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

PALEOVALES QUATERNÁRIOS NA LAGOA DOS PATOS, RIO GRANDE DO SUL, BRASIL: PREENCHIMENTO, EVOLUÇÃO E INFLUÊNCIA NA DINÂMICA LAGUNAR

EDUARDO CALIXTO BORTOLIN

ORIENTADOR – Prof. Dr. Jair Weschenfelder (UFRGS)

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RESUMO

A planície costeira do Rio Grande do Sul (RS) é uma grande área (33.000 km^2) de relevo suave, que se estende desde Torres até o Chuí. A fisiografia desta região modificou-se ao longo do Quaternário, respondendo regionalmente às variações de nível eustático e forçantes locais. Esta região preserva depósitos que podem oferecer pistas de como os paleoambientes evoluíram até atingir a configuração atual. A Lagoa dos Patos é uma das feições mais marcantes da planície costeira do RS, representada por uma área continental submersa de 10.000 Km^2, onde paleovales incisos foram reconhecidos em cruzeiros científicos realizados nos anos de 2002 e 2006. Cerca de 1.000 km de perfis sísmicos de alta resolução (3,5 e 10 kHz) foram analisados no presente trabalho, assim como furos de sondagem estratigráfica e datações por radiocarbono. O reconhecimento das facies deposicionais foi feito por meio de parâmetros sísmicos, tais como: geometria externa, configuração interna, amplitude, frequência e continuidade dos refletores. Os furos de sondagem atestaram as interpretações feitas a partir dos dados sísmicos, a respeito dos paleoambientes e as datações contextualizaram os depósitos quanto ao nível eustático. O arcabouço estratigráfico detalhado foi estabelecido por meio do mapeamento de superfícies-chave, que possibilitaram a indidualização de 4 unidades sísmicas, cada uma associada a um respectivo trato de sistema. A construção deste arcabouço permitiu a diferenciação entre a paleotopografia e os depósitos formados a partir do último máximo glacial. As imagens sísmicas foram comparadas à batimetria lagunar, revelando a influência de feições pretéritas na morfologia lagunar atual. Taxas de acumulação foram determinadas por meio da datação de pacotes sedimentares, objetivando comparar deposição em diferentes porções dos paleovales. No subfundo da Lagoa dos Patos, canais tipicamente fluviais foram registrados em estágios de nível do mar em queda ou baixo (FSST e LST). Nestes estágios, os rios Camaquã e Jacuí preencheram vales mais antigos, reajustando suas rotas para regiões de topografia mais deprimida ou de substrato mais suscetível à erosão. Facies estuarinas formam os pacotes sedimentares mais volumosos, sendo reconhecidas em estágios de nível do mar em queda, de nível baixo e abundantemente em estágios transgressivos. Os

registros estuarinos transgressivos ocorridos após o último máximo glacial são principalmente sedimentos lamosos, preenchendo em conformidade os paleovales a medida que os vales eram inundados. O preenchimento holocênico dos vales não foi completo devido a insuficiência de aporte sedimentar fluvio-estuarino durante o Holoceno, preservando a morfologia dos vales na batimetria lagunar, que afeta a dinâmica sedimentar atual. Dados sísmicos revelaram coincidência entre a posição dos paleointerflúvios e dos bancos submersos, sob os quais se desenvolvem pontais arenosos. A formação da Lagoa dos Patos ocorreu após o máximo transgressivo holocênico (~ 5,1 ka antes do presente), com a justaposição da barreira arenosa IV sob a barreira arenosa III, represando e submergindo os vales adjacentes. Estes depósitos de estágio de nível de mar alto reduziram consideravelmente as taxas de sedimentação em relação ao trato de sistemas transgressivo. A evolução dos vales respondeu primeiramente a forçantes alogênicas e secundariamente a autogênicas.

ABSTRACT

The Rio Grande do Sul (RS) coastal plain is a broad area (33,000 km^2) with a gentle relief, extending from Torres to Chuí. The physiography of this area has been modified over the Quaternary, responding to eustatic variations and local forcings. This region preserves deposits, which offer clues about the paleoenvironment evolutionary processes ocurred until it reaches the current configuration. The Patos Lagoon is one of the most remarkable features in the RS coastal plain, representing a submerged continental area of 10,000 Km^2, where incised paleovalleys were recognized during scientific cruises carried out in 2002 and 2006. About 1,000 km of high resolution seismic profiles (3.5 and 10 kHz) were analysed in the current work, as well as sediment cores and radiocarbon dating. The depositional facies recognition was carried out by means of the seismic parameters, such as: external geometry, internal configuration, amplitude, frequency and continuity of the reflectors. The core information attested the seismic interpretations made about the paleoenvironment and the datings contextualized the deposits with relationship to the eustatic level. The detailed stratigraphic framework was established by the mapping of key-surfaces, which allowed the individualization of 4 seismic units, each one associated to a respective system tract, it allowed the differentiation between the paleotopography and the post last glacial maximum infilling. The seismic images were compared to the lagoon bathymetry, revealing the influence of previous features in the current lagoon morphology. Accumulation rates were determined by dating sedimentary packages, aiming compare deposition in different portions of the paleovalleys. In the lagoon sub-bottom, tipically fluvial channels were recorded in falling stages or lowstands (FSST and LST). In these stages, the Camaquã and Jacuí rivers fulfilled older valleys, readjusting their route to lower areas or with a more erodible substrate. The estuarine facies are the most voluminous sedimentary packages and they were recognized in falling stages, lowstands and most widely in transgressive stages of sea level. The transgressive estuarine records of the post last glacial maximum are mainly muddy sediments, infilling in conformably the paleovalleys as they were flooded. The Holocene valleys infilling was not complete due to the low sediment supply of fluvio-

