison with other localities

Late Pleistocene toxodontid remains are found from Central America to Argentina. The only valid genus of this group recognized for the Pleistocene of Southern South America is *Toxodon* (Bond, 1999). MacFadden (2005) analyzed teeth of *Toxodon* from several localities of South America and found a large variation in δ^{13}C values, showing that this taxon was a generalist, feeding on both C3 and C4 plants, according to the available type of vegetation that existed in the area. The overall variation of δ^{13}C values in fossils from Chuí Creek (excluding the outlier E0011) is smaller in comparison with values from other localities (Fig. 7a), and are similar to those found in *Toxodon*

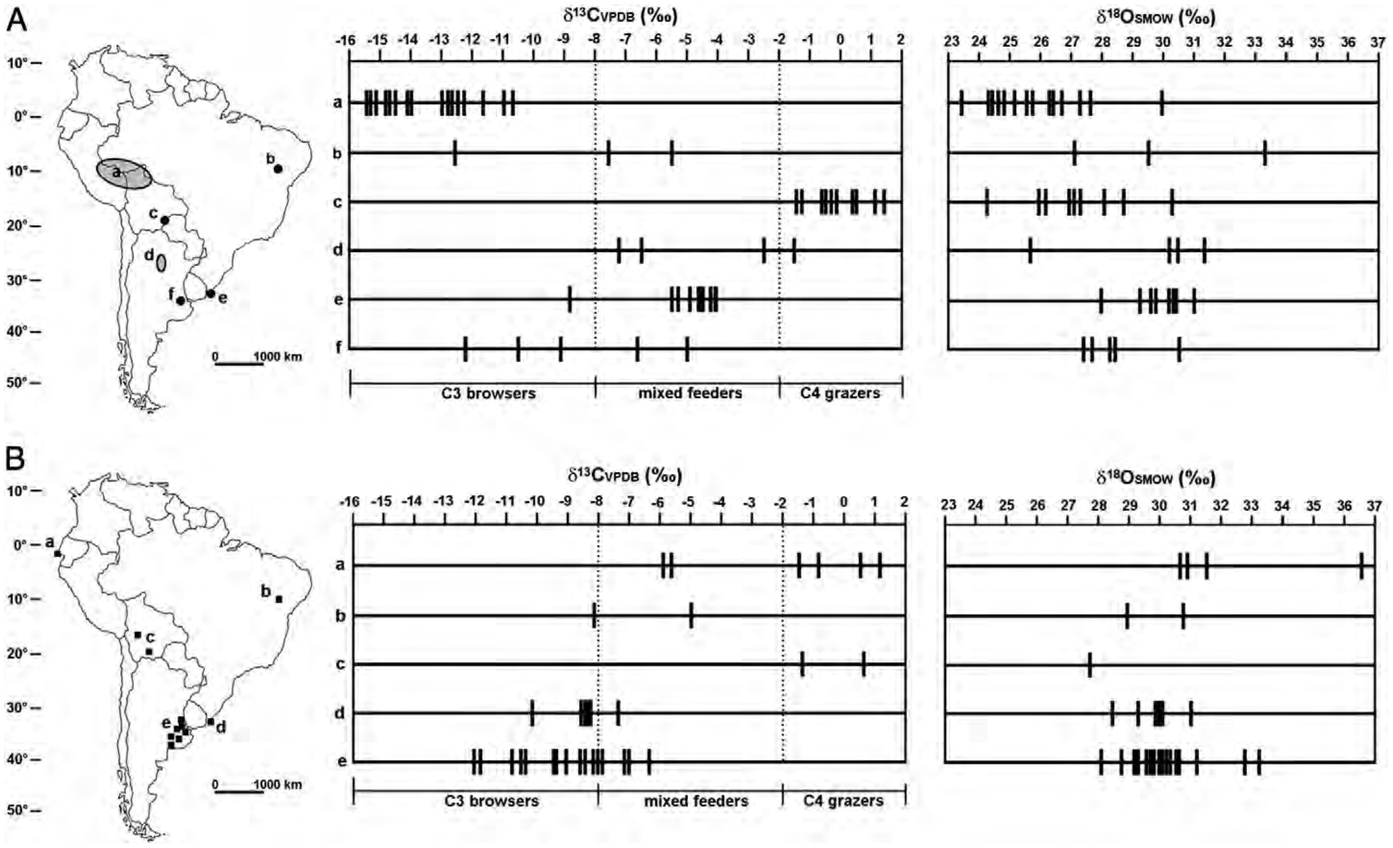

Fig. 7. A) Carbon and oxygen isotope values of *Toxodon* from Late Pleistocene localities of South America (from MacFadden, 2005): a) Amazon basin; b) Northeastern Brazil (Toca dos Ossos); c) Bolivia (Chaco area); d) northern Argentina; e) Chuí Creek; and f) Buenos Aires Province; B) Carbon and oxygen isotope values of *Stegomastodon* from Late Pleistocene localities of South America: a) Ecuador; b) Northeastern Brazil (Toca dos Ossos); c) Southwestern Bolivia (from Alberdi et al., 2008); d) Chuí Creek; and e) Buenos Aires Province (from Sánchez et al., 2004).

from northern Argentina (MacFadden, 2005). The latitudinal distribution of the δ^{13}C values in Late Quaternary fossils of *Toxodon* shows a clear southwards increase in C3 vegetation in the diet, except for the specimens from the Amazon basin and Toca dos Ossos (NE Brazil), which had a lower proportion of C4 plants on their diet (MacFadden, 2005). The variation in δ^{18}O values, however, do not show a clear pattern, probably because the oxygen content is dependent of several external factors such as the δ^{18}O content of the ingested water, temperature and local precipitation.

Gomphotheriidae proboscideans were widespread in South America during the Middle to Late Pleistocene and remains of *Stegomastodon* have been found from Colombia to the Pampean region of Argentina (Prado et al., 2005; Alberdi et al., 2007). Similarly to the pattern observed in *Toxodon*, carbon isotope analyses revealed a latitudinal pattern of dietary preferences: while specimens from lower latitudes had a higher content of C4 plants (including an exclusive C4 grazer from northern Argentina), those living in latitudes south of ~30° S had a greater proportion of C3 plants in their diet (Sánchez et al., 2004; Alberdi et al., 2008; Asevedo et al., 2012), a pattern reinforced by the present study (Fig. 7b). Except for specimens from Ecuador and northern Argentina, which had a higher proportion of C4 plants on their diet, specimens from Chuí Creek had δ^{13}C more similar to those found in northeastern Brazil and the Buenos Aires Province, all very close to values found in modern *L. africana*.

The oxygen isotopic values do not exhibit a latitudinal pattern as seen in carbon isotopes; mean δ^{18}O values from Chuí Creek are close to all other localities of South America, except for Ecuador and northern Argentina. In comparison with *Toxodon*, the oxygen values for *Stegmastodon* remains from South America seem to exhibit much less range of variation; no fossils of this taxon exhibit δ^{18}O values lower than ~28‰ (Fig. 7b).

5.4. Paleoclimatic and paleoecological implications

Toxodon is a taxon with widespread records in South America, and is considered a generalist herbivore adaptable to a wide range of diets (MacFadden, 2005), so it seems reasonable to consider that the δ^{13}C values reported here are reliable indicators of the type of vegetation that existed in the CPRS during the interval represented by the fossils (Late Middle to Late Pleistocene). The available palynological surveys show that the landscape during the Late Pleistocene–Early Holocene of Rio Grande do Sul State consisted of grasslands ("campos") with gallery forests, dominated by Poaceae, Cyperaceae, Asteraceae, but also included Caesalipiniaceae, Papilionaceae and Verbenaceae (Behling et al., 2004). It seems likely that the diet of *Toxodon* consisted of C4 grasses and C3 herbs, while *Stegomastodon* fed mostly on C3 herbs and shrubs (and possibly trees) but included also C4 grass in their diet.

The small range of variation of 1.54‰ in the composition of the carbon values of *Toxodon* teeth (excluding the outlier E0011 mentioned before), indicates that these animals had very strict feeding habits, regarding the relative proportion of C3 and C4 plants in the diet. Among the four dated specimens (E0038, E0040, E0053 and MOT0050) the total range of variation is of 0.5‰, indicating that their feeding habit didn't change much through time, despite of the large (~180 thousand years) of difference between the oldest and youngest dated specimens. Such a specialized diet may indicate that *Toxodon* inhabited southern Brazil during times of stable environmental conditions, without drastic changes that could affect the composition of the vegetation assemblages. Another possible explanation could be the competition with other large herbivores such as glyptodonts and ground sloths, considered grazers and browsers, respectively (Vizcaíno et al., 2006), that were common in the Late Pleistocene of South America. This competition could also explain why horses are relatively scarce in the fossil deposits of Chuí Creek.

Despite of the small number of analyzed samples, the variation of 2.8‰ in the carbon values of *Stegomastodon* teeth suggests that it had a more generalistic feeding habit, based on C3 plants but also including between 20 and 40% of C4 plants. The lack of specimens of the same age do not allow to infer whether the inclusion of C4 plants reflects a possible seasonal feeding pattern, as seen in modern elephants, or if it represents different diet habits related to changes in the composition of the plant assemblages through time. Nevertheless, the dated specimens (G0001, G0036 and G0037) exhibit a range of variation of only 0.3‰.

The time interval represented by the dated specimens (except for MOT0050) encompasses the glacial interval corresponding to marine isotope stages (MIS) 4 (71–60 ky BP) and MIS 3 (60–24 ka BP; Table 1). This interval, mainly MIS 3, was marked by several millennial-scale oscillations, related to climatic changes in the Northern Hemisphere and recorded in geological records from other areas of southern Brazil (Cruz et al., 2005, 2006; Wang et al., 2007). Considering that there is no overlapping in ages between the dated specimens of *Toxodon* and *Stegomastodon*, it is possible that the distinct dietary patterns and oxygen values deduced from the isotopic composition of the two taxa may reflect distinct environmental conditions, related to the climatic oscillations within the last glacial period.

The oxygen values in hydroxyapatite of obligatory drinkers are correlated to those from ingested water (δ^{18}Ow), which in turn depends on local climatic conditions, thus can be used as proxies for isotopic values in paleoprecipitation (Dansgaard, 1964; Longinelli, 1984). Such a relationship is well-established for modern elephants (Ayliffe et al., 1992; Koch, 1998; Kohn and Cerling, 2002). Because the oxygen isotopic content of *Stegomastodon* appears to be independent of the diet as in elephants, it probably mirrors the isotopic composition of the local waters. The ^{18}Ow for *Stegomastodon* was calculated using the relationship between the oxygen content of the PO$_4$ component of bioapatite (δ^{18}Op) and ingested water in modern elephants (Ayliffe et al., 1992):

$$\delta^{18}\mathrm{Op} = 0.9\delta^{18}\mathrm{Ow} + 23.3.$$

The carbonate in enamel is ~8.7‰ more enriched in δ^{18}O than phosphate and both are in isotopic equilibrium in mammalian enamel (Bryant et al., 1996). The isotopic values from enamel carbonate obtained here (δ^{18}Oc) were first converted to phosphate values (δ^{18}Op) by reducing the δ^{18}Oc values by 8.7‰. The δ^{18}Ow results (Table 2) varied between −4.5‰ and −2.1‰ (mean = −3.0‰). The Lagoon System III where Chuí Creek is located is isolated by the Barrier II (see Fig. 2) from other water bodies such as large rivers and lakes located landwards, thus local precipitation was the only source of water that formed the rivers and possible small lakes from where the mammals drank.

In medium and low latitudes there is no correlation between the latter and local temperatures, but good correlation between precipitation and oxygen isotopic composition of meteoric waters (Dansgaard, 1964; Rozanski et al., 1992; Bowen and Revenaugh, 2003). In southern Brazil today there is a good positive correlation between δ^{18}O in precipitation and the amount of precipitation (Fig. 8). This pattern is related to the extratropical origin of rain during the wet seasons (Winter and Spring), that brings ^{18}O-enriched precipitation; during Summer and Autumn there is less precipitation and the rain is ^{18}O-depleted because of its distant tropical (Amazonian) origin related to southwards migration of the South American Summer Monsoon (SASM) when the intertropical convergence zone (ITCZ) is located closer to the equator (Gan et al., 2004; Cruz et al., 2005).

If the ^{18}Ow calculated from *Stegomastodon* represents the isotopic content of meteoric water, and the relationship between oxygen in precipitation and the amount of precipitation seen today is valid for the past, then the ~2.2‰ drop in δ^{18}O between the oldest specimen (G0036) and the youngest (G0001) indicates a change in precipitation (from extratropical to monsoonal) and possibly a reduction in the amount of precipitation in Southern Brazil. The small range of variation in the isotopic values of oxygen seen in specimens of *Stegomastodon* from several localities of the continent suggests that these animals required very specific environmental conditions, at least regarding the amount of available water, and a drastic reduction in the water supply may have been detrimental. Despite of the small number of available isotopic data from northern areas of South America, it seems that *Stegomastodon* did not inhabit areas with low precipitation, as would have been indicated if these had δ^{18}O-depleted values (Fig. 7b). In Southeastern Brazil, a population of mastodonts died apparently as result of a dry period some 55 thousand years ago (Avilla et al., in press).

If we consider the relationship between oxygen isotopes and precipitation, it seems likely that the specimens with enriched δ^{18}O values (G0036 and G0037) lived during periods of increased precipitation, while the most depleted in δ^{18}O (G0001) indicate drier interval. Although it is not possible to estimate precisely the values of δ^{18}Ow from *Toxodon* remains, because its physiology is not known and there are no living relatives from which to establish a basis for comparison, the enrichment or depletion in ^{18}O may as well indicate changes in the isotopic content of meteoric water ingested by those animals. The specimens E0038 and E0053, ~2 ky older and younger, respectively, than G0001, exhibit comparatively more enriched δ^{18}O

Table 2
Values of $\delta^{18}O_{P\text{-}SMOW}$ and $\delta^{18}O_{W\text{-}SMOW}$ obtained from oxygen isotopes in carbonate enamel ($\delta^{18}O_C$) of *Stegomastodon*.

Sample	$\delta^{18}O_P$	$\delta^{18}O_W$	Age (ky BP)
LGP G0001	19.2	−4.5	44 ± 3
LGP G0002	19.8	−3.8	–
LGP G0034	21.4	−2.1	–
LGP G0036	20.6	−2.3	80 ± 10
LGP G0037	20.4	−3.1	52 ± 7
LGP G0038	20.9	−2.6	–
Mean	**20.4**	**−3.0**	

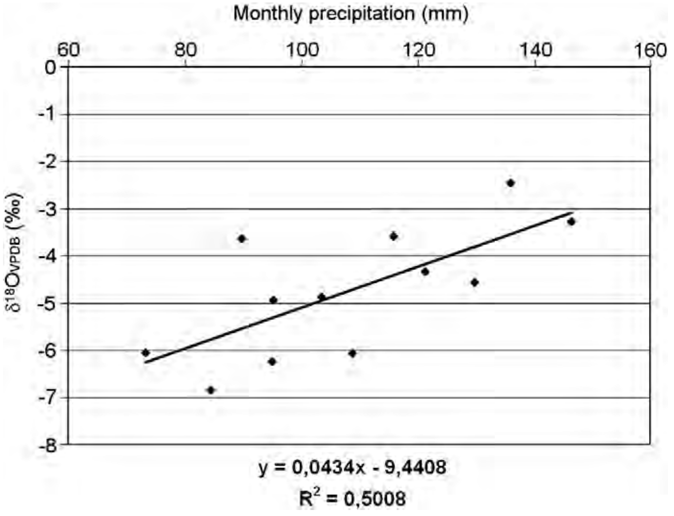

Fig. 8. Relationship between δ^{18}O and precipitation in Rio Grande do Sul from the IAEA-GNIP database (http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis.html); the station is located in Porto Alegre (30° S) and the data represent a 30-year period.

values, suggesting periods of increased precipitation of extratropical origin.

Behling et al. (2004) described pollen records from the highlands of Rio Grande do Sul state (some 600 km to the north of Chuí Creek) and concluded that climate was wetter between ~43 and ~27 ky BP in comparison with the last glacial maximum (LGM). During this interval the pollen records show high-frequency, small random changes in vegetation, indicating relatively stable climate conditions. This relative stability seems compatible with the conservative dietary pattern of *Toxodon*, inferred from carbon isotopes. On the other hand, the seemingly conservative diet habit of this taxon suggests that it may have been very sensitive to drastic changes in vegetation, although not much affected by variations between dry and wet conditions, as suggested by the high variations in δ^{18}O seen in specimens from several localities (Fig. 7a).

The main driver of changes in the composition of plant assemblages during the Late Pleistocene seems to have been moisture, because after ~27 ky BP there was a reduction of the arboreal vegetation and predominance of grasses, indicating drier conditions (Behling et al., 2004). The changes in moisture were probably related to the increased latitudinal displacement of the polar front, enhanced by the increased continentality due to the sea-level lowstand (some 130 m below present sea-level (Lopes and Buchmann, 2010)). In fact, several studies have shown the northwards displacement of the “campos” vegetation, reaching as far as 750 km from their present distribution (Ledru et al., 1996; Behling and Lichte, 1997; Salgado-Laboriau, 1997; Behling, 2002).

In Chuí Creek, the large mammals are so far absent from the upper stratigraphic levels, which also record an increase in silt-sized particles probably of loessic origin (Lopes et al., 2011), suggesting drier conditions; this is reinforced by the presence in the fossil assemblage of taxa that indicate semiarid environments, such as *Catagonus* cf. *stenocephalus*, Dolichotis sp., *Lagostomus maximus* and *Microcavia* sp. (Oliveira et al., 2005; Ubilla et al., 2008; Kerber et al., 2011; Pereira et al., 2012; Lopes, in press). This dryness is probably correlated to the LGM, and the corresponding environmental stress may have resulted in dramatic changes in the composition of the vegetation, and consequently upon the large mammals communities.

Oliveira (1999) proposed that the fauna from the Chuí Creek represented cold and dry grassland environment. Although the data presented here and faunal composition of the fossil assemblage corroborate the open environment interpretation, the isotopic data and the recent findings of intertropical taxa, indicate that dry periods were intercalated with more humid phases. Millenial-scale climatic oscillations, in time scales of 1 to 7 thousand years, have been recorded in deep sea and ice cores, and were most prominent during glacial intervals (Siddall et al., 2005). The ESR ages obtained from fossil teeth indicate that most of the remains encompass the time interval corresponding to MIS 3 (between 60 and 24 ky BP), which was marked by several millennial-scale oscillations. The changes in the pattern of precipitation in scales of 2 thousand years are compatible with the high-frequency and high-amplitude climatic oscillations during the last glacial phase, which were probably a major factor behind the disappearance (pseudoextinction) of these large-bodied herbivores from southern Brazil.

6. Conclusions

- The δ^{13}C values presented here indicate that *Stegomastodon* was a browser to mixed feeder, with a high content of C3 plants in its diet, while *Toxodon* was a mixed feeder that fed mostly on C4 plants, probably grasses, and had a very specific dietary composition regarding the proportion o C3/C4 plants in Southern Brazil.
- The δ^{13}C values in *Stegomastodon* are similar to those found in modern *L. africana*, but the lower coefficient of variation found in δ^{13}C values of *Stegomastodon* indicate that it was mostly a C3 feeder, with lower proportion of C4 plants in its diet than *L. africana*.
- The distinct carbon values from both taxa suggest that an open grassland environment with patches of trees and shrubs occupied the coastal plain of Southern Brazil between the Late Middle to Late Pleistocene.
- The carbon content in fossils of *Stegomastodon* and *Toxodon* reinforces the existence of a latitudinal variation in their diet, with specimens from lower latitudes consuming more C4 plants than those from higher latitudes.
- In both taxa there is no correlation between the carbon and oxygen content, thus indicating that the δ^{18}O values mirror the oxygen composition of the ingested water, rather than the isotopic content of ingested plants.
- The δ^{18}O values obtained for *Toxodon* are more enriched than those found in living and fossil hippopotamuses and thus do not seem to support the similar semiaquatic habit that has been attributed to it.
- The very conservative diet preferences of *Toxodon*, indicated by the low variability in δ^{13}C values, suggest that this taxon may have been very sensitive to drastic changes in the composition of the local vegetation.
- If the relationship between δ^{18}O in precipitation and the amount of precipitation in mid- to low latitudes of South America is valid for the past, then the low variability in δ^{18}O values of *Stegomastodon* could indicate that these animals required a constant water supply, while *Toxodon* also could have inhabited dry/semiarid environments.

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GEOLOGICAL AND ENVIRONMENTAL EVOLUTION OF LAGOON SYSTEM III IN THE SOUTHERNMOST COASTAL PLAIN OF RIO GRANDE DO SUL STATE

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Here is presented a preliminary report of an ongoing research on the deposits of the Lagoon System III found in the Santa Vitória do Palmar county, in southernmost Rio Grande do Sul state. This contribution includes new paleoenvironmental and paleontological data that provide further information regarding the evolution of this unit. The southernmost portion of the Brazilian coast comprises the Coastal Plain of Rio Grande do Sul State (RSCP). This 620 km-long geomorphological unit had its morphology influenced by glacioeustatic oscillations during the Neogene and Quaternary. Between late Pleistocene and Holocene, sea-level transgressions originated four major barrier-lagoon depositional systems parallell to the coastline. The transgressive event of 123 ka AP formed the Barrier-Lagoon System III, which is well represented along the entire RSCP (Tomazelli & Dillenburg, 2007). In the southern sector of RSCP, the Lagoon System III, located between Barrier III and the older Barrier II, is well preserved, and the facies associated to this system are exposed along the banks of Chuí Creek (Fig. 1A). The creek flows in a NE-SW direction, parallel to the coastline, but near the town of Chuí its course changes to NW-SE before discharging into the Atlantic Ocean.

Chuí Creek was originally a shallow creek flowing through the plain between Pleistocene barriers II and III. During the late 1960s, it was further excavated for agriculture purposes and during the excavations the underlying sedimentary facies were exposed, revealing marine sediments and continental sediments containing fossils of Pleistocene mammals (Figure 1B). The first stratigraphic study on Chuí Creek was made by Soliani Jr. (1973), who correlated the marine deposits at the base of the stratigraphic sequence to the "Chuí Formation" of Delaney (1965), and the overlying fossiliferous layer to a new lithostratigraphic unit that he named "Santa Vitória Formation". During the 1980s the lithostratigraphic scheme of the RSCP was abandoned in favour of the concept of depositional systems, replacing the lithostratigraphic units by chronocorrelated stratigraphic units. Under this new scheme, both the marine and continental deposits are now correlated to the Lagoon System III.

Marine facies

Today the banks of Chuí Creek measure some 4,5 meters in height above the creek bed (Figure 1C). The lowermost 2 meters of the sequence is the marine facies correlated to the "Chuí Formation". The total thickness of this layer is still unknown, but manual drillings revealed that it is more than 4 meters. Ichnofossils *Ophiomorpha nodosa* are common throughout this facies (Figure 1D); the sediment is a fine yellow sand, exhibiting parallel and low-angle cross stratifications (Figure 2A). Recently, an accumulation of marine mollusks was identified at the base of the exposed portion of this facies, with abundant remains of sandy bottom dwellers such as *Amiantis purpurata, Pitar rostrata* and *Mactra isabelleana* (Lopes, 2010). It is noteworthy that above this accumulation *Ophiomorpha* galleries are found but no shells have been observed yet.

Fluvial facies

The transition between the marine facies and the overlying layer is gradual (Figure 2B). The latter is the fossiliferous unit that Soliani Jr. named "Santa Vitória Formation" and interpreted as deposited in a lagoon environment. However, the taphonomic features of the vertebrate fossils, mostly unidentified fragments but also including articulated remains, and the presence of dark sand lenses interpreted as oxbow lakes, indicate a meandering fluvial environment. These lenses are massive and measure between 20 and 30 centimeters in thickness and 3 to 7 meters in length (Figure 2C); the top and bottom exhibit iron oxide crusts. The lenses protrude into the marine facies below and may contain small fragments of vertebrate fossils. Adjacent to these lenses paleosols with abundant root traces can be observed (Figure 2D).

Until now, vertebrate fossils were found only on the lower portion of the fluvial facies, in a ~1m-thick level. ESR datings on fossil teeth found in this layer revealed ages between 42 and 33 thousand years (Lopes *et al*., 2010). No sedimentary structures have been observed in this facies. Above the fossiliferous layer only root traces have been recorded, but at some points along the banks a carbonate layer can be found, which was named "Caliche Cordão" by Delaney (1965) (Figure 2E). It measures some 40 cm in thickness, and although its distribution is not homogeneous, its longest continuous exposition is 461 meters in length. The carbonate forms irregular nodules and rhizocretions.

The sediment that constitutes the fluvial facies is composed mainly by fine sand, but there is an upwards increase in silt-sized particles. Although no vertebrate fossils have been recovered so far from the upper portions of this facies, some structures that suggest burrows made by micromammals were recently found (Figure 2F). The uppermost portion of the sequence is formed by a ~70 cm-thick layer of organic matter-rich fine clayey sand, which contains archaeological artifacts and vertebrate remains indicative of a Holocene wetland environment.

DISCUSSION

The sedimentary sequence exposed along the banks of Chuí Creek shows the transition between a shallow marine environment to a continental one. Although detailed regional stratigraphic data are not available yet, the present data suggest that the marine facies may be correlated to the Barrier System II, formed by the marine transgression estimated to have occurred around 325 ka AP, by correlation with the Marine Isotope Stage (MIS) 9 by Villwock & Tomazelli (1995), but it may also represent the transgression of 200 ka BP, correlated to MIS 7. One tooth of an extinct mammal found in the same level of the marine facies and dated on 226 ka BP (Lopes *et al*., 2010), suggests that the transgression may have occurred at 200 ka BP and reworked older continental deposits. Until datings for the sediments and large-scale, detailed stratigraphic surveys are available, the exact age of this depositional system is still debatable. Anyway, the stratigraphic sequence indicates that after the marine transgression that formed the Barrier II, sea-level retreated and continental sediments started to accumulate on top of the marine facies. During the interval before the marine transgression of 123 ka BP, that formed the Barrier System III seawards of Barrier II, all drainage presumably would flow eastwards to the ocean. Seismic surveys on the continental shelf have shown the existence of several fluvial paleochannels with an E-W orientation that were correlated to fluvial systems that existed during sea-level lowstands. Thus, during the interval between 325 or 200 ka AP and 123 ka BP, Chuí Creek on its present NE-SW orientation wasn’t established yet. After the 123 ka BP transgression, drainage coming from the surrounding higher areas of Barriers II and III would have flown to Lagoon System III, increasing the sedimentation. Although Soliani Jr. (1973) and other authors considered the sediments above the marine facies were deposited in lagoon environment, no evidence of such lagoon have been found yet. The dark, organic matter-rich sand lenses contain palynomorphs that suggest the existence of shallow lentic environments, such as the margins of a lake or lagoon or oxbow lakes. Because this dark sand layer is not continuous along the banks, the correlation with oxbow lakes, formed by abandoned channels in a meandering fluvial system, seems more plausible. The presence of mostly fragmented remains of fossil mammals, with clear indication of post-fossilization reworking, reinforces the existence of a fluvial system (Lopes, 2009).

It’s not clear yet whether this fluvial system was continuously active after the formation of Barrier-Lagoon System III. The only available ages obtained so far from three fossil mammal teeth revealed ages of 42, 38 and 33 ka BP, which suggest an active fluvial system around 30 ka BP. However, additional ages should probably reveal the existence of older fossils and fluvial sediments. The ages between 42 and 33 thousand years are correlated to a more humid climatic phase that has been recorded in other parts of central-southern Brazil (Ledru, 1993) and Argentina (Prado & Alberdi, 1999), coincident with the milder climate of MIS 3. The fossil record of the aquatic rodent *Myocastor coypus* on this layer indicates the presence of a stable water body (Pereira *et al*., 2009). The vertebrate fossils are concentrated on the ~1 meter-thick basal portion of the fluvial facies, and the apparent absence of such remains on the upper portion may be related to climatic and environmental changes, as recorded in the Luján Formation of the Pampean Region of Argentina (Tonni *et al*., 1999). The deposition of the caliche layer and the upwards increase in silt-sized sediments seem to be result of an increasingly drier climate and deposition of finer, probably loessic sediment, correlated to the climate deterioration that led to the last glacial maximum (LGM) during MIS 2. During the LGM the dry (Patagonian) climatic belt was displaced some 750 km NE of its present position, as indicated by loessic deposits in Uruguay (Iriondo, 1999) and probably southern Rio Grande do Sul. The presence in Chuí Creek of fossil mammals that indicate drier environments such as *Catagonus stenocephalus*, *Dolichotis* sp. and *Microcavia* sp. (Pereira *et al*., 2009) also reinforces a drier climatic phase. The Pleistocene-Holocene transition in the study area is represented by the dark clayey sand layer on top of the sequence. The increase in organic matter, plus the vertebrate remains and archaeological evidence found in this layer indicate a more humid environment that allowed the development of wetlands in the area. The excavation of Chuí Creek, in the 1960s, changed this environmental condition, favoring the drainage of the wetlands for agriculture purposes

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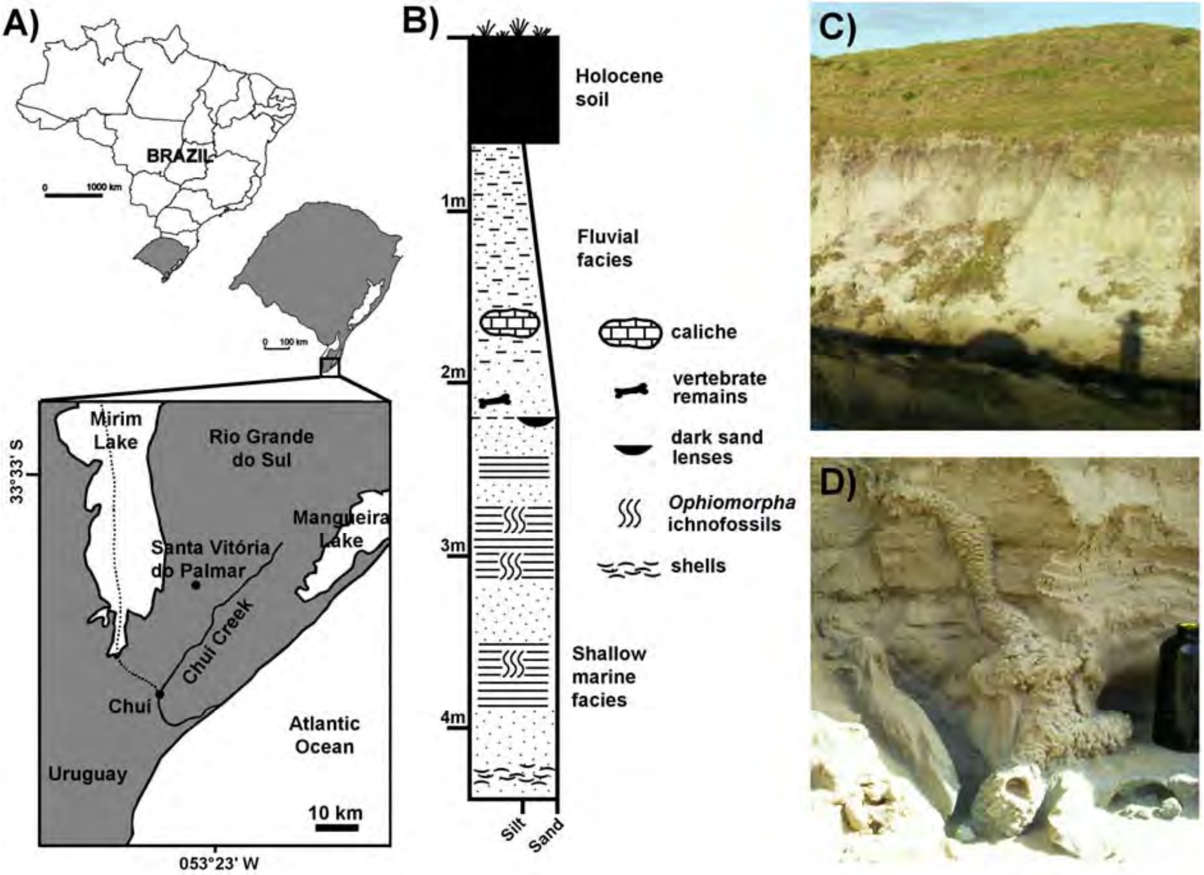

Figure 1 – A) Location of Chuí Creek; B) Stratigraphic sequence exposed along the banks; C) View of the banks; D) gallery of *Ophiomorpha nodosa*.