estuarine systems, preserving the valleys morphology in the lagoon bathymetry, influencing the current sedimentary processes. Seismic data revealed coincidence between the position of the paleointerfluves and the submerse banks, over which the sandy spits are developed. The formation of Patos Lagoon occurred after the Holocene sea level maximum (~ 5.1 ka before present), with the juxtaposing of the Holocene coastal barrier (IV) to the pleistocene barrier (III), damming and submerging the adjacent valleys. These deposits of highstand sea level diminished significantly the accumulation rates in comparison with transgressive system tract. The valleys evolution responded firstly to allogenic forcings and secondly to autogenic one.

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SUMÁRIO

ESTRUTURA DA TESE

Esta Tese de Doutorado está estruturada de acordo com a Norma 103 do Programa de Pós-graduação em Geociências (PPGGEO) da Universidade Federal do Rio Grande do Sul (UFRGS). A Tese é composta por um texto de '**Introdução'** à temática da pesquisa (capítulo 1), seguido de '**3 Artigos Científicos'** submetidos a periódicos indexados (capítulos 2, 3 e 4) e por um '**Texto Integrador'** final (capítulo 5) seguido de referências bibliográficas.

Capítulo 1 – Apresenta uma introdução ao tema da tese, favorecendo a compreensão da relação entre os conteúdos específicos abordados em cada artigo científico. Este capítulo contém o estado da arte, os objetivos, as premissas, as hipóteses e os métodos.

Capítulo 2 – O artigo deste capítulo apresenta a descrição dos parâmetros físicos utilizados na identificação de paleoambientes sedimentares, assim como a classificação das fácies em Tratos de Sistema específicos. Este artigo é intitulado de "***Incised valley paleoenvironments interpreted by seismic stratigraphic approach in Patos Lagoon, Southern Brazil*"** e foi submetido à revista *Brazilian Journal of Geology* em novembro de 2017.

Capítulo 3 – Neste capítulo se apresenta um artigo sobre a influência dos paleovales Quaternários na batimetria atual e nos processos hidrodinâmicos da Lagoa dos Patos. O título do artigo é "***Holocene evolution of Patos Lagoon, Brazil: the role of antecedent topography*"** e foi submetido à revista *Journal of Coastal Research* em novembro de 2017. Este trabalho permitiu compreender melhor a dinâmica atual de deposição nas células morfológicas da Lagoa dos Patos, as taxas holocênicas de sedimentação e o desenvolvimento de pontais arenosos da margem lagunar.

Capítulo 4 – O artigo deste capítulo aborda as mudanças no curso das paleodrenagens quaternárias identificadas no substrato da Lagoa dos Patos. O artigo foi submetido à revista *International Journal of Sediment Research* com o título "***Drainage reorganization of southern Brazilian coastal rivers***" em novembro de 2017. Este artigo discute a importância de compreender as antigas rotas de cursos fluviais na Lagoa dos Patos e propõem uma teoria para a causa das mudanças de curso dos rios ao longo do Quaternário.

Capítulo 5 – Aborda os temas dos capítulos anteriores, na forma de um capítulo integrador da temática da tese.

As referências bibliográficas citadas nos capítulos 1 e 5 se encontram no final do texto. As referências bibliográficas citadas nos artigos são apresentadas ao final de cada um dos mesmos.

As figuras são numeradas sequencialmente nos capítulos 1 e 5. As figuras utilizadas nos artigos (capítulos 2, 3 e 4) são apresentadas ao final de cada um dos mesmos.

CAPÍTULO 1 - INTRODUÇÃO

As zonas costeiras são extremamente vulneráveis às mudanças fisiográficas causadas por fatores alogênicos, autogênicos e antrópicos. A resposta de ambientes costeiros às variações eustáticas tem recebido atenção desde o fim do último século (SCHUM, 1993; SHANLEY; MC CABE, 1994; ZAITLIN; DALRYMPLE; BOYD, 1994; BLUM; TÖRNQVIST, 2000).

Vales incisos foram formados nas plataformas continentais do mundo todo durante as glaciações do Quaternário, preservando uma grande variedade de facies deposicionais (DALRYMPLE; BOYD; ZAITLIN, 1994; ZAITLIN; DALRYMPLE; BOYD, 1994; DALRYMPLE, 2006). A elevação do nível eustático ocorrida após o último máximo glacial alagou enormes áreas continentais ao redor do mundo, formando estuários, lagunas e lagos nas áreas costeiras.

A Lagoa dos Patos, na zona costeira do RS, é uma das maiores áreas continentais do mundo inundada durante a transgressão holocênica. Um sistema de vales foi reconhecido em registros sísmicos coletados durante cruzeiros científicos na laguna. Este sistema é complexo e possui paleovales incisos dispostos em latitudes adjacentes, coincidindo geograficamente com as células morfológicas do corpo lagunar.

As depressões topográficas ocupadas pelos vales incisos são as zonas mais vulneráveis à inundação e normalmente são as primeiras a serem afogadas durante os eventos transgressivos. Um grande número de facies sedimentares é gerado desde o processo de formação dos vales, até seu completo preenchimento; o capítulo 2 desta tese objetiva investigar este tema.

No capítulo 2 também se encontra a descrição das fácies, considerando critérios sísmicos, sedimentológicos, fossilíferos e estratigráficos. Depois de interpretado o paleoambiente as facies foram agrupadas em tratos de sistemas e correlacionadas a posições específicas da curva de nível relativo do mar.

O capítulo 3 desta tese destina-se a compreender a influência da paleotopografia na morfodinâmica atual da Lagoa dos Patos e nos processos deposicionais modernos. Perfis sísmicos foram associados ao mapa batimétrico, possibilitando o estabelecimento de estreita relação entre a morfologia dos vales incisos e a morfologia de fundo lagunar. Os pontais arenosos estabelecem-se sobre estruturas submersas

(≤1m de cota), que limitam células morfológicas da laguna e são interpretadas como paleointerflúvios. As áreas mais profundas das células são associadas às porções mais profundas dos paleovales incisos. O capítulo 3 também investiga as taxas de deposição em diferentes porções dos vales, analisando os fatores que controlaram a proporção das taxas.

O capítulo 4 apresenta uma discussão sobre os reajustes das linhas de drenagem reconhecidas no substrato da Lagoa dos Patos. Uma possível causa para a mudança no curso dos rios é proposta e é discutida a importância da compreensão dos processos de reajuste de drenagens.

O capítulo 5 é um apanhado dos resultados e ideias abordados nos artigos científicos submetidos aos periódicos indexados neste trabalho. De maneira a sintetizar e integrar os trabalhos.

Esta tese foi elaborada com a colaboração de pesquisadores de universidades parceiras à UFRGS: os professores Andrew Cooper da University of Ulster (Reino Unido) e Andrew Green da University of KwaZulu-Natal (Africa do Sul). Estes pesquisadores integram um projeto em associação com a UFRGS chamado "*Application of marine geophysics to continental shelf evolution: control of sediment supply on nearshore stratigraphy*" e auxiliaram durante a elaboração dos artigos científicos aqui apresentados.

Concretizou-se um "doutorado sanduíche" em parceria com a University of Ulster, onde o doutorando teve a oportunidade de morar pelo período de um ano na Irlanda do Norte realizando reuniões semanais com seu supervisor no exterior Andrew Cooper. Durante este ano a University of Ulster financiou uma visita acadêmica do doutorando à University of KwaZulu-Natal na África do Sul.

1.1 – ESTADO DA ARTE

Geologia regional

Província Costeira do Rio Grande do Sul refere-se a dois elementos geológicos, Embasamento e Bacia de Pelotas, característicos da margem continental brasileira entre os paralelos 28°40` e 33°45` de latitude sul. O embasamento é composto pelo complexo cristalino pré-cambriano e pelas sequências sedimentares e vulcânicas, paleozóicas e mesozóicas, da Bacia do Paraná. A Bacia de Pelotas é uma bacia marginal subsidente, siliciclástica, que formou-se sobre o Escudo, cuja espessura atinge 12.000 metros no depocentro (VILLWOCK, 1972).

Na Província Costeira do RS está contida a mais ampla planície costeira do país (Fig. 1), abrangendo uma área de ~ 33.000 km^2, orientada na direção NE-SW por uma extensa distância de 620 km, desde Torres (NE) até a desembocadura do Arroio Chuí (SE). A planície costeira do Rio Grande do Sul (PCRS) preserva boa parte dos registros geológicos do Quaternário, fornecendo dados relevantes aos estudos de evolução costeira (TOMAZELLI; VILLWOCK, 2000).