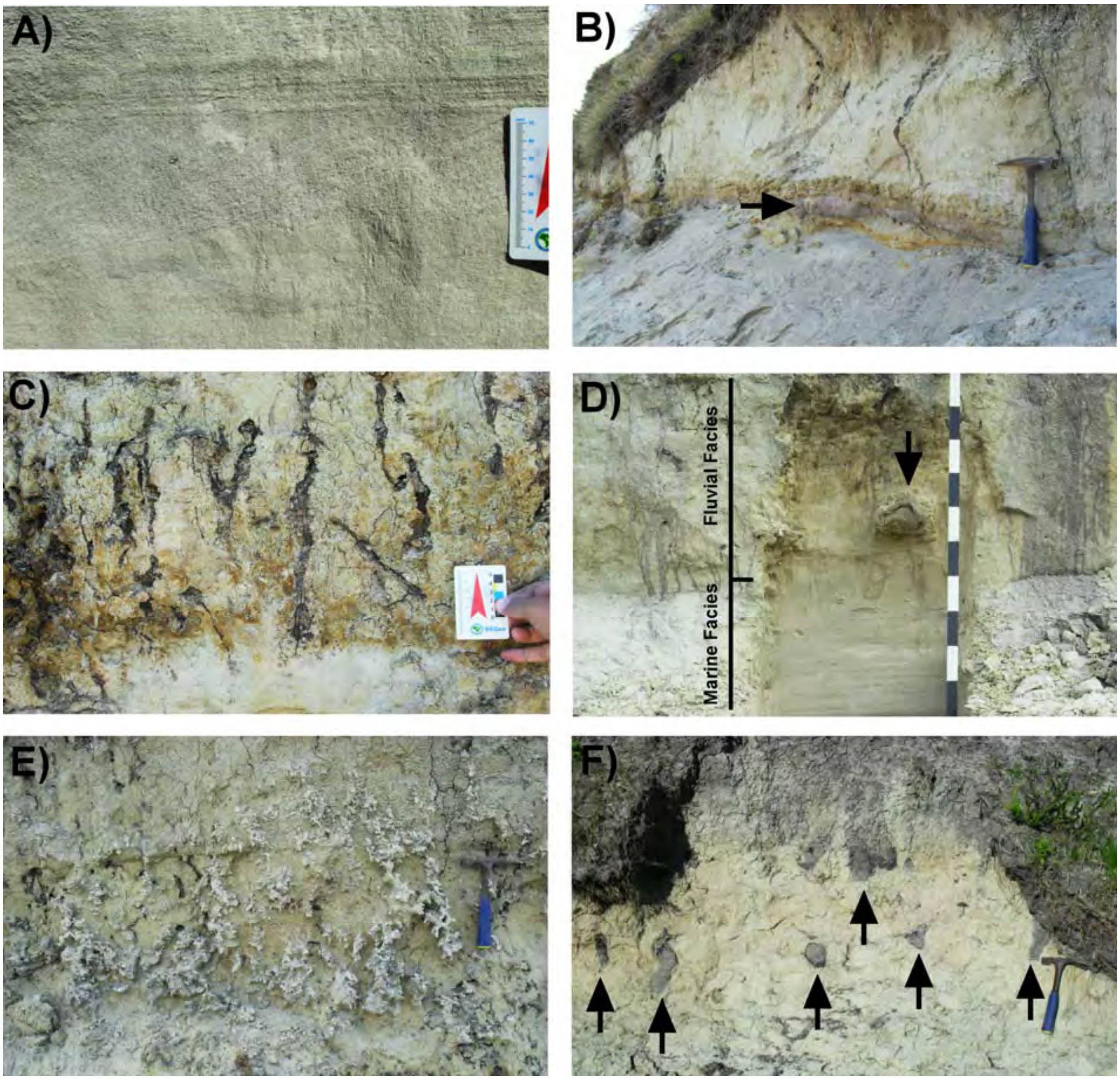

Figure 2 - A) Parallell and cross stratifications in the marine facies (scale bar = 7 cm); B) Dark sand lens (indicated by arrow); C) Detail of the paleosol on top of the marine facies (scale bar = 7 cm); D) Transition between the marine and fluvial facies, with a mammal fossil indicated by arrow (each division of the scale measures 10 cm); E) Detail of the caliche layer; F) Possible micromammal burrows (indicated by arrows).

ANEXOS

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CHINCHILLIDAE AND DOLICHOTINAE RODENTS (RODENTIA: HYSTRICOGNATHI: CAVIOMORPHA) FROM THE LATE PLEISTOCENE OF SOUTHERN BRAZIL

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ABSTRACT – New records of rodents from the late Pleistocene Chuí Creek, Rio Grande do Sul State, southern Brazil, are here described. A partial dentary with fragmented cheek teeth is identified as Chinchillidae, *Lagostomus* Brookes cf. *L. maximus* (Desmarest). Other two specimens are identified as cheek teeth of Dolichotinae indet. (Caviidae). Pleistocene fossils of *Lagostomus* were previously reported for Argentina and Uruguay. The material of *Lagostomus* from Chuí Creek represents the first confidently record of this taxon Brazil. Pleistocene fossil remains of Dolichotinae have been found in Argentina, Uruguay and other areas of southern Brazil, though the Brazilian find lack precise stratigraphic information. These new records widen the paleobiogeographic distribution of *Lagostomus* and confirm the presence of Dolichotinae during the late Pleistocene of southern Brazil.

Key words: *Lagostomus*, Lagostominae, Dolichotinae, Chuí Creek, Rio Grande do Sul, Quaternary.

RESUMO – Este trabalho reporta novos materiais de roedores provenientes dos depósitos fossilíferos do arroio Chuí (Rio Grande do Sul, sul do Brasil). O material de Chinchillidae é identificado como *Lagostomus* Brookes cf. *L. maximus* (Desmarest) e é representado por um dentário esquerdo faltando sua região posterior, com o incisivo preservado e a série p4-m3 fragmentada. Os outros dois espécimes são identificados como molariformes de Dolichotinae indet. (Caviidae). Os fósseis de *Lagostomus* durante o Pleistoceno estavam restritos a Argentina e Uruguai. O material aqui reportado caracteriza o primeiro registro seguro deste táxon no Brasil. Fósseis de Dolichotinae têm sido encontrados em depósitos pleistocênicos da Argentina, Uruguai e sul do Brasil, porém este último provém de uma localidade sem contexto estratigráfico preciso. Desta forma, estes novos registros ampliam a distribuição paleobiogeográfica de *Lagostomus* e confirmam a presença de Dolichotinae durante o Pleistoceno final do sul do Brasil.

Palavras-chave: *Lagostomus*, Lagostominae, Dolichotinae, arroio Chuí, Rio Grande do Sul, Quaternário.

INTRODUCTION

Chinchillidae are South American hystricognath rodents that include the extant chinchillas (*Chinchilla* Bennett, 1829), mountain vizcachas (*Lagidium* Meyen, 1833) and pampas vizcachas (*Lagostomus* Brookes, 1828). The stratigraphic distribution of Chinchillidae extends from Eocene/early Oligocene to Recent (Vucetich *et al*., 1999, 2010; Flynn *et al*., 2003). Molecular studies confirmed that the extant Chinchillidae are a monophyletic group (Spotorno *et al*., 2004) and suggest a close relationship with Dinomyidae (Huchon & Douzery, 2001). Extant chinchillids have euhypsodont cheek teeth, composed of laminar and oblique prisms, labially (upper teeth) or lingually (lower teeth) united, with a very thin interlaminar cement layer, bullae well developed and locomotion partially saltatory (Wood, 1955; Bondesio *et al*., 1975). According to Pocock (1922), Chinchillidae includes two subfamilies, Chinchillinae and Lagostominae. Chinchillines have cheek teeth with two flexi/flexids and three lophs/ids, and the lagostomines have two lophs/ids, separated by only one flexus/flexid. Lagostomines are represented in the fossil record since the Oligocene (Vucetich *et al*., 1999, 2010). For the Pliocene and Pleistocene, two genera have been described: *Lagostomopsis* Kraglievich, 1926 from Montehermosan and Chapadmalalan ages, and *Lagostomus* from Barrancalobian to Recent (Vucetich & Verzi, 1995). However, according to Vucetich & Verzi (1995) the differences between these taxa are mainly of size. In the absence of more diagnostic characters, Vucetich & Verzi (1995) suggested that the only valid genus in the Pliocene/Pleistocene is *Lagostomus*. The same problem is present in the extinct species of *Lagostomus* because their diagnoses are also based on size (see Gervais & Ameghino, 1880), which is quite variable in the living *Lagostomus* (Llanos & Crespo, 1952). The current taxonomy of the family and extinct species of *Lagostomus* needs review (Vucetich & Verzi, 1995; Candela, 2005), as well as cladistic analyses, including fossil and extant taxa.

Caviidae are taxonomically diverse caviomorphs, often small and cursorial, with euhypsodont cheek teeth (Wood, 1955). The group originated in the middle/late Miocene (Vucetich *et al*., 1999) and achieved its greatest diversity during the late Pliocene (Quintana, 1997). According to Paula Couto (1979), the family includes an extinct subfamily, the Cardiomyinae (but see Pérez, 2010), and two extant subfamilies, the Caviinae and the Dolichotinae. Dolichotines share the following characters: the skull with the foramen magnum displaced ventrally, diastema longer than P4-M3 series, absent nasolacrimal foramen on the maxilla, and mesopterygoid fossa reaching the M2 (Paula Couto, 1979; Quintana, 1998; Ubilla & Rinderknecht, 2003). The Quaternary dolichotines are represented by a single genus, *Dolichotis* Desmarest, 1820 (including *Pediolagus*), with two species, *D. patagonum* Zimmermann, 1780 and *D. salinicola* (Burmeister, 1876).

Until now, the Pleistocene fossil record of caviomorph rodents in southern Brazil only included Caviidae, Hydrochoeridae and Echimyidae. For the continental shelf of Rio Grande do Sul State (RS), Rodrigues & Ferigolo (2004) described several teeth and a fragment of a dentary of *Myocastor coypus* (Molina, 1782), a P4 of Dolichotinae indet., and a dentary of Eumysopinae indet. For Chuí Creek, southernmost of RS, Ubilla *et al*. (2008) reported cranial fragments and postcranial elements of *Microcavia* Gervais & Ameghino, 1880. From Touro Passo Formation, remains of *H. hydrochaeris* (Linnaeus, 1766), Caviidae indet., and *Galea* Meyen, 1832 have been recognized (Kerber & Oliveira, 2008; Kerber & Ribeiro, 2011; Kerber *et al*., 2011) and for Quaraí River, Oliveira (1992) referred *H. hydrochaeris*.

This paper reports new remains assigned to a Chinchillidae and a Dolichotinae from Chuí Creek (upper Pleistocene), southern Brazil and discusses the late Pleistocene fossil record of both taxa as well as the paleobiogeographic implications of these findings.

MATERIAL AND METHODS

The specimens studied herein are stored in the paleovertebrate collection of Museu Coronel Tancredo Fernandes de Melo (MCTFM in Santa Vitória do Palmar, RS) and Laboratório de Geologia e Paleontologia da Universidade Federal do Rio Grande (LGP-V in Rio Grande, RS).

The material of Chinchillidae was compared to the extant chinchillids *Lagostomus maximus* (Desmarest, 1817), *Chinchilla* and *Lagidium* (from Argentina); and the Dolichotinae were compared with the caviids *Dolichotis patagonum*, *D. salinicola*, *Microcavia*, *Galea* (from Argentina) and *Kerodon* F. Cuvier, 1825 (from northeast Brazil) (Appendix 1). Traditionally, *Kerodon* was considered a Caviinae. However, in recent papers, using molecular and paleontological evidence, it has been considered more closely related to Hydrochoeridae (Rowe & Honeycutt, 2002; Pérez, 2010). It was included in this comparison because it shares several dental features with Caviidae.

The mandibular nomenclature follows Woods & Howland (1979) and Pérez (2010), and the dental nomenclature of Caviidae follows Quintana (1996). The measurements were taken with a digital caliper accurate to 0.01 mm and stereomicroscope, and are expressed in millimeters.

Institutional abbreviations. LGP-V, Laboratório de Geologia e Paleontologia, Universidade Federal do Rio Grande (FURG), Rio Grande, RS, Brazil; **MCN-M**, Coleção de Mamíferos do Museu de Ciências Naturais da Fundação Zoobotânica do Rio Grande do Sul, Porto Alegre, RS, Brazil; **MCPU-M**, Coleção de Mastozoologia do Museu de Ciências da Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre, RS, Brazil; **MCTFM**, Museu Coronel Tancredo Fernandes de Melo, Santa Vitória do Palmar, RS, Brazil; **MDJ-Mr**, Coleção de Mamíferos recentes do Laboratório de Paleontologia do Museu Dom José, Sobral, Ceará State, Brazil; **MLP**, Colección de Mastozoología, Museo de La Plata, La Plata, Buenos Aires Province, Argentina.

LOCATION AND GEOLOGICAL SETTING

Chuí Creek (53º23 S, 33º22 W) is located in southernmost Brazil, and is part of the Coastal Plain of Rio Grande do Sul State (PCRS) (Figure 1). Late Pleistocene mammal remains of

Lujanian age [*Equus* (*A.*) *neogaeus* Biozone, *sensu* Cione & Tonni, 1999] are found in Chuí Creek (Oliveira *et al*., 2005), collected from a ~1.5 meter-thick muddy sandstone bed (Lopes *et al*., 2001, 2005). The fossils are found articulated or isolated, mostly fragmented, but sometimes complete and well-preserved specimens, probably deposited and reworked in a meandering fluvial system. According to Buchmann *et al*. (2009) the presence of a fossiliferous bed, lenses of organic matter-rich sediments interpreted as abandoned meanders (oxbow lakes), a high proportion of fossils broken after burial, and occurrence of fossils at a considerable distance from the present course of the creek, suggest that the fossils were accumulated and reworked in a wide flood plain. Lopes *et al*. (2010) dated teeth of megamammals from the fossiliferous level using Electron Spin Resonance, showing ages between 42 and 33 Ka BP. The fossiliferous bed contains fossils of large-bodied mammals, mostly herbivores, including xenarthrans and ungulates, while carnivores are very scarce in comparison (Oliveira, 1992; Oliveira *et al*., 2005; Marcon, 2008; Oliveira & Pereira, 2009; Scherer *et al*., 2009; Lopes & Pereira, 2010). Remains of medium- and small-sized mammals are scarcely represented.