As oscilações glacio-eustáticas ocorridas durante o Quaternário modelaram a fisiografia dos sedimentos siliciclásticos da Bacia de Pelotas. Nos estágios de deposição inicial desenvolveram-se leques aluviais nas regiões proximais à área-fonte. A PCRS progradou para leste, formando quatro sistemas deposicionais do tipo “laguna-barreira” (VILWOCK; TOMAZELLI, 1995; TOMAZELLI; VILLWOCK, 2000).

Cada sistema laguna-barreira registra o pico de um evento transgressivo, seguido de um evento regressivo (TOMAZELLI; VILLWOCK, 2000). O ápice dos eventos transgressivos são correlacionáveis aos picos dos estágios isotópicos do oxigênio descritos por Imbrie *et al*. (1984). Assim, os sistemas laguna barreira I, II, III e IV estariam associados aos estágios isotópicos 11, 9, 5 e 1, respectivamente (IMBRIE *et al.,* 1984; TOMAZELLI; VILLWOCK, 2000).

A Lagoa dos Patos é a feição morfológica de maior destaque da PCRS, abrangendo uma área de aproximadamente 10.000 Km^2, 40 Km de largura média, profundidade média de 6 metros e 240 Km de comprimento orientados na direção NE-SW (TOLDO Jr. *et al*., 2000). O relevo submerso da laguna pode ser dividido em 2 regiões: flanco lagunar (isóbatas ≤ 5m) e piso lagunar (isóbatas > 5m). Amostras sedimentares revelaram um tamanho de grão essencialmente arenoso nos flancos lagunares, enquanto o piso lagunar apresenta uma composição síltico-arenosa (TOLDO Jr., 1991).

A principal feição morfológica da Lagoa dos Patos são os pontais arenosos, que desenvolvem-se sob bancos submersos do flanco lagunar. Os esporões submersos foram formados por meio da dinâmica pretérita e atualmente são praticamente estáveis, sofrendo apenas erosão local (TOLDO Jr., 1991).

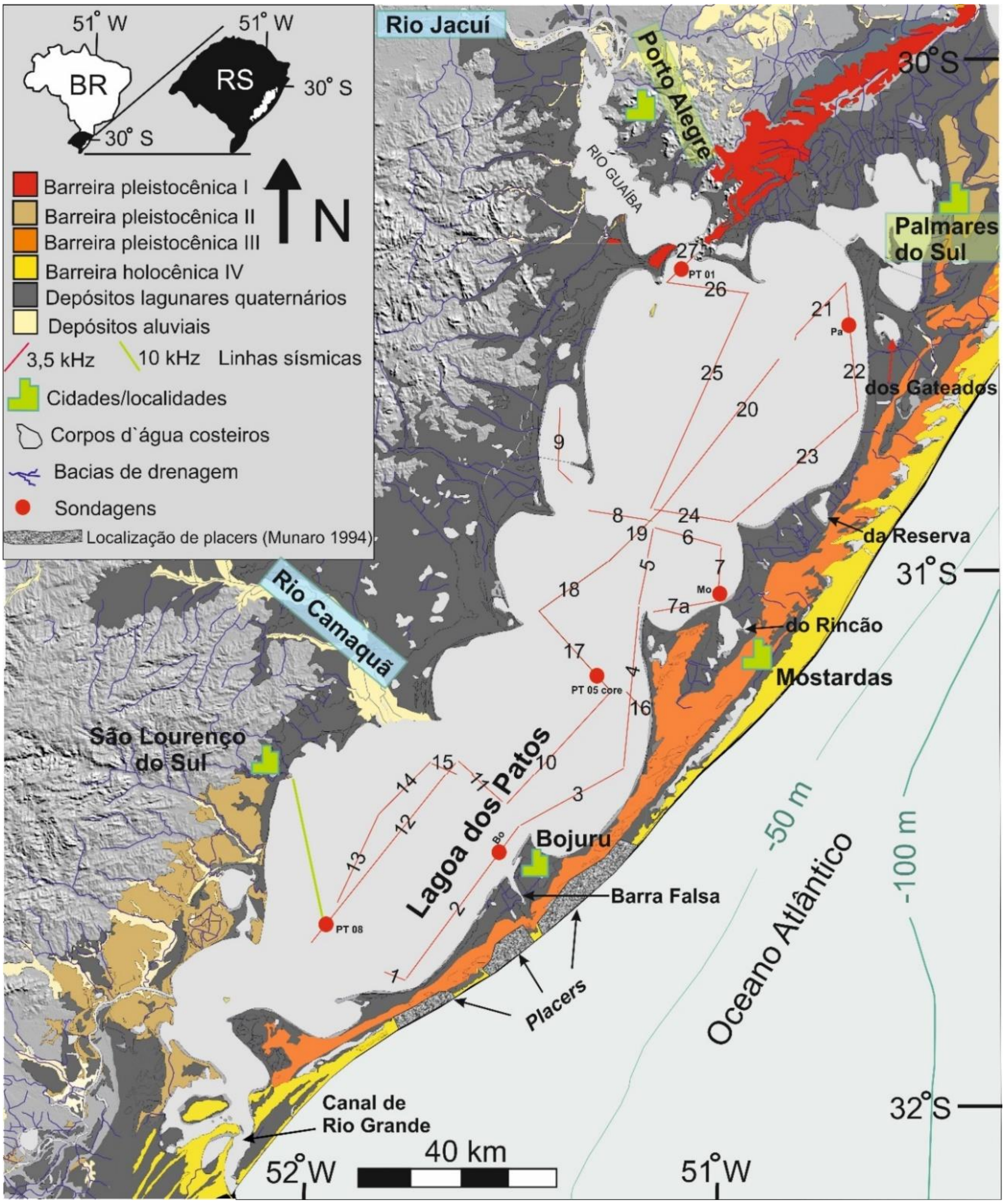

Figura 1: Geologia regional, destacando localização de furos de sondagem e perfis sísmicos.

A Lagoa dos Patos representa uma importante bacia sedimentar continental, cujo aporte de sedimentos é majoritariamente proveniente das bacias dos rios Jacuí e Camaquã. Os rios destas bacias de drenagem escavaram a PCRS durante eventos regressivos quaternários, formando um complexo de vales compostos dipostos lateralmente. Durante os eventos transgressivos estes paleovales eram parcialmente ou completamente preenchidos por sedimentos fluviais, estuarinos, lagunares e marinhos (GIBLING, 2006; WESCHENFELDER *et al*., 2014).

Estes paleovales foram reconhecidos por estudos sísmicos anteriores, que estabeleceram possíveis paleorotas para as paleodrenagens, assim como um modelo de preenchimento sedimentar preliminar para os paleovales (WESCHENFELDER *et al.,* 2008 a, 2008b, 2010, 2014).

Durante o último máximo glacial (18 ka AP), o nível do mar baixou cerca de 120 metros em relação a posição atual, expondo subaeriamente a atual plataforma continental do RS, formando vales incisos adjacentes, oriundos da erosão fluvial (IMBRIE *et al.*, 1984; CORRÊA, 1986; WESCHENFELDER *et al*., 2014). O subsequente evento transgressivo pós-glacial aconteceu em pulsos, associados aos pulsos de degelo, inundando progressivamente a zona costeira atual. Antigas linhas de costa formaram-se na plataforma continental submersa, associadas às estabilizações ocorridas entre os pulsos de degelo, progradando em direção ao continente (CORRÊA, 1986; GORNITZ, 2007; SMITH *et al*., 2011).

Na PCRS, o nível do mar provavelmente atingiu o nível atual cerca de 7,7 a 6,9 ka AP, atingido o nível máximo cerca de 5,6 ka AP (CORRÊA, 1986; ANGULO; LESSA; SOUZA, 2006; ROSA *et al*., 2017). Após o máximo transgressivo (5,6 ka AP) o nível do mar baixou (2-4 m) de maneira constante e lenta, causando progradação e estabilização da barreira arenosa holocênica, que se justapôs à barreira pleitocênica III (DILLENBURG; TOMAZELLI; BARBOZA, 2004; ANGULO; LESSA; SOUZA, 2006; LIMA *et al.*, 2013).

Paleovales incisos

Vales incisos são zonas topograficamente rebaixadas, escavadas por drenagens fluviais, erodindo depósitos mais antigos. Podem ser incisos por eventos de queda do nível eustático (mais documentado), movimentos tectônicos e mudanças climáticas. Estas depressões são facilmente alagadas e preenchidas durante transgressões marinhas. Paleovales incisos podem refletir de maneira condensada todo o arcabouço estratigráfico de uma zona costeira (FISK, 1944; POSAMENTIER; VAIL, 1988; POSAMENTIER; JERVEY; VAIL, 1988; VAN WAGONER *et al.*, 1990; ZAITLIN; DALRYMPLE; BOYD, 1994).

Paleovales incisos podem conter reservatórios significativos de hidrocarbonetos, logo a compreensão de sua formação, preenchimento e preservação é de grande interesse da indústria do petróleo. A evolução destes vales costeiros também serve como guia estratigráfico, indicando variações eustáticas, cuja importância é crescente uma vez que há uma preocupante tendência de elevação no nível eustático, devido ao aquecimento global. Paleovales afogados (estuários) abrigam uma significativa parcela da população mundial, também abrigam portos, berçários de fauna e pesqueiros.

Paleovales podem incidir em três distintos segmentos: embasamento cristalino, planície costeira e plataforma continental. Os principais fatores que controlam os processos sedimentares dentro de um vale inciso são: clima, tectônica e eustasia (alocíclicos). Estes fatores exercem distintas influências de acordo com o segmento do paleovale. Porções mais proximais à area fonte são mais subordinadas ao clima e movimentos isostáticos. Enquanto segmentos de planície costeira e plataforma continental são sistemas efêmeros, sujeitos às variações eustáticas (SHANLEY; MC CABE, 1994; CATUNEANU et *al*., 2011; BLUM *et al*., 2013) .