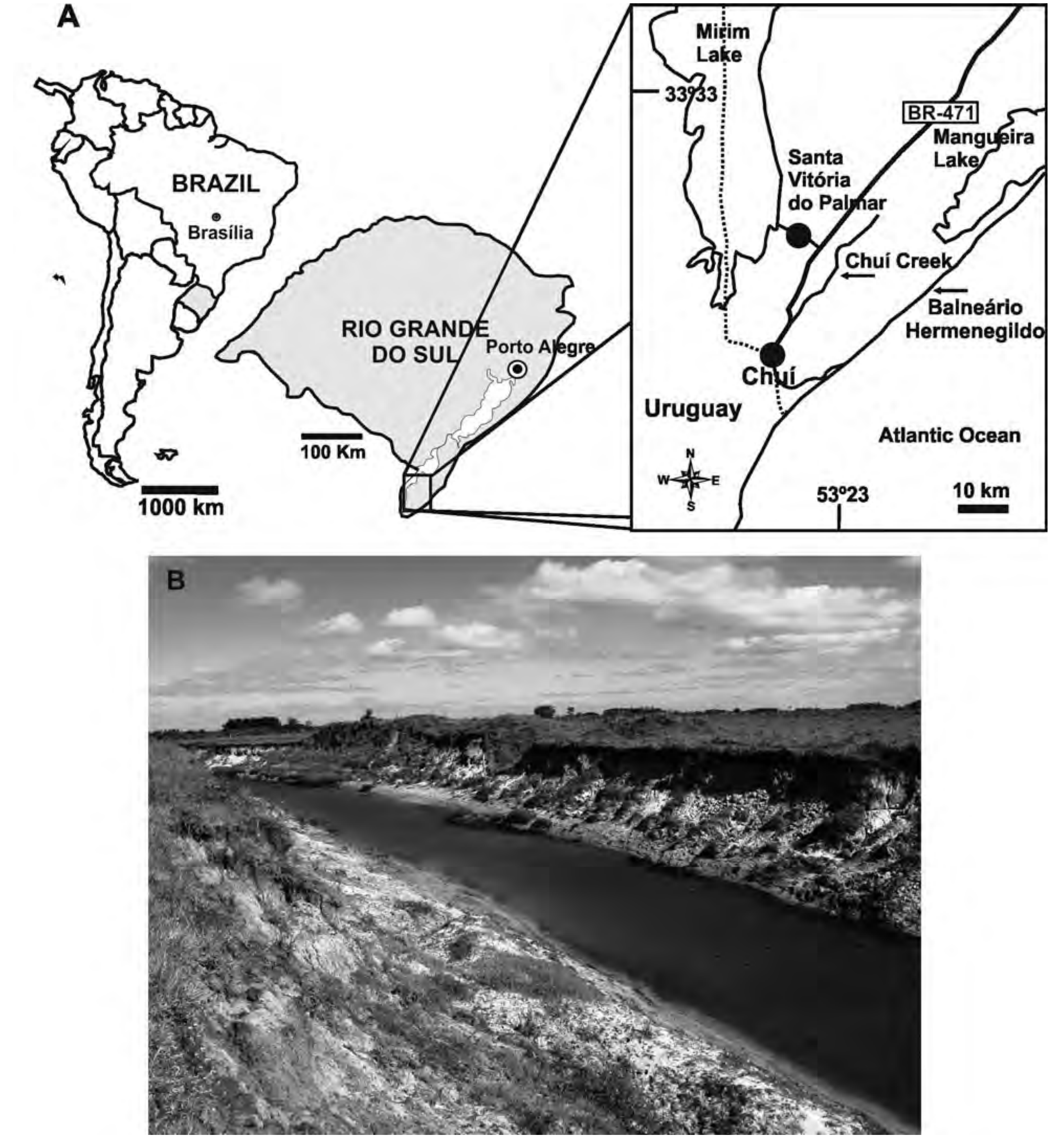

Figure 1. A, Geographical location of Chuí Creek; **B**, Panoramic view of Chuí Creek.

SYSTEMATIC PALEONTOLOGY

RODENTIA Bowdich, 1821
HYSTRICOGNATHI Tullberg, 1899
CAVIOMORPHA Wood & Patterson (*in* Wood, 1955)
CHINCHILLOIDEA Kraglievich, 1940
CHINCHILLIDAE Bennett, 1833
LAGOSTOMINAE Wiegman, 1832
Lagostomus Brookes, 1828

Lagostomus cf. *L. maximus* (Desmarest, 1817)
(Figure 2)

Material. MCTFM-PV 0769, left dentary lacking the posterior portion, with very fragmented cheek teeth.

Geographical and stratigraphic provenance. Chuí Creek, in the upper portion of the muddy sandstone bed. Santa Vitória do Palmar, Rio Grande do Sul State, Brazil.

Description and comparison. The dorsal area of the diastema is thin and forms a tenuous crest that extends from the mesial face of p4 alveolus up to the symphysis. The alveolus of the incisor forms a well-developed prominence on the medial surface of the dentary, which extends up to the level of m3, as in *Lagostomus maximus* and different from *Chinchilla* and *Lagidium*, in which it extends up to the m1/m2 level. The coronoid process is located at the level of the distal area of the m3 alveolus, being posteriorly oriented. This process is thin and is different from *Chinchilla* and *Lagidium*, in which it is located posteriorly to the m3 and more vertical. The lunar notch is deeper than in *Chinchilla* and *Lagidium*. The mandibular foramen is located on the dorsal surface of the dentary, posteromedially to the m3 alveolus. The notch for the insertion of the tendon of the *masseter medialis pars infraorbitalis* muscle is located below m1 and m2, as in *L. maximus* and *Lagidium*, while in *Chinchilla* the notch is below m1. The incisor is slightly longitudinally striated on the labial face. The cheek teeth are very fragmented, but it can be seen that they are bilophodont and obliquely oriented, features that characterize Lagostominae. In size, MCTFM-PV 0769 is smaller than the adult males of *L. maximus*, but more similar to the young males and adult females analyzed (Table 1).

CAVIOIDEA Fischer de Waldheim, 1817
CAVIIDAE Fischer de Waldheim, 1817
DOLICHOTINAE Pocock, 1922
Dolichotinae indet.
(Figure 3)

Material. Isolated left m1 or m2, lacking the lingual end of Pr. II (MCTFM-PV 0736) plus another poorly preserved tooth (LGP-V 0001).

Geographic and stratigraphic provenance. Chuí Creek, MCTFM-PV 0736 was recovered from sediments dredged from the bottom of the creek, while LGP-V 0001 was found in the muddy sandstone bed. Santa Vitória do Palmar, Rio Grande do Sul State, Brazil.

Description and comparison. The description is based on MCTFM-PV 0736, which is the best preserved, but the same characters are also observed in LGP-V 0001. MCTFM-PV 0736 is euhypsodont and biprismatic (Figure 3A). It has a linguolabial curvature (Figure 3B) and is slightly mesiodistally curved, with the apex more distal than the occlusal surface (Figures 3C-D), characterizing a lower tooth.

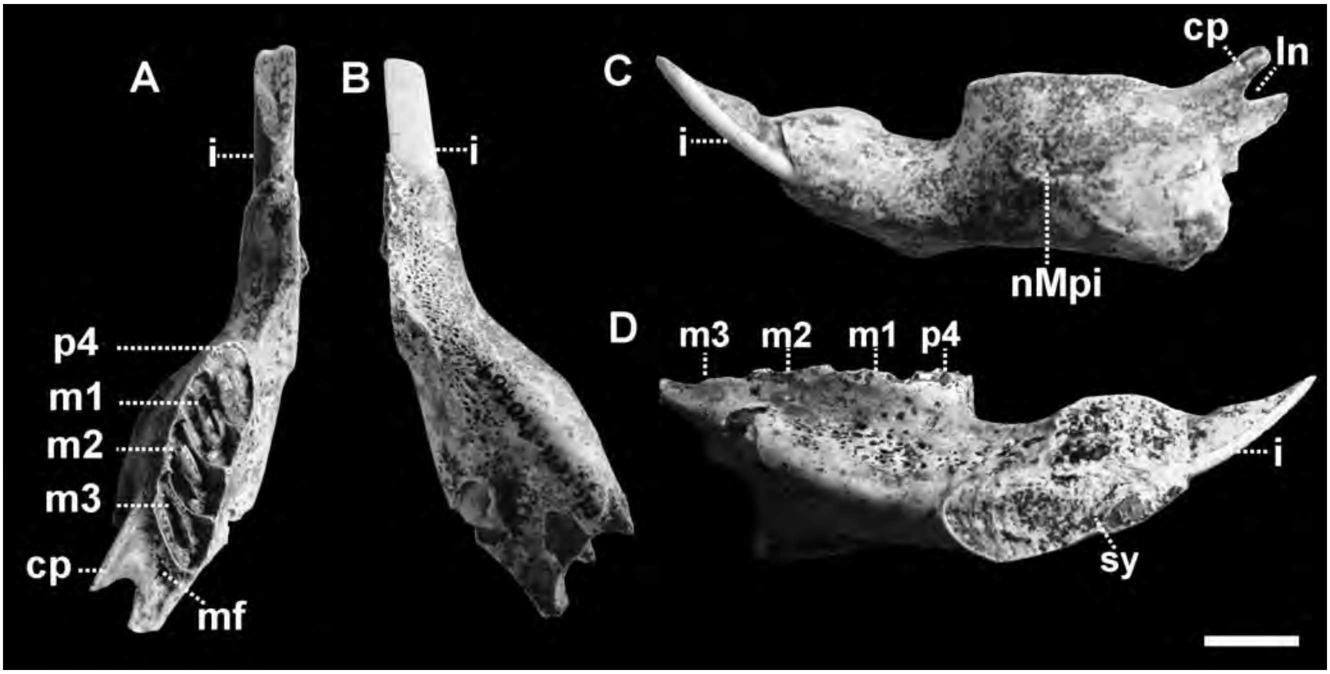

Figure 2. *Lagostomus* cf. *L. maximus* (MCTFM-PV 0769) from Chuí Creek, in occlusal (**A**), ventral (**B**), lateral (**C**) and medial (**D**) views. **Abbreviations: cp**, coronoid process; **ln**, lunar notch; **mf**, mandibular foramen; **nMpi**, notch for insertion of the tendon of the *masseter medialis pars infraorbitalis* muscle; **i**, incisor; **p4**, fourth premolar; **m1**, first molar; **m2**, second molar; **m3**, third molar; **sy**, symphysis. Scale bar = 10 mm.

Figure 3. Left m1 or m2 of Dolichotinae (MCTFM-PV 0736) from Chuí Creek, in occlusal (**A**), distal (**B**), lingual (**C**) and labial (**D**) views. Scale bar: A = 4 mm; B, C, D = 6 mm.

Table 1. Measurements (mm) of the specimen MCTFM-PV 0769 and comparative specimens (young and adults) of *Lagostomus maximus*. Since there is sexual dimorphism in *L. maximus* (Llanos & Crespo, 1952), we separated the males (n= 7) from females (n= 10), and performed a statistic analysis with males, females and the specimens without determined sex (n= 22) to estimate variation within the species. Measurements: 1, diastema length; 2, height of the dentary body at the level of p4; 3, length of p4-m3 alveolar series; 4, mesiodistal length (MDL) of p4 alveolus; 5, linguolabial width (LLW) of p4 alveolus; 6, MDL of m1 alveolus; 7, LLW of m1 alveolus; 8, MDL of m2 alveolus; 9, LLW of m2 alveolus; 10, MDL of m3 alveolus; 11, LLW of m3 alveolus; 12, width of the incisor. **Abbreviations: M**, measurements; **n**, specimens; **SD**, standard deviation; (**m**) males; (**f**) females; ***** males, females plus the specimens without sex determined.

	MCTFM-PV 0769	*L. maximus* (m)				*L. maximus* (f)				*L. maximus**			
M		n	Mean	Min/Max	SD	n	Mean	Min/Max	SD	n	Mean	Min/Max	SD
1	19.97	7	24.22	18.96/29.84	4.14	9	20.15	17.87/23.15	1.80	35	22.61	17.65/29.84	3.90
2	16.16	7	19.93	16.17/23.38	2.88	9	16.46	14.22/18.81	1.51	37	18.41	13.67/25.05	3.23
3	23.82	7	25.65	20.7/30.33	3.57	9	23.49	19.84/25.82	2.0	37	24.62	19.34/30.45	3.23
4	4.36	7	4.46	3.4/6.0	0.93	9	4.29	3.33/5.16	0.61	36	4.49	3.33/6.01	0.70
5	8.11	7	7.87	6.56/9.74	1.03	9	6.98	5.6/8.39	0.94	36	7.50	5.33/11.11	1.28
6	4.51	7	4.92	3.92/5.67	0.70	9	4.64	3.98/5.73	0.53	36	4.83	3.17/6.1	4.83
7	8.23	7	8.12	4.36/10.08	1.90	9	7.58	5.78/9.01	0.94	36	8.08	4.36/10.88	1.42
8	4.78	7	4.88	3.83/5.96	0.72	9	4.93	4.16/7.68	1.09	36	4.94	3.72/7.68	0.84
9	7.47	7	8.62	6.32/9.96	1.29	9	7.59	6.74/8.35	0.59	36	8.23	5.91/10.85	1.34
10	4.31	7	5.31	4.04/9.8	2.02	9	4.64	4.0/5.37	0.44	36	4.99	3.78/9.8	1.11
11	8.01	7	8.64	6.44/10.29	1.42	9	7.62	5.54/8.49	1.16	36	8.29	5.54/13.5	1.65
12	4.61	6	5.03	3.59/6.33	1.08	9	4.27	3.31/4.79	0.53	32	4.57	3.23/6.33	0.93

The hypoflexid is well developed, transversally oriented, and its lingual end largely surpasses the middle of the tooth. Opposite to the hypoflexid, there is a shallow furrow located between both prisms (Figure 3A). The prisms are transversally oriented, with similar size and shape, and are united by a thinner and shorter isthmus (Figure 3A) than those of the *Galea*, *Microcavia* and *Kerodon* (Figures 4A-C). The lingual area of the prisms is more convex than in *Galea*, *Microcavia* and *Kerodon*. The material is morphologically very similar to *D. salinicola* and *D. patagonum* (Figures 4D-E), but smaller than the adult specimens of *D. patagonum* (Table 2).

Dimensions (mm). Mesiodistal length, 4.28; linguolabial width, 3.5; height, 14.4.

Table 2. Measurements (mm) of *Dolichotis salinicola* and *D. patagonum*. **Abbreviations: MDL**, mesiodistal length; **LLW**, linguolabial width.

	m1		m2	
	MDL	LLW	MDL	LLW
D. salinicola				
MLP 673	4.10	3.61	4.41	3.60
MLP 672	4.76	3.99	4.56	3.57
D. patagonum				
MLP 371	-----	-----	-----	-----
MLP 8-XI-95-5	5.19	4.60	5.49	4.64
MLP 488	6.25	5.56	6.50	5.50
MLP 247	------	------	-----	-----
MLP 371	4.29	3.26	3.95	3.27
MLP 5-II-49-2	3.50	2.84	3.69	2.69
MLP 1418	5.63	5.97	5.54	4.84

DISCUSSION AND CONCLUSIONS

The specimen MCTFM-PV 0769 is assigned to the genus *Lagostomus* based on the tooth structure with two oblique laminae, coronoid process located at the level of the distal area of the m3 alveolus and posteriorly oriented and striated incisor extending up to the m3 level. The material does not differ from *L. maximus*, but given its fragmentary status, it is assigned to *Lagostomus* cf. *L. maximus*.

The specimens MCTFM-PV 0736 and LGP-V 0001 are assigned to Dolichotinae based on the characteristic tooth structure of two chordiform lobes with only one poorly-developed external furrow opposite to the hypoflexid (Kraglievich, 1930). These characteristics are similar to *Dolichotis* (Figures 4D-E); however the material is scarce and there are no characters that allow it to be confidently assigned to a genus or species.

Today, *Lagostomus maximus* inhabits plains of southern Bolivia, western Paraguay and central Argentina (Figure 5A) (Llanos & Crespo, 1952; Jackson *et al*., 1996 and references therein). Extant Dolichotinae are also represented in these regions, but reaching higher latitudes than *Lagostomus* (Cabrera, 1961; Eisenberg & Redford, 1989; Campos *et al*., 2001 and references therein) (Figure 5B).

Previous confirmed Pleistocene records of *Lagostomus* were from Argentina and Uruguay (Figure 5A). The Danish naturalist Peter W. Lund (1841) mentioned a Lagostominae (*Lagostomus brasiliensis*) from the karst of Lagoa Santa (Minas Gerais State, Brazil), based on a fragmented dentary and one euhypsodont and bilaminar tooth (Lund, 1841:pl. XXV, figs. 1-3; pl. XXVI, figs 1-4). However, in the review of Lagoa Santa rodents, Winge (1888) did not recognize this taxon (Paula Couto, 1950: footnotes 36 and 318). In fact, the drawings by Lund (1841) are not clear enough to identify this material. For example, the tooth is about 50% narrower than in *Lagostomus maximus*. In addition, the occlusal design shows completely independent laminae separated by a thick layer of cement (Lund, 1841:pl. XXV, fig. 2a), even thicker than in Miocene lagostomines.

The confirmation of the presence of *Lagostomus* in the Quaternary from the Intertropical region of Brazil (*sensu* Cartelle, 1999) depends on the discovery of new remains. According to Cione *et al*. (1999), during the Quaternary of Argentina, *Lagostomus* first occurs in the Ensenadan. In Argentina, *Lagostomus* sp. is recorded for late Pleistocene in Buenos Aires Province at Punta Hermengo (Tonni & Fidalgo, 1982) and Dolores locality (Chimento, 2007), and also in Córdoba Province (Cruz *et al*., 2009). *L. maximus* is a guide fossil for the Platan age (Holocene) (Cione & Tonni, 1999), though the species also occurs in the late Pleistocene at Paso Otero (Prado *et al*., 1987) and Punta Hermengo, both in Buenos Aires Province (Tonni & Fidalgo, 1982), and at Córdoba Province (Sarrat, 2009); and late Pleistocene/Holocene at Arroyo Seco 2 (Gómez *et al*., 1999) and Cueva Tixi, both in Buenos Aires Province (Tonni *et al*., 1988). In Uruguay, *Lagostomus* sp. was reported for the late Pleistocene at El Caño locality, and Libertad and Dolores formations (Ubilla & Perea, 1999; Ubilla *et al*., 2009).