Os rios que drenam a superfície, erodindo o substrato e obedecendo à lei da gravidade fluem por áreas mais baixas preexistentes. As principais razões para a existência desta paleotopografia são: A- a erosão durante um episódio não-deposicional, que não foi preenchido durante a fase deposicional subsequente, provocando sua reocupação pela drenagem moderna e gerando os “vales compostos”; B- topografia gerada por depósitos sedimentares expostos pela queda do nível do mar; C- deformação tectônica ou deslocamento da superfície gerado por falhamentos (DALRYMPLE, 2006).

Uma enorme variabilidade de facies já foi identificada preenchendo vales incisos. Os segmentos continentais mais distais são predominantemente preenchidos por facies estuarinas durante transgressões eustáticas, principalmente quando há um pequeno aporte fluvial. Alguns vales podem até mesmo não ter sedimentos fluviais na sua base (preenchimento inteiramente estuarino e marinho), apesar de evidências indicarem que o vale foi erodido por rios. Em casos de grandes sistemas fluviais com aportes sedimentares expressivos, o vale pode ser inteiramente preenchido com aporte fluvial e deltaico, com facies estuarinas clássicas preenchendo o vale em espessuras pouco significativas (DALRYMPLE; BOYD; ZAITLIN, 1994; ZAITLIN; DALRYMPLE; BOYD, 1994; DALRYMPLE, 2006; BLUM *et al*., 2013).

Trabalhos pioneiros compreendiam estes sistemas como áreas de passagem direta de sedimentos (*bypass*) do continente para a zona de quebra da plataforma, sem reter aporte sedimentar nos paleovales durante regressões marinhas (POSAMENTIER; VAIL, 1988; DALRYMPLE; BOYD; ZAITLIN, 1994; ZAITLIN; DALRYMPLE; BOYD, 1994; DALRYMPLE, 2006). Entretanto, trabalhos mais modernos tem demonstrado que a maior parte do sedimento exportado não corresponde a períodos de incisão, contendo fases de fornecimento significativas durante períodos de reajuste lateral de canais (migração lateral) (BLUM; TÖRNQVIST, 2000; BLUM *et al.,* 2013).

Nível eustático durante o Quaternário

O clima sofreu forte controle astronômico durante o Quaternário, respondendo às variações periódicas nos ciclos de excentricidade (95 mil anos), obliquidade (40 mil anos) e precessão (21 mil anos) (MILANKOVITCH, 1920). Durante os últimos 150 mil anos, o nível do mar atingiu globalmente um nível máximo durante o estágio isotópico 5e (último interglacial) e outro momento de nível de mar alto cerca de 5-6 ka AP (IMBRIE *et al.,* 1984; SCHNACK; PIRAZZOLI, 1990).

Massivas calotas de gelo armazenam água em regiões polares do globo durante “eras glaciais”, rebaixando o nível do mar. Em contraponto, períodos de clima quente resultam em níveis de mar alto, devido ao derretimento das calotas polares. O nível do mar subiu 120 metros desde o último máximo glacial; desde o início do derretimento das calotas polares o nível eustático subiu rapidamente, com vários momentos de elevação ainda mais rápidos. Estes momentos de elevação súbita no nível eustático são denominados de pulsos de degelo (*Melt Water Pulses*) (PELTIER, 2002; GORNITZ, 2007; SMITH *et al.*, 2011).

Eventos globais, como glaciações e deglaciações foram responsáveis por mudanças significativas na fisiografia das planícies costeiras do mundo inteiro ao longo do Quaternário. Inúmeras evidências indicam que as respostas das planícies costeiras não ocorreram uniformemente aos eventos globais, respondendo a fatores locais e regionais. Nos entanto, essas respostas apresentam uma tendência global (SCHNACK; PIRAZZOLI, 1990).

A região que abrange desde o extremo sul do Brasil (Santa Catarina e Rio Grande do Sul) até a zona do “*Río de la Plata*” apresentou um comportamento semelhante no que se refere a nível do mar desde o último máximo glacial (ISLA, 1989; ANGULO; LESSA; SOUZA, 2006).

No sul do Brasil, Corrêa (1986) identificou 5 terraços marinhos distintos na plataforma continental do RS por meio de dados batimétricos, interpretados como antigas linhas de costa, evidências da transgressão pós-glacial. A partir do máximo glacial, o nível elevou-se da cota de -120 metros em relação ao atual até atingir o ápice (± 2 a 4 metros acima do atual) há aproximadamente 5-6 mil anos, quando começou a baixar de forma lenta e constante até atingir o nível atual (CORRÊA,1986; ANGULO; LESSA; SOUZA, 2006; GORNITZ, 2007; ROSA *et al*., 2017).