The Quaternary fossil record of Dolichotinae is very scarce. The only genus recognized is *Dolichotis* (Figure 5B),

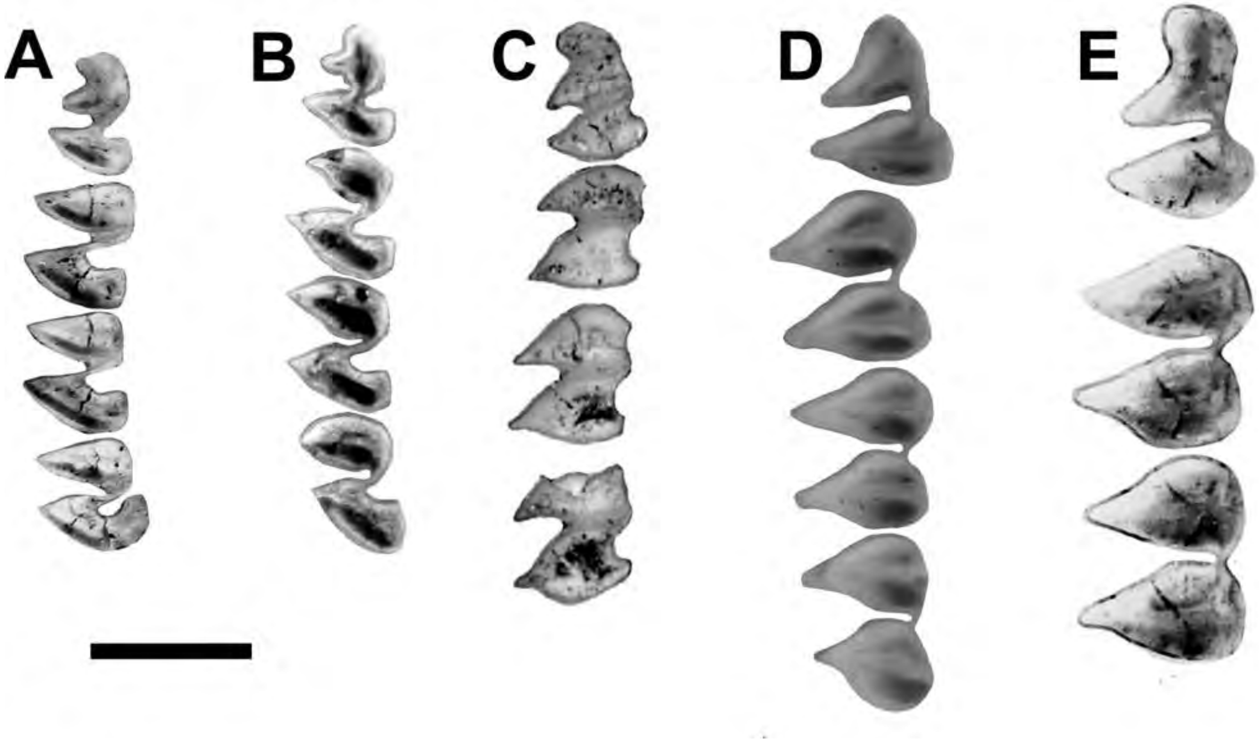

Figure 4. Lower left cheek teeth of Caviidae used for comparison with MCTFM-PV 0736 and LGP-V 0001. **A**, *Galea musteloides*, MLP 738 (4); **B**, *Microcavia australis*, MLP 683 (2); **C**, *Kerodon rupestris*, MDJ/Mr 002; **D**, *Dolichotis salinicola*, MLP 673; **E**, *Dolichotis patagonum*, MLP 8-XI-95.5 (p4-m2 series). Scale bar = 5 mm.

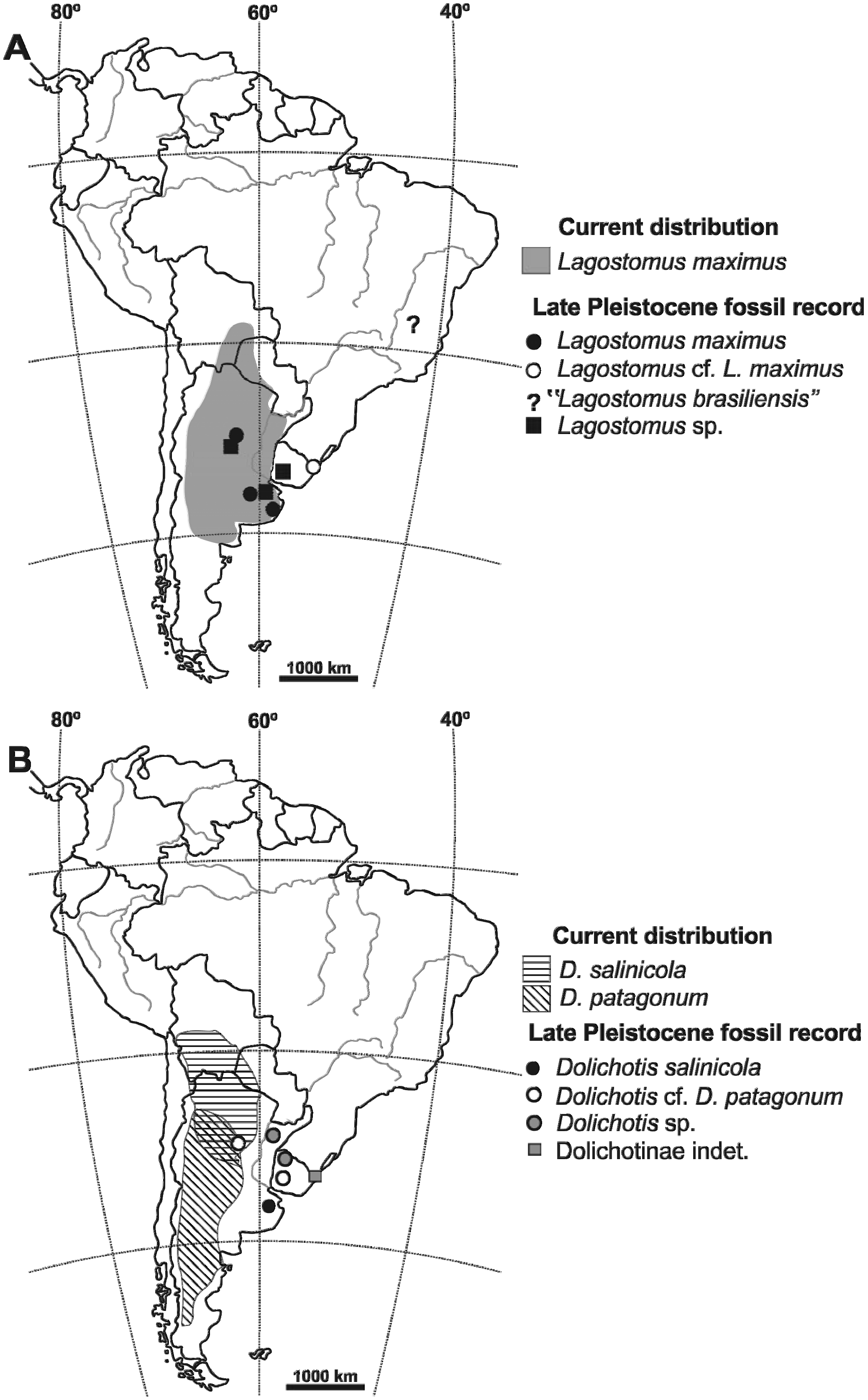

Figure 5. A, Current distribution of *Lagostomus* (Llanos & Crespo, 1952; Eisenberg & Redford, 1989; Jackson *et al*., 1996) and its late Pleistocene fossil record. Fossil record based on: Tonni & Fidalgo (1982), Prado *et al*. (1987), Tonni *et al*. (1988), Gómez *et al*. (1999), Ubilla & Perea (1999), Sarrat (2009) and Ubilla *et al*. (2009). **B**, Distribution of extant Dolichotinae (Cabrera, 1961; Eisenberg & Redford, 1989; Campos *et al*., 2001) and their late Pleistocene fossil record. Fossil record based on: Tonni (1981), Scillato-Yané *et al*. (1998), Ubilla *et al*. (2004), Sarrat (2009) and Ubilla *et al*. (2009).

which is known from the late Pliocene at least (Vucetich & Verzi, 1995; Verzi & Quintana, 2005). In the late Pleistocene, *Dolichotis* sp. was reported for Arroyo Toropí, Corrientes Province, Argentina (Scillato-Yané *et al*., 1998); and the Sopas Formation, Uruguay (Ubilla *et al*., 2004). *Dolichotis* cf. *D. patagonum* was mentioned for the late Pleistocene at Jesús María, Córdoba Province, Argentina (Sarrat, 2009) and Dolores Formation, Uruguay (Ubilla *et al*., 2009). *D. salinicola* was reported for the late Pleistocene of Buenos Aires Province (Tonni, 1981). A P4 of Dolichotinae indet. was reported for the continental shelf of southern Brazil (Rodrigues & Ferigolo, 2004), but unfortunately these submarine deposits have no stratigraphic context, and the associated fossils encompass ages from Ensenadan to Lujanian (Lopes *et al*., 2010). Thus, *Lagostomus* cf. *L. maximus* described here is the first positive record of a Chinchillidae from Brazil, and Dolichotinae confirms the presence of this subfamily in the late Pleistocene of southern Brazil.

Lagostomus maximus usually lives in open areas, with grasslands or shrubs, often characterized by little rain (Eisenberg & Redford, 1989). They are colonial diggers that live in colonial burrows systems, the “vizcacheras”, which are occupied by many generations (Llanos & Crespo, 1952; Villarreal *et al*., 2001). According to Villarreal *et al.* (2001), the vizcachas are found together with other mammals that indicate dry environments, such as the xenarthrans *Chaetophractus villosus* (Desmarest, 1804) and *Zaedyus pichiy* (Desmarest, 1804). Although predominantly associated with dry environments, *Lagostomus* seems to be more tolerant than *Chinchilla* and *Lagidium*, being found in arid to subtropical environments, with rainfall ranging from <300 mm in west central region of Argentina to > 1000 mm in the north the country (Jackson *et al*., 1996). The dolichotines are cursorial rodents and restricted to arid and semi-arid environments (Einsenberg & Redford, 1989; Campos *et al*., 2001).

Diverse taxa indicative of open areas and environments drier than today’s have been reported for the late Pleistocene of southern Brazil, such as camelids, the tayassuid *Catagonus* and the rodent *Microcavia* (Scherer *et al*., 2007; Ubilla *et al*., 2008; Gasparini *et al*., 2009). However, the presence of *Myocastor* in Chuí Creek suggests the presence of permanent water bodies. These discrepancies perhaps can be explained by the presence of mosaic environments (Bombin, 1975; 1976). The palynological data available for the late Pleistocene of Rio Grande do Sul State suggest a predominance of open areas and grasslands (Bauermann *et al*., 2009 and references therein). Based on the ecology of the living taxa, the material reported here is consistent with this pattern. The presence of *Lagostomus* and Dolichotinae in southern Brazil, together with *Microcavia* which has a similar distribution, is probably related to the latitudinal displacements of the environmental and climatic belts during the late Pleistocene.

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Appendix 1. Comparative specimens.

Caviidae: *Dolichotis patagonum*: MLP 8-XI-9-5, MLP 488, MLP 247, MLP 371 (Juvenile), MLP 5-II-49-2 (Juvenile), MLP 1418; *D. salinicola*: MLP 672 – 673; *Kerodon rupestris*: MDJ/Mr 002; *Microcavia australis*: MLP 683 (1-10), MLP 684 (1-23). *Galea musteloides*: MLP 738 (2, 4, 6, 7). Chinchillidae: *Chinchilla laniger*: MCN-M 2805, MLP 1767; *Lagostomus maximus*: MCPU-M 013, MLP 2-VI-60-7, MLP 5-II-49-4, MLP 359, MLP 5-IX-97-01, MLP 693, MLP 1597, MLP 1598, MLP 1599, MLP 1601, MLP 1602, MLP 1617, MLP 1636, MLP 1637, MLP 1639, MLP 1642, MLP 1649, MLP 1650, MLP 1656, MLP 1657, MLP 1659, MLP 1728, MLP 1729, MLP 1773, MLP 1774, MLP 1781, MLP 26-V-99-5, MLP 30-V-97-1, MLP 30-XII-02-3, MLP 19-V-98-1, MLP 1654, MLP 19-IX-47-3, MLP 19-V-98-2, MLP 19-V-98-3, MLP 19-IX-47-4, MLP 25-X-95-2, MLP 26-V-99-6; *Lagidium viscacia*: MLP 1429, MLP 1432, MLP 20-V-96-1; *Lagidium* sp.: MLP 22-IV-47-4, MLP 343, MLP 377.

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NEW REMAINS OF LATE PLEISTOCENE MAMMALS FROM THE CHUÍ CREEK, SOUTHERN BRAZIL

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ABSTRACT – The Chuí Creek, located in the southernmost Brazil, is a fossiliferous outcrop known since the late 1960s, which bears important records of late Pleistocene mammals, other vertebrates and invertebrate fossils. The presence of some taxa (*e.g*. *Hydrochoerus hydrochaeris* Linnaeus, *Tapirus terrestris* Linnaeus, *Ozotoceros bezoarticus* Linneaus), although mentioned on the literature, is still to be confirmed. Specimens from Chuí Creek belonging to several collections are reexamined and new excavations and geological surveys in the area are being conducted. The new records include isolated teeth of cf. Ursidae and Rodentia (*Myocastor* cf. *M. coypus* Molina); a complete and articulated skull and jaw of a tayassuid, *Catagonus* Ameghino, as well as a left dentary of a juvenile ground sloth, *Eremotherium* cf. *E. laurillardi* Lund. The ongoing systematic revision led to the confirmation of the presence of the glyptodont *Doedicurus* Burmeister, represented by a portion of the carapace; the cervid genera *Antifer* Ameghino and *Morenelaphus* Carette; and the equids *Equus* Linnaeus and *Hippidion* Owen, represented by cranial and dental remains. These findings expand the knowledge on the diversity of the extinct fauna found in the Chuí Creek, and have biogeographic, biostratigraphic and paleoenvironmental implications, which are herein discussed.

Key words: Quaternary, Pleistocene, megafauna, Rio Grande do Sul, Brazil.

RESUMO – O Arroio Chuí, situado no extremo sul do Brasil, é um afloramento fossilífero conhecido desde o final da década de 1960 e contém importantes registros de mamíferos, outros vertebrados e invertebrados fósseis do final do Pleistoceno. A presença de determinados táxons mencionados na literatura (*e.g. Hydrochoerus hydrochaeris* Linnaeus, *Tapirus terrestris* Linnaeus, *Ozotoceros bezoarticus* Linnaeus) ainda necessita confirmação. Fósseis provenientes do Arroio Chuí depositados em diferentes coleções vêm sendo revisados, e novas escavações e levantamentos geológicos vêm sendo desenvolvidos neste depósito. Os novos registros incluem dentes isolados de cf. Ursidae e Rodentia (*Myocastor* cf. *M. coypus* Molina); crânio e mandíbula completos e articulados de *Catagonus* Ameghino e um dentário esquerdo de *Eremotherium* cf. *E. laurillardi* Lund. A revisão sistemática levou à confirmação da presença do gliptodonte *Doedicurus* Burmeister, representado por parte de carapaça; de cervídeos dos gêneros *Antifer* Ameghino e *Morenelaphus* Carette, representados por galhadas incompletas; e dos equídeos *Equus* Linnaeus e *Hippidion* Owen, representados por restos cranianos e dentários. Estes achados ampliam o conhecimento sobre a diversidade da fauna extinta encontrada no Arroio Chuí, além de terem implicações biogeográficas, bioestratigráficas e paleoambientais, as quais são aqui discutidas.

Palavras-chave: Quaternário, Pleistoceno, megafauna, Rio Grande do Sul, Brasil.