1.2 – OBJETIVOS

O principal objetivo desta tese é apresentar uma nova perspectiva a respeito da evolução da Lagoa dos Patos, considerando a influência de paleovales incisos. Para isso foi integrada uma gama de dados já publicados e inéditos. A morfologia dos paleovales foi analisada, assim como os principais fatores alogênicos e autogênicos influenciando no seu preenchimento.

A Planície Costeira do Rio Grande do Sul responde rapidamente às variações de nível eustático, que agem em escala regional e modulam vários processos autogênicos. Reconhecer a assembléia de facies formadas desde a formação dos paleovales incisos até o seu preenchimento é um dos objetivos específicos desta tese. Os possíveis paleoambientes também foram interpretados após a identificação das facies.

Outro objetivo específico deste trabalho é classificar as assembléias de facies em Tratos de Sistema, de acordo com a posição estratigráfica, obtendo um maior entendimento a respeito da sucessão de facies em resposta a variação do nível do mar.

Ao integrar perfis sísmicos ao mapa batimétrico da Lagoa dos Patos atingiu-se outro objetivo, de compreender o papel da plaeotopografia na distribuição de fácies desde os estágios iniciais de gênese dos vales até a sedimentação lagunar atual.

Por meio de datações realizadas pelo método carbono 14 também atingiu-se outro objetivo, o de comparar as taxas de sedimentação em porções mais profundas dos vales de maior espessura sedimentar com áreas mais rasas e de menor espessura.

Comparando a importância da paleotopografia com as variações eustáticas nas taxas de sedimentação.

Identificar as possíveis causas que forçaram os rios Camaquã e Jacuí a reorganizarem as rotas de suas paleodrenagens também é um objetivo específico deste trabalho.

1.3 – PREMISSAS

As planícies costeiras alteram significativamente sua paisagem de acordo com as variações eustáticas (SHANLEY; MCABE, 1994). Durante as regressões da linha de costa significativas áreas continentais são expostas subaeriamente e drenadas por sistemas fluviais (DALRYMPLE; BOYD; ZAITLIN, 1994; ZAITLIN; DALRYMPLE; BOYD, 1994; POSAMENTIER; VAIL, 1988).

As bacias de drenagem costeiras tipicamente formam vales incisos, que representam depressões topográficas propensas a inundação durante eventos transgressivos. A Planície Costeira do Rio Grande do Sul (PCRS) teve sua morfologia modelada pelas variações eustáticas Quaternárias (TOMAZELLI; VILLWOCK, 2000). Os Rios Jacuí e Camaquã escavaram seus vales perpendicularmente à linha de costa durante os períodos regressivos, sendo parcialmente preenchidos durante eventos transgressivos.

Vários paleovales dispostos em latitudes adjacentes foram reconhecidos no fundo da Lagoa dos Patos, formaram-se por consequência do abandono de bacias de drenagem antigas e ocupação de novas áreas de relevo deprimido ao longo do Quaternário. Estes paleovales foram drenados em períodos distintos (BAITELLI, 2012; WESCHENFELDER *et al.,* 2014). Cada bacia de drenagem formada durante um evento regressivo pode ser analisada como uma bacia de deposição durante eventos transgressivos.

Os principais fatores responsáveis pelo controle dos processos sedimentares (erosão e deposição) podem ser classificados em alogênicos e autogênicos. Fatores alogênicos são externos à unidade sedimentar, de abrangência regional, os principais controladores do espaço de acomodação e tipicamente registram: variações eustáticas, tectonismo e mudanças climáticas. Fatores autogênicos regulam processos de auto-organização dentro de um ambiente deposicional, determinando a arquitetura da sucessão de facies (CATUNEANU *et al.*, 2011). Os fatores autogênicos mais comuns em planícies costeiras são a paleotopografia e a variação de aporte sedimentar.

1.4 – HIPÓTESES

O espaço de acomodação da Lagoa dos Patos foi gerado em resposta às variações eustáticas, o que gerou padrões de empilhamento semelhantes organizados em Tratos de Sistemas, atuantes em escala regional. Variações faciológicas locais dentro de cada trato de sistema devem-se a fatores autogênicos como a paleotopografia e aporte sedimentar.

Paleovales reconhecidos no substrato da Lagoa dos Patos influenciam na configuração batimétrica lagunar atual e nos processos deposicionais atuais.

As reorganizações nas rotas de drenagem ocorridas durante o Trato de Sistemas Em Queda (FSST) e de Nível Baixo (LST) foram moduladas por forçantes autogênicas como paleotopografia, aporte sedimentar e fluxo d`água subterrânea.