INTRODUCTION

The fossil mammals from the Coastal Plain of Rio Grande do Sul State (CPRS), southern Brazil; have been known since the final of the Century XIX, after the first records by the German naturalist Hermann Von Ihering (Oliveira, 1996). In this geomorphologic unit, such remains are found in fossiliferous concentrations along the continental shelf (Lopes & Buchmann, 2010) and in the outcrops exposed along the banks of the Chuí Creek (Lopes *et al*., 2001, 2009). The fossils from the continental shelf are collected along the beach, where are thrown by storm waves, therefore do not have a precise stratigraphic context (Buchmann, 2002). Fossils of extinct mammals from the Chuí Creek were first reported in 1965, when the Departamento Nacional de Obras Contra as Secas (DNOCS) excavated and modified the course of this creek for irrigation purposes. During these excavations, the fossiliferous beds were exposed, and the paleontologists Carlos de Paula Couto and Fausto de Souza Cunha brought a large number of fossils to the Museu Nacional in Rio de Janeiro (Paula Couto & Souza Cunha, 1965; Henriques, 1992).

Recently, several studies have expanded the knowledge about the fossil content, geology and biostratigraphy (*e.g.* Oliveira, 1992; Lopes *et al*., 2001; Oliveira *et al*., 2005; Lopes *et al*., 2001, 2009; Kerber *et al*., 2011a; Lopes, *in press*). In a geologic survey of the CPRS (Delaney, 1965), the fossil mammals were considered of Tertiary age, associated to the Graxaim Formation. In the same year, however, Paula Couto & Souza Cunha (1965) correlated the fossils to the "Pampeano superior (Bonaerense)" of Argentina (late Pleistocene) (see also Soliani Jr., 1973). Posteriorly, Bombin (1975) analyzed the faunal similarity of the fossil mammals from Argentina, Uruguay and Rio Grande do Sul (RS), concluding that fossils from RS are from Lujanian Land-Mammal Age (*sensu* Pascual *et al*., 1966). Absolute ages obtained by Electron Spin Resonance (ESR) dating of fossil teeth from Chuí Creek showed results between 226 and 34 ka (Lopes *et al*., 2010), thus indicating that the fauna from the Chuí Creek encompasses a larger time span than was estimated before by Bombin (1975). The lithologies exposed along the banks and the taphonomic features suggest that the fossils were deposited and reworked in a meandering fluvial system (Lopes, 2009; Lopes *et al*., 2009).

Although studied for several years, the exact taxonomic composition of mammals from the creek is discussed. In a report about the geology and paleontology of CPRS, Paula Couto & Souza Cunha (1965) have listed several mammalian taxa, but did not discriminate between fossils collected along the beach and those collected in the creek. In his stratigraphic and paleontologic study on this creek, Soliani Jr. (1973) presented a systematic list based on verbal communication by Carlos de Paula Couto and in the description of ungulate fossils collected by Souza Cunha (1959) along the beach.

Most of the fossils deposited in the Museu Nacional (Rio de Janeiro) by Carlos de Paula Couto and Fausto de Souza Cunha were never formally described, except for *Lestodon armatus* Gervais, 1855 reported by Henriques (1992) and *Holmesina paulacoutoi* Cartelle & Bohórquez, 1985 described by Oliveira (1992) and Oliveira & Pereira (2009). Other papers (*e.g.* Oliveira *et al*., 2005; Oliveira & Pereira, 2009) have listed taxa from Chuí Creek such as *Equus neogaeus* Lund, 1840, *Hippidion principale* Lund, 1845, *Ozotocerus bezoarticus* Linnaeus, 1758, *Blastocerus dichotomus* Illiger, 1815, *Antifer* sp. Ameghino, 1889, *Smilodon populator* Lund, 1842, *Megatherium americanum* Cuvier, 1796, and *Hydrochoerus hydrochaeris* Linnaeus, 1766, whose occurrence have never been confirmed, neither formally described.

In this paper, new findings of Pleistocene mammals from Chuí Creek are described; the presence of some previously mentioned taxa are confirmed and biogeographic, biostratigraphic and paleoenvironmental implications are discussed. An updated list of known taxa is presented (Appendix 1).

MATERIAL AND METHODS

The specimens reported herein are deposited in the paleovertebrate collections of the Museu Coronel Tancredo Fernandes de Mello (Santa Vitória do Palmar, RS) and Universidade Federal do Rio Grande (FURG, Rio Grande, RS). All specimens were measured using precision calipers. **Institutional abbreviations**. **EPM**, Coleção Emidio Pinto Martino, Museu Coronel Tancredo Fernandes de Mello, Santa Vitória do Palmar, RS; **LGP**, Laboratório de Geologia e Paleontologia, Universidade Federal do Rio Grande, Rio Grande, RS; **MCTFM**, Museu Coronel Tancredo Fernandes de Mello, Santa Vitória do Palmar, RS.

LOCATION AND GEOLOGICAL SETTING

The specimens come from a fossiliferous bed exposed along the banks of Chuí Creek, located 6 km from Santa Vitória do Palmar municipality, in the southernmost RS, next to the border between Brasil and Uruguay (Figure 1). The creek flows in a NE-SW direction, parallell to the coastline up to the Chuí County, where it turns eastwards until reaching the Atlantic Ocean. The plain through which the creek flows is located between two Pleistocene coastal barriers: the Barrier II, located westwards and the Barrer III located eastwards of the creek. Although precise ages have not yet been determined, it is estimated that the Barrier II was formed by the 325 ka AP marine transgression and the Barrier II by the 123 ka AP transgression (Tomazelli *et al*., 2000).

The base of the sedimentary sequence exposed along the banks is constituted by shallow marine sediments, containing the ichnofossil *Ophiomorpha nodosa* Lundgren, 1891 and large numbers of marine shells. The layer above contains the mammalian remains; it is composed by sand with an upward increase in silt. This layer seems to have been deposited in a meandering fluvial system (Lopes *et al*., 2009). Although this layer is some 2,5 m thick, until now the mammalian fossils found *in situ* are restricted to a ~1meter-thick horizon at its lower portion. Fossils were not found in the uppermost portion of this layer until now. At some points along the banks, just above the mammalian remains, the fossiliferous layer exhibits a 30 to 40 cm thick level of carbonate nodules and rhizocretions, called "Caliche Cordão" by Delaney (1965). Besides the remains found *in situ*, several other fossils can be found removed from the original layer due to erosion of the banks and by dredging activities. The uppermost portion of sequence is composed by a ~70 cm-thick dark, muddy sand, corresponding to the Holocene and containing archaeological artifacts (Schmitz *et al*., 1997).

Except for the bear canine and the equid skull, collected and donated by other persons, all remains were collected by authors on the fossiliferous level exposed along the banks of the creek.

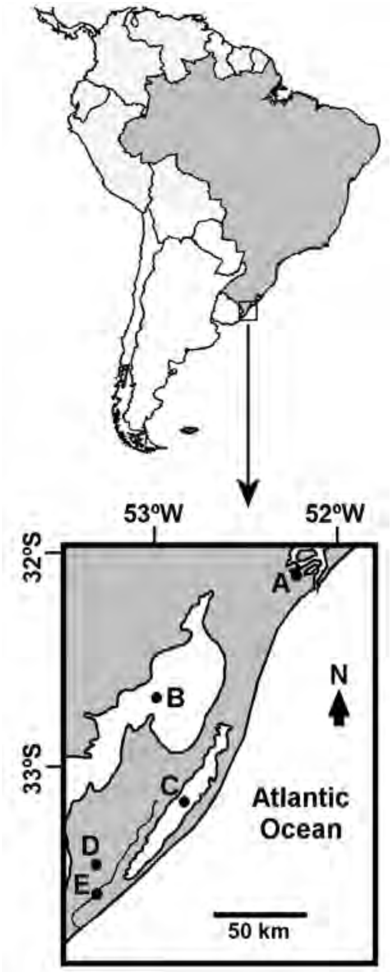

Figure 1. Detail of the coastal plain of Rio Grande do Sul State (CPRS): **A**, Rio Grande municipality; **B**, Mirim Lake; **C**, Mangueira Lake; **D**, Santa Vitória do Palmar Municipality; **E**, Chuí Creek.

SYSTEMATIC PALEONTOLOGY

XENARTHRA Cope, 1889
PILOSA Flower, 1883
MEGATHERIIDAE Owen, 1843
Genus *Eremotherium* Spillmann, 1948

Eremotherium cf. *E. laurillardi* Lund, 1842
(Figure 2A)

Material. Left dentary (EPM-PV 0133).

Description. The dentary has the molariforms preserved, with exception of m1, which is fragmented. The small size of the specimen indicates that it is a juvenile. The dorsal portion of the symphysis is fragmented; the first alveolus is fragmented on both labial and lingual sides, and the remaining of the dental series is fragmented in the lingual side. The m1 has preserved only a fragment of its base, which shows that its distal portion was slightly convex and wider than the mesial one. The remaining molars are well preserved and all exhibit the distal side more convex than the mesial one. The m2 exhibit labial side slightly longer mesiodistally than the lingual one; the m3 exhibit subquadrate outline and is the widest one; the m4 bears a mesial ridge considerably wider and mesiodistally compressed than the distal one, giving it a subtriangular outline. The posterior end of the angular process and the coronoid process were not preserved. The articular condyle is partly broken, mostly the medial portion.

The specimen EPM-PV0133 is assigned as *Eremotherium* on the basis of the following characteres: symphysis reaching up to the m1 (in *Megatherium* Cuvier, 1796 it reaches up to the m2) and slightly projected dorsally, above the level of dental series (which is ventrally curved in *Megatherium*); ventral bulge of the dentary less developed than in *Megatherium*; a shallow sulcus between m4 and the ascending ramus (in *Megatherium* a deep sulcus); angular process posteriorly projected, at the same level of the horizontal ramus (in *Megatherium* dorsally projected, above the dental series) and articular condyle projected posteriorly (in *Megatherium* dorsally projected) (Owen, 1861; Cartelle, 1992; Cartelle & De Iullis, 1995).

Measurements (mm). Maximum length: 217,0; length of the cheek teeth series: 80,0; dentary height (measured in the m3 region): 56,0; maximum height at the level of the mandibular condyle: 92,0.

Comments. Two taxa of Pleistocene megatheriids are currently referred for Brazil: *Megatherium americanum*, restricted to RS, and *Eremotherium laurillardi*, which inhabited the intertropical areas of Americas (Cartelle & DeIuliis, 1995). The fossil record of *Eremotherium* is common in the intertropical region of Brazil (*e.g.* Cartelle & DeIullis, 1995; Dantas & Zucon, 2005; Dantas & Zucon, 2007; Dantas & Tasso, 2007; Ribeiro & Carvalho, 2009), with only one previous record for southern Brazil (Toledo, 1986). Cartelle (1992) stated that the morphological characters of *Eremotherium* do not differ considerably between juveniles and adults, thus the specimen reported here is assigned to this genus. It probably represents *E. laurillardi*, the only valid species from the Brazilian Pleistocene (Cartelle & DeIuliis, 1995). The southernmost record of this species was in Caçapava do Sul municipality, located in the central area of RS, some 400 km NW of Chuí Creek (Toledo, 1986); thus, the record of *Eremotherium* in the outcrops of Chuí Creek expands its known paleogeographic distribution being in this way the southernmost record for the Americas until now.

CINGULATA Illiger, 1881
GLYPTODONTIDAE Burmeister, 1879
Genus *Doedicurus* Burmeister, 1874

Doedicurus sp.
(Figure 2B)

Material. Fragment of carapace (MCTFM-PV 0445).

Description. The specimen presents about 13 fused osteoderms. The sutures between them are barely discernible. Each osteoderm has 30-50 mm in diameter and bears 5-6 pilose foramina measuring about 5 mm in diameter. The osteoderms of *Doedicurus* are distinguished by the presence of large foramina in a circle on the central portion. Differently from other glyptodonts, such as *Glyptodon* and *Panochthus*, their surface is smooth without ornamentation.

Comments. The occurrence of *Doedicurus* in Brazil is restricted to RS (Paula Couto 1975, 1979), and the known specimens come mostly from the continental shelf. This taxon is rare in comparison to *Glyptodon* and *Panochthus*, what also happens among the remains from Chuí Creek. The only previous record of this taxon in Chuí Creek was presented by Oliveira (1992).

RODENTIA Bowdich, 1821
HYSTRICOGNATHI Tullberg, 1899
CAVIOMORPHA Wood & Patterson (*in* Wood, 1955)
ECHIMYIDAE Gray, 1825
MYOCASTORINAE Ameghino, 1904
Genus *Myocastor* Kerr, 1792

Myocastor cf. *M. coypus* (Molina, 1782)
(Figure 2C)

Material. Right M2 (MCTFM-PV 0732).

Description. The specimen is protohypsodont, with rectangular outline and all flexi open. The hypoflex is extended up to the middle of the occlusal surface, and is opposite to the protoloph, between the paraflex and the mesoflex, as described for *Myocastor* (Verzi *et al*., 2002). The labial flexi (paraflex and mesoflex) have the same size than the hypoflex, while the metaflex is more developed, reaching almost the entire width of the occlusal surface. The characters observed in this specimen are the same of *M. coypus*; however, due to the scarcity of the material, it is assigned to *Myocastor* cf. *M. coypus*.

Measurements (mm). Maximum height: 12,9; mesiodistal length: 8,14; labiolingual width: 7,04.

Comments. The previous record of fossil rodents from Chuí Creek is very scarce, represented by cranial and postcranial remains of *Microcavia* Gervais & Ameghino, 1880 described by Ubilla *et al*. (2008) and remains of Dolichotinae indet. and *Lagostomus* Brookes, 1828 reported by Kerber *et al*. (2011a). The stratigraphic distribution of *Myocastor* extends from the late Miocene (Mesopotamian) (Candela & Noriega, 2004) to Recent. For Pleistocene assemblages, *Myocastor* have been reported for Bolivia, Uruguay, Argentina and Brazil (Frailey *et al*., 1980; Ubilla, 2004; Ferrero & Noriega, 2009). Rodrigues & Ferigolo (2004) described remains of *M. coypus* from the continental shelf of RS, and Kerber *et al.* (2011b) referred remains of *Myocastor* sp. from the continental upper Pleistocene beds from RS. The extant *M. coypus* lives in permanently wet environments of Uruguay, Argentina, Chile and southern Brazil (Woods *et al*., 1992).

CARNIVORA Bowdich, 1821
cf. URSIDAE Fischer de Waldheim, 1817
(Figure 2D)

Material. Complete right upper canine (MCTFM-PV 0710).

Description. The specimen is large and exhibits wear on the crown apex, exposing dentine. The crown represents 1/3 of the tooth, and bears a distinct ridge on the mesial side. The cross section is subcircular, and the root is wider at its middle, becoming narrower towards the base. The root is closed, a little narrower than the limit of the crown. The root exhibit surface crackings that suggest weathering.

Measurements (mm). Maximum height: 99,0; crown height: 40,0; mesiodistal length (at the crown base): 25,0; labiolingual width (at the crown base): 22,0; maximum diameter: 32,0.

Comments. Fossil remains of Carnivora are very scarce in RS. The previous record of this group in CPRS is almost exclusively from the continental shelf. It includes the felid *Smilodon populator* Lund, 1842; the pinnipeds *Arctocephalus* sp. Saint-Hilaire & Cuvier, 1826 and *Otaria byronia* Blainville, 1820; and the canids *Dusicyon* cf. *avus* and *Theriodictis* sp. Mercerat, 1891 (Moreira, 1970; Oliveira & Drehmer, 1997; Drehmer & Ribeiro, 1998; Rodrigues *et al*., 2004). From the Chuí Creek, the only records so far are *Protocyon troglodytes* and *Dusicyon avus* Burmeister, 1866 (Oliveira *et al*., 2005; Pereira *et al*., 2011). Paula Couto (1975) mentioned the presence of *S. populator* in the “Santa Vitória Formation”, but did not specify whether the specimen came from the Chuí Creek or from the continental shelf.

In South America, the Ursidae are recorded from the early Pleistocene to the Recent, and represented by the extinct genus *Arctotherium*, the only valid Pleistocene taxon (Soibelzon, 2004; Soibelzon *et al.*, 2005) and the living *Tremarctus ornatus* Cuvier, 1825 in Geoffroy St. Hilaire & Cuvier, 1825.

ARTIODACTYLA Owen, 1848
CERVIDAE Gray, 1821
Genus *Antifer* Ameghino, 1889

Antifer sp.
(Figures 3A-B)

Material. Incomplete antler (MCTFM-PV 0581); fragment of the base of an antler (LGP-I0003).

Description. Both specimens are assigned as *Antifer* by their large dimensions and presence of surface ornamentation in the form of well-marked longitudinal grooves, with small tubercles at the base (Castellanos, 1945). The specimen MCTFM-PV 0581 is an almost complete right antler (Figure 3A), concave on the medial side and convex on the lateral one. The medial surface bears a longitudinal depression; the 1st ramification is mediolaterally flattened, and the rami are subcircular in cross section. At the height of the 2nd ramification the axis of the antler is flattened mediolaterally, giving it a subrectangular cross section. The specimen LGP-I0003 consists of the basal portion of a left antler (Figure 3B), longitudinally broken on the posterior side.

Measurements (mm). MCTFM-PV 0581. Maximum height: 440,0; height of the bifurcation: 163,0; maximum anteroposterior and transversal diameters: 58,0 and 53,0, respectively. LGP-I0003. Maximum height: 68,5; anteroposterior diameter: 34,0; transversal diameter: 35,0.

Comments. The morphological features of the specimen

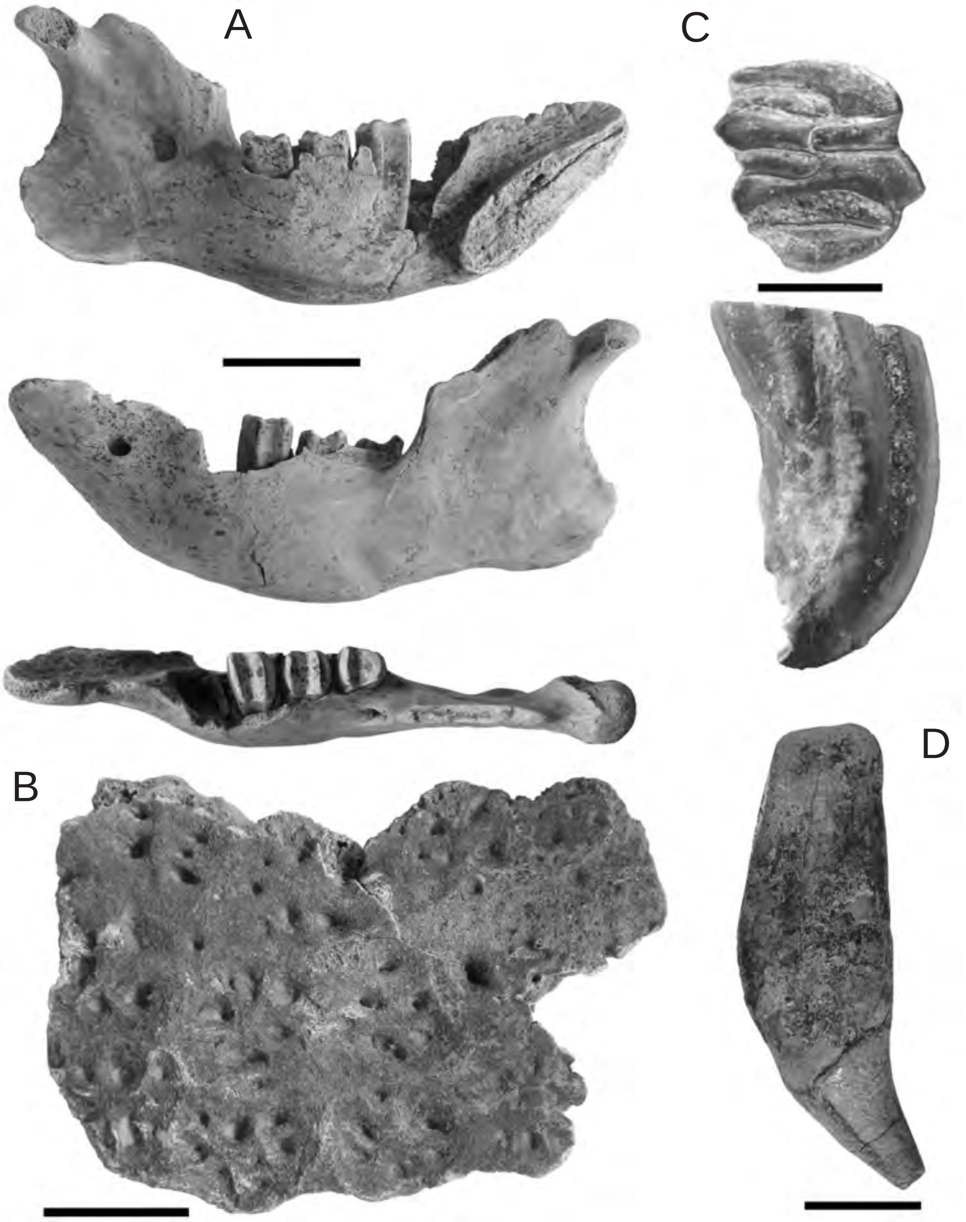

Figure 2. **A**, *Eremotherium* cf. *E. laurillardi*. EPM-PV 0133, left dentary in mesial, lateral and occlusal views. **B**, *Doedicurus* sp. MCTFM-PV 0445, fragment of the carapace in external view. **C**, *Myocastor* cf. *M. coypus.* MCTFM-PV 0732, right M2 of in occlusal and lingual views. **D**, cf. Ursidae. MCTFM-PV 0710, upper right canine in mesial view. Scale bars: A-B = 50 mm; C = 5 mm; D = 25 mm.

MCTFM-PV 0581 are similar to the description of *Antifer ultra* (Ameghino, 1888) by Castellanos (1945). The distinction between the two species of this genus recognized by Ameghino, *A. ensenadensis* (Ameghino, 1888) and *A. ultra*, is based on size differences between both, but it is possible that these are only a result of intraspecific variations (Menégaz, 2000). In the Buenos Aires Province of Argentina, the genus *Antifer* is restricted to Ensenandan Stage/Age (*A. ensenadensis*) and Bonaerian Stage/Age (*A. ultra*) (Cione & Tonni, 1999; Cione *et al*., 1999). However, this taxon has been reported for the late Pleistocene of northern Chile (Quebrada Quereo Formation, Labarca & López, 2006), Argentine Mesopotamian (Toropí Formation, Alcaraz & Zurita, 2004; Tezanos Pinto Formation, Ferrero & Noriega, 2009; El Palmar Formation, Ferrero *et al*., 2007), Uruguay (Sopas Formation, Ubilla, 2004) and western RS (Touro Passo Creek, Scherer *et al*., 2007; Kerber & Oliveira, 2008a). This fact suggests that *Antifer* may have survived in the late Pleistocene of this area (Lopes & Pereira, 2009).

Genus *Morenelaphus* Carette, 1922

Morenelaphus sp.
(Figures 3C-K; Table 1)

Material. Incomplete antlers (MCTFM-PV 0578 e MCTFM-PV 0579) and basal fragments of antlers (EPM-PV 0106, EPM-PV 0145, MCTFM-PV 0534, LGP-I0005, LGP-I 0006 and LGP-I 0008).

Description. These specimens are smaller in comparison to specimens of *Antifer* and the surface ornamentation is less evident; slightly curved in "S", as described for *Morenelaphus* (see Figure 3 C') (Kraglievich, 1940; Menégaz & Ortiz Jaureguizar, 1995); and less robust than *Blastocerus* Wagner, 1844. The angle between the axis and the 1st ramification is more open than that of *Antifer*. Specimen MCTFM-PV0578 (Figures 3C, C') is still attached to a skull fragment, portions of occipital and parietal regions. Specimen MCTFM-PV0579 (Figures 3D, D') also bears part of the skull, but smaller; the space between the rosette and the 1st ramus is large, and the axis is less sinuous in comparison to the specimen MCTFM- PV0578. Specimen LGP-I0005 is the only fossil known so far from the Chuí Creek that exhibits carbonate concretions on its surface (Lopes, 2009).

Comments. In previous publications (*e.g.* Paula Couto & Souza Cunha, 1965; Soliani Jr., 1973; Souza Cunha & Magalhães, 1981), the presence of the cervids *Morenelaphus* and *Ozotoceros* Ameghino, 1889 was mentioned for the Chuí Creek. Oliveira *et al*. (2005) listed *Antifer* and *Ozotoceros* for Chuí Creek, but they not referred and described the materials. Scherer *et al*. (2007), in a review of the fossil cervids from the CPRS, did not identify remains of *Ozotoceros*. Here we confirmed the presence of *Antifer* and *Morenelaphus* in the Chuí Creek. Besides the remains described here, there are several other cervid fragments that could not have been conclusively identified either as *Antifer*, *Morenelaphus* or other genera.

Table 1. Measurements (mm) of the specimens of *Morenelaphus*. **Abbreviations: MH**, maximum height; **BH**, height of the bifurcation; **AD**, maximum anteroposterior diameter (measured above the rosette); **TD**, maximum transverse diameter (above the rosette).

Specimen	MH	BH	AD	TD
MCTFM-PV 0578	250.0	46.0	38.0	29.0
MCTFM-PV 0579	245.0	71.0	30.0	27.0
EPM-PV 0106	57.0	44.0	21.0	16.0
EPM-PV 0145	53.0	41.0	29.0	24.0
MCTFM-PV 0584	84.0	47.0	17.0	16.0
LGP-I0005	91.5	54.0	27.0	22.0
LGP-I0006	97.5	49.0	27.0	21.5
LGP-I0008	83.5	59.0	33.0	30.0

TAYASSUIDAE Palmer, 1897
Genus *Catagonus* Ameghino, 1904

Catagonus sp.
(Figure 4A)

Material. Skull (MCTFM-PV 0575a) and mandible (MCTFM-PV 0575b).

Description. The skull is almost complete, with the right side best preserved, lacking the canine and I2, and with the I1 broken. The left side was partially destroyed by weathering. In the mandible, the right ramus is well preserved, but without canine, incisors and m2; the posterior portion of the left side was destroyed by weathering. Among the diagnostic characteristics of the genus *Catagonus* are the convex dorsal profile of the nasal portion of the rostrum and the orbit posteriorly displaced some 34 mm in relation to the M3 (Gasparini *et al*., 2009).

Measurements (mm). MCTFM-PV 0575a. Skull, total length: 315,0; maximum height: 114,0; upper cheek teeth length: 74,0. MCTFM-PV 0575b. Mandible, total length: 168,0; height at the condyle: 93,0; lower cheek teeth length: 80,0.

Comments. In South America, the Tayassuidae have a stratigraphic distribution that range from late Pliocene to Recent, and is represented by three genera (Gasparini, *in press*): *Platygonus* Le Conte, 1848, *Tayassu* Fischer, 1814, and *Catagonus*. Only the last two have living representatives. The living species *Catagonus wagneri* Rusconi, 1930 was discovered only in the 1970s (Wetzel *et al*., 1975). Fossils of *Catagonus* have been reported for Pleistocene of Bolivia, Argentina and Uruguay (Gasparini, *in press*); in Brazil it has been recorded for caves of Minas Gerais, Tocantins and Paraná states and Touro Passo Creek (RS) (Paula Couto, 1981; Gasparini *et al*., 2009; Silva *et al*., 2010; Ávilla *et al*., 2010). The current distribution of *C. wagneri* is restricted to the Chaco, in Paraguay and Bolivia, where semi-arid conditions are predominant (Mayer & Brant, 1982; Mayer & Wetzel, 1986). The wide paleobiogeographic distribution of *Catagonus* can be related to the presence of dryer environments during the Pleistocene (Menégaz & Ortiz Jaureguizar, 1995). This specimen needs a more comparative study to determine its specific status, as well as, a complete description of its anatomic features.

PERISSODACTYLA Owen, 1848
EQUIDAE Gray, 1821
Genus *Equus* Linnaeus, 1758

Equus cf. *E. (A.) neogaeus* Lund, 1840
(Figures 4B-C)

Material. Incomplete skull (MCTFM-PV 0618).

Description. The specimen represents part of the rostral portion of a skull, without incisors but with the left canine and cheek teeth series preserved (lacking the M2 and M3). The nasals are fractured, but it is visible that the retraction of the nasal fissure begins anteriorly to the P2, differently from *Hippidion* which have a long fissure reaching at least the M2 or M3 (Alberdi & Prado, 1992; Alberdi *et al*., 2003). The palatal surface is flattened and the incisive foramina are located slightly anteriorly to the canine. The parastyle and mesostyle are well developed and bigger than the metastyle on both P2 and P3. In the M1 the parastyle is absent. The lingual sides of the anterofossae and posterofossae have poorly developed plis, except for the anterofossa of the P2. The hypocone is oval, with a constriction that separates itself from the the metaloph, except on the M1. The outline of the protocone on the P2 is oval on its distal end, while on the P3, P4 and M1 it is subtriangular, with distal end more developed than the mesial one, differently from *Hippidion*, which bears an oval protocone.

Measurements (mm). Mesiodistal length (MDL) of the P2: 35,0; Labiolingual width (LLW) of the P2: 22,0; MDL of the P3: 23,0; LLW of the P3: 27,0; MDL of the P4: 21,0; LLW of the P4: 24,0; MDL of the M1: 20,0; LLW of the M1: 23,0.

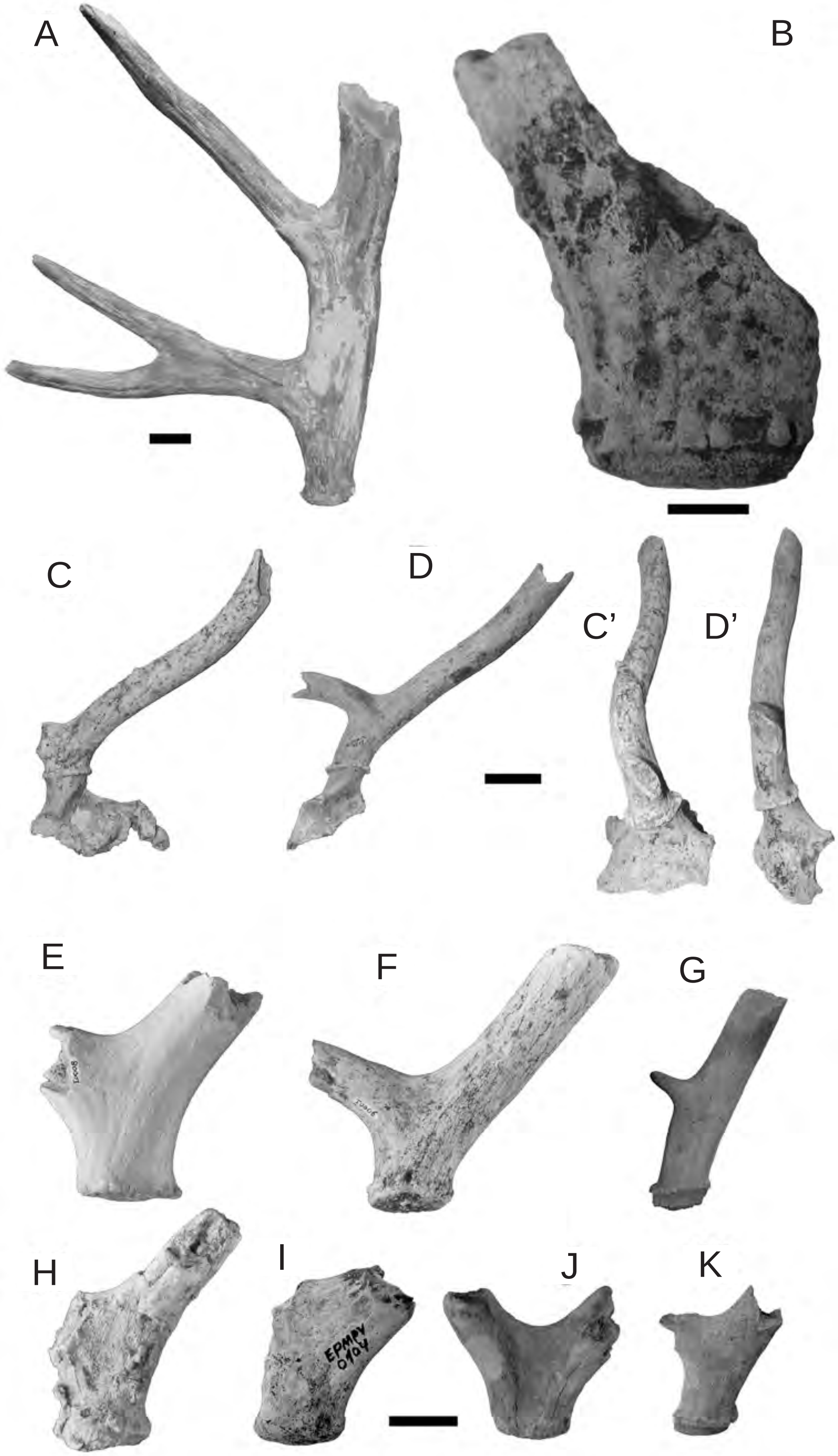

Figure 3. *Antifer* sp. **A**, MCTFM-PV 0581, antler in medial view; **B**, LGP-I 0003, basal fragment of an antler in lateral view. *Morenelaphus* sp. **C**, MCTFM-PV 0578, fragmented antler plus a portion of the skull of in lateral (C) and anterior (C’) views; **D**, MCTFM-PV 0579, antler in lateral (D) and anterior (D’) views; **E-K**, fragments of antlers in lateral views, LGP-I0008 (E); LGP-I0006 (F); MCTFM-PV 0534 (G); LGP-I0005 (H); EPM-PV 0104 (I); EPM-PV 0145 (J); EPM-PV 0106 (K). Scale bars: A, C-D’ = 50 mm; B = 10 mm; E-K = 25 mm.

Genus *Hippidion* Owen, 1869

Hippidion sp.
(Figure 4D)

Material. Upper molar (M1?), (EPM-PV 0137).

Description. The specimen consists of a partial crown of the tooth. The material is diagnosed as *Hippidion* by the presence of an oval-shaped protocone (Alberdi & Prado, 1992). The occlusal surface exhibits a labiolingual depression between the metacone and paracone. The parastyle and mesostyle are well developed, and the metastyle is absent. The hypocone is poorly developed. The tooth is longitudinally curved, concave on the lingual side. The distal side exhibit bioerosion traces as irregular sulci near the occlusal surface, possibly caused by plant roots or worms. Part of the enamel on the mesial side was lost, and the presence of longitudinal crackings suggests weathering.

Measurements (mm). Maximum height: 53,0; mesiodistal length: 27,0; labiolingual width: 29,0.

Comments on the equids. According to the review of South American equids by Alberdi & Prado (1993) and Prado & Alberdi (1994), two genera are recognized, *Hippidion* and *Equus*. *Hippidion* is represented by three species: *H. devillei* (Gervais, 1855), *H. principale* and *H. saldiasi* Roth, 1899. *Equus (Amerhippus)* is represented by five species: *E.(Amerhippus) neogaeus*, *E. (Amerhippus) insulatus* C. Ameghino (in F. Ameghino 1904), *E. (Amerhippus) santaeelenae* Spillmann, 1938, *E. (Amerhippus) andium* Branco, 1883 and *E. (Amerhippus) lasallei* Daniel, 1948. For Brazil, only *H. devillei*, *H. principale* and *E.* (*A.*) *neogaeus* are referred (Alberdi *et al*., 2003). In RS, *Hippidion* was previously reported for Touro Passo Creek, Sanga da Cruz and the Continental Shelf; and *E.* (*A.*) *neogaeus* for Quaraí River, Garupá Creek, Touro Passo Creek and the continental shelf (Oliveira, 1992; Scherer & Da Rosa, 2003; Kerber & Oliveira, 2008a,b). The material here reported confirms the presence of these taxa in the Chuí Creek. *E.* (*A.*) *neogaeus,* the only species of *Equus* recorded in late Pleistocene of southern South America, is considered the fossil-guide of the Lujanian Stage/Age of the Pampean Region (Tonni, 2009). The equids are indicatives of open areas and grasslands (Alberdi & Prado, 1992).

FINAL REMARKS

The remains here reported contribute to the knowledge of the fossil mammals from Chuí Creek. Some specimens are new records (*Eremotherium*, *Myocastor*, cf. Ursidae, *Catagonus*), while others confirm the presence in this area of

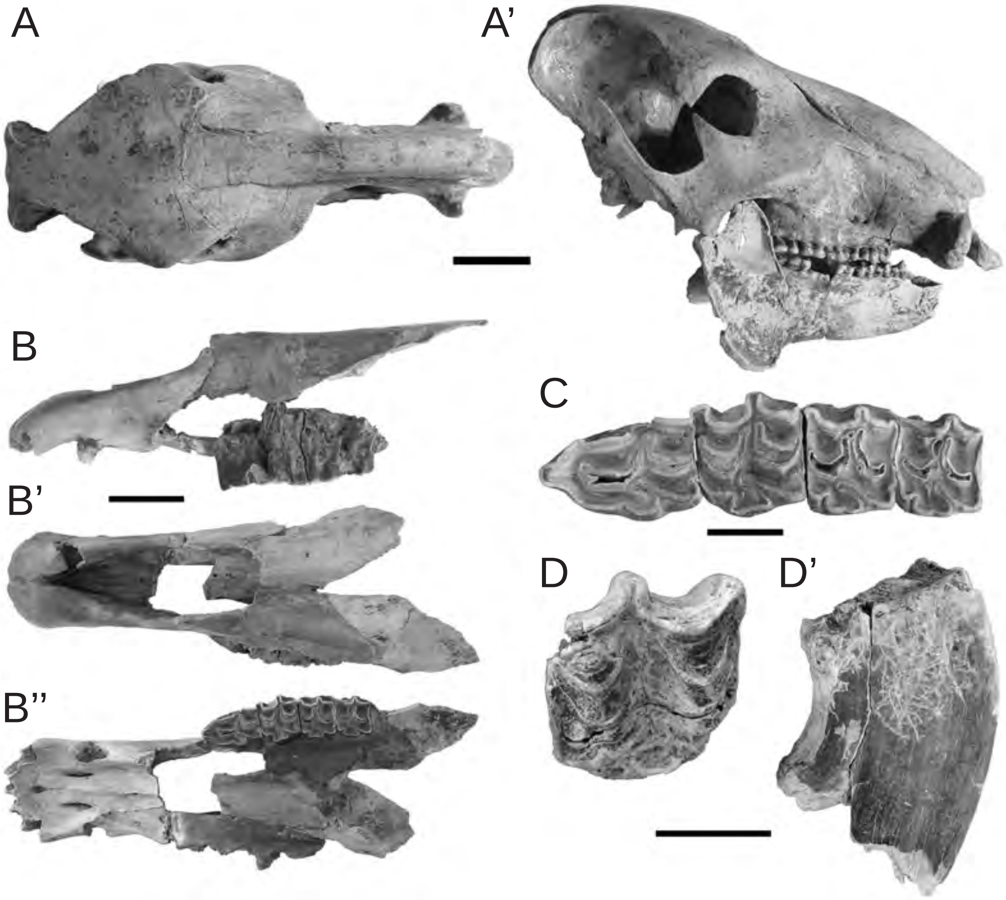

Figure 4. *Catagonus* sp. **A-A’**, skull and mandible of MCTFM-PV 0575a, b in dorsal (A) and lateral views (A’). *Equus* cf. *E. (A.) neogaeus.* **B-C**, portion of the skull of MCTFM-PV 0618 in lateral (B), dorsal (B’) and ventral (B’’) views; detail of the cheek teeth series (C). *Hippidion* sp. **D-D’**, molar of EPM-PV 0137 in occlusal (D) and distal views (D’) (scale bar = 20 mm). Scale bars: A-B = 50 mm; C-D = 20 mm.

certain taxa that have been previously mentioned but never formally published, such as *Antifer*, *Morenelaphus*, *Equus* and *Hippidion*. This report increases the known taxonomic diversity of the fossil assemblage from the creek and contributes to a better understanding of faunal and climatic changes in the coastal area of southern Brazil during the Late Pleistocene.

The occurrence of *Eremotherium* increases the number of intertropical (Brazilian) taxa known from Chuí Creek, together with *Protocyon troglodytes*, *Propraopus sulcatus*, *Pampatherium humboldti*, *Holmesina paulacoutoi* and *Catonyx* cf. *C. cuvieri* (Oliveira *et al*., 2005; Oliveira & Pereira, 2009; Lopes & Pereira, 2010), besides increasing its distribution. The presence of *Myocastor* in this assemblage indicates the existence of perennial wet environments during some phase in the past, which seem to corroborate the interpretation that most remains were preserved and reworked in fluvial systems (Lopes *et al*., 2001; 2009). On the other hand, the fossil assemblage of Chuí Creek contains fossils of Pampean taxa such as *Doedicurus* sp., *Macrauchenia patachonica*, and *Lestodon* sp. and also taxa that indicate semi-arid environments such as the Dolichotinae, *Lagostomus* cf. *L. maximus*, *Microcavia* sp. and *Catagonus* (Ubilla *et al*., 2008; Kerber *et al*.,2011a; Lopes, *in press*).

Besides southern Brazil, northern Uruguay and the Mesopotamian region of Argentina have also shown a similar faunal composition during the Late Pleistocene, characterized by the co-occurrence of taxa of Pampean and Brazilian affinities. This pattern has been pointed by several authors (*e.g*. Oliveira, 1996; 1999; Carlini *et al*., 2004; Ubilla *et al*., 2004; Gasparini & Zurita, 2005; Kerber & Oliveira, 2008a; Ferrero & Noriega, 2009; Oliveira & Kerber, 2009; Oliveira & Pereira, 2009) and is likely to be caused by the latitudinal displacement of climatic belts and corresponding environments, correlated to glacial-interglacial cycles. Several pollinical studies show that cold-tolerant vegetation found today in southern Brazil migrated up to 750 km northwards during the last glacial maximum (LGM), which probably also occurred during past glacials (Lopes, *in press*). It is likely that Pampean taxa followed these latitudinal migrations, thus reaching areas to the north of the Pampean Region. The presence of intertropical taxa in southern Brazil, Uruguay and Argentina permit to suggest that the opposite also occurred, with southwards migration of warmer climates, either during full interglacials but also during interstadials. Tapirids, for example, appear in the fossil record of the Pampean Region during the Ensenadan Stage / Age, between ~2 myr and ~780 kyr BP (Cione & Tonni, 1999), but their current distribution is much farther to the north.

One major problem that hampered the bio- and chronostratigraphic correlations of the Pleistocene faunas of the region is the lack of absolute ages for most deposits. Lopes *et al.* (2010) published dating between 226 kyr and 34 kyr BP for the assemblage of Chuí Creek obtained by electron spin resonance (ESR) datings on teeth. These ages indicate that the fauna encompasses the final part of an interglacial, correlated to marine isotope stage (MIS) 7, two interglacials (MIS 5 and 3) and two glacials (MIS 6 and 4). Taking into account these datings, it seems reasonable to argue that the intertropical fauna may have reached the area of Chuí Creek during the climatic optimum of MIS 5 (Eeemian stage, between 131 and 114 kyr BP) or during one of warmer climate fluctuations (interstadials) of MIS 3.

Besides the lacking of absolute datings, another problem for a batter understanding of paleoenvironmental and paleoclimatic conditions at Chuí Creek is the fact that most remains have been reworked due to erosion of the banks by fluvial activities. Geological and taphonomic studies in Chuí Creek indicate that the fossiliferous level represents meandering fluvial systems that have reworked most of the remains, thus removing them from their original stratigraphic setting. Nevertheless, the stratigraphic successions exposed along the banks of the creek seem to indicate environmental modifications related to the climatic changes during Late Pleistocene. Until now, no mammalian remains, but only traces of plant roots have been found so far above the ~1 meter-thick fossiliferous horizon. The absence of vertebrate remains, the high silt content and the presence of carbonate nodules and concretions in some points along the banks, seem to indicate that the climate changed to more dry and arid conditions, which may have contributed to the disappearance of large mammals in the area.

The continuous research efforts in this area, focusing on stratigraphy, fossil collecting, mineralogical and palynological analyses, are likely to provide new information regarding the mammalian community from southernmost Brazil permitting to establish comparisons with other fossil localities in order to understand the responses of this community to the climatic changes in the late Pleistocene.

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Appendix 1. Updated list of fossil mammals from Chuí Creek.

Glyptodon clavipes Owen, 1838; Oliveira (1992)
Glyptodon reticulatus Owen, 1845; Oliveira (1992)
Doedicurus Burmeister, 1867; Oliveira (1992) and this paper
Panochthus Burmeister, 1866; Oliveira (1992)
Neuryurus rudis (Gervais, 1878); Lopes *et al*. (2011)
Mylodon darwini Owen, 1840; Oliveira (1992)
Lestodon Gervais, 1855; Oliveira (1992)
Catonyx cf. *C. cuvieri* Lund, 1839; Lopes & Pereira (2010)
Eremotherium cf. *E. laurillardi* Lund, 1842; this paper
Propraopus aff. *sulcatus* Lund, 1842; Oliveira & Pereira (2009)
Dasypus sp. Linnaeus, 1758; Oliveira & Pereira (2009)
Pampatherium humboldti Lund, 1839; Oliveira & Pereira (2009)
Holmesina paulacoutoi Cartelle & Bohórquez, 1985; Oliveira & Pereira (2009)
Toxodon platensis Owen, 1840; Lopes *et al*. (2001)
Macrauchenia patachonica Owen, 1838; Scherer *et al*. (2009)
Hemiauchenia aff. *paradoxa* Gervais & Ameghino, 1880; Oliveira (1992)
Antifer Ameghino, 1889; this paper
Morenelaphus Carette, 1922; this paper
Catagonus Ameghino, 1904; this paper
Equus cf. *E. (A.) neogaeus* Lund, 1840; this paper
Hippidion Owen, 1869; this paper
Stegomastodon waringi Holland, 1920; Marcon (2008)
Microcavia Gervais & Ameghino, 1880; Ubilla *et al*. (2008)
Myocastor cf. *M. coypus* (Molina, 1792); this paper
Dolichotinae Pocock, 1922; Kerber *et al*. (2011a)
Lagostomus cf. *L. maximus* (Desmarest, 1817); Kerber *et al*. (2011b)
Protocyon troglodites Lund, 1838; Oliveira *et al*. (2005)
Dusicyon avus Burmeister, 1866; Pereira *et al.* 2011
cf. Ursidae; this paper

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Às oito horas e trinta minutos do dia quinze de agosto de dois mil e treze, no Anfiteatro do Centro de Estudos em Geologia Costeira e Oceânica – CECO, no Campus do Vale, reuniu-se a Comissão Examinadora constituída pelos doutores: Martin Ubilla (Universidad de la Republica - Uruguay), Francisco Sekiguchi de Carvalho Buchmann (Universidade Estadual Paulista - UNESP) e Luiz José Tomazelli (PPGGEO/IG/UFRGS), para a defesa da tese intitulada: **"RECONSTITUIÇÃO PALEO-CLIMÁTICA E PALEO-AMBIENTAL DO PLEISTOCENO TARDIO NO SUL DA PLANÍCIE COSTEIRA DO RIO GRANDE DO SUL."**, a que se submete **RENATO PEREIRA LOPES**, depois de haver cumprido as exigências regulamentares do Programa. O Prof. Dr. Sérgio Rebello Dillenburg, na qualidade de orientador fez a abertura da sessão e presidiu os trabalhos de acordo com o previsto no artigo 69 do Regimento do Programa. O candidato fez a apresentação do seu trabalho e a seguir foi arguida pelos membros da Comissão Examinadora. Às onze horas e cinco minutos a sessão foi suspensa por dez minutos para julgamento e atribuição dos conceitos, que foram os seguintes: Martin Ubilla **"A" (EXCELENTE)**, Francisco Sekiguchi de Carvalho Buchmann **"A" (EXCELENTE)**e Luiz José Tomazelli **"A" (EXCELENTE)**. Face aos conceitos atribuídos foi conferido ao candidato o grau de **DOUTOR EM CIÊNCIAS** pela Universidade Federal do Rio Grande do Sul. Às onze horas e quinze minutos a sessão foi encerrada, do que para constar, eu, Roberto Martins, lavrei a presente Ata que é assinada pela Comissão Examinadora.

Prof. Dr. Martin Ubilla

Fran. S. C. Bh.
Prof. Dr. Francisco Sekiguchi de Carvalho Buchmann

Prof. Dr. Luiz José Tomazelli

Prof. Dr. Sérgio Rebello Dillenburg
(Presidente)

Homologação pela Comissão de Pós-Graduação,	
Ata nº 004/2013	Data: 21/8/2013
Conceito Final: "A" (Excelente)	
Rubrica:	

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