1.5 – MÉTODOS

Aproximadamente 1.000 km de perfis sísmicos de alta resolução (3,5 e 10 kHz) foram coletados com objetivo de mapear o registro geológico preservado abaixo do fundo da Lagoa dos Patos (Fig. 1). Os registros sísmicos de 3,5 kHz foram coletados em 2002 e 2006 a bordo da Lancha Oceanográfica LARUS da Fundação Universidade do Rio Grande do Sul (FURG). Os perfis de 10 kHz foram coletados em 2015 a bordo da embarcação “Nave Mãe”.

Um perfilador de subsuperfície GeoAcoustics foi utilizado na aquisição dos dados sísmicos de 3,5 kHz. O perfilador possui sistema analógico e digital, que pode operar em um intervalo de frequência de 2 a 12 kHz. Esse sistema de aquisição é composto basicamente por transmissor (Geopulse 510 A), transdutor (Geopulse 132 B) de quatro elementos, impressora (EPC HSP 108), unidade de processamento (Geo Pro) e unidade digital com software de aquisição (SonarWiz) da *Chesapeake Technology Inc.* Os dados sísmicos de 10 kHz foram coletados e processados utilizando o equipamento *Stratabox* da empresa *SyQwest.* A velocidade média aplicada à onda acústica foi de 1.500 m/s para água e 1650 m/s para os sedimentos (JONES , 1999).

Após o mapeamento das principais superfícies reconhecidas, foram aplicados os conceitos de Mitchum (1977) para limitar as sequências deposicionais, definir as unidades sísmicas e descrever os parâmetros para individualização de fácies. O termo genérico descontinuidade é aplicado às superfícies que representam uma quebra na continuidade dos parâmetros físicos, seja por contraste na impedância acústica ou por mudança nas relações geométricas entre os estratos. O termo inconformidade é aplicado apenas aos limites de sequências, especialmente quando um hiato ou erosão é identificado.

O critério utilizado para individualizar unidades sísmicas é o mesmo usado para separar as sequências deposicionais em unidades estratigráficas (tratos de sistema), sendo: padrão de empilhamento (sucessão de estratos), posição dentro da sequência e tipos de superfície limítrofe (CATUNEANU *et al*., 2011). Portanto, unidades sísmicas podem ser associadas à tratos de sistema específicos.

As fácies sísmicas foram identificadas por meio de parâmetros sísmicos, tais como amplitude, frequência, continuidade dos refletores, configuração interna, geometria externa, independentemente da posição dentro da sequência deposicional. As fácies sísmicas foram usadas como ferramentas para identificação de paleoambientes, baseado em James e Dalrymple (1992). Assim, uma facie sísmica específica (paleoambiente) pode ocorrer em distintos tratos de sistemas.

Superfícies de impedância acústica foram detalhadamente analisadas, tomando-se o cuidado para desconsiderar reflexões múltiplas (EMERY; MYERS, 1996), as quais podem ser produzidas pela reflexão do fundo lagunar ou refletores anômalos devido à ocorrência de gás disseminado no pacote sedimentar. A continuidade de algumas superfícies sísmicas foi obliterada em alguns locais, causada por anomalias acústicas relacionadas a sedimentos com gás.

Dados sísmicos associados a mapas batimétricos auxiliaram na individualização entre a paleotopografia e a espessura dos depósitos sedimentares pós-glaciais. Assim, destacando a influência da paleotopografia na morfologia e na dinâmica holocênica lagunar. Causas para o reajuste lateral das rotas de drenagens também foram propostas, baseadas na espessura de depósitos sedimentares e diferenças na paleotopografia.

Uma calibração estratigráfica foi realizada por meio de furos de sondagem: três *Standard Penetration Test* (SPT), cujas profundidades ultrapassaram 20 metros e oito furos realizados por sondagem de gravidade, cujas profundidades médias foram de 3 metros. Conchas foram selecionadas para datações por radiocarbono (C^{14}), para fins de estabelecer a idade absoluta de algumas unidades deposicionais e estabelecer um arcabouço estratigráfico regional (tabela 1). As datações também possibilitaram estimar as taxas de sedimentação holocênicas.

Tabela 1: Compilação de datações realizadas pelo método C^{14}.

Sondagem/profundidade	Idades calibradas (anos AP)	Material	Amostra	Publicação
Bo (-8 m coluna d'água)				
Bo 12 (4 m)	7535 ± 105 (7640/7430)	concha	BETA 294867	Weschenfelder *et al.* 2014
Bo 15 (7 m)	7790 ± 140 (7930/7650)	concha	BETA359870	Santos-Fischer *et al.* 2016
Bo 19 (11 m)	7875 ± 115 (7990/7760)	concha	BETA 294868	Weschenfelder *et al.* 2014
Bo 20 (12 m)	8010 ± 140 (8150/7870)	concha	BETA 359871	Santos-Fischer *et al.* 2016
Mo (-7,3 m coluna d'água)				
Mo 8 (0,70 m)	7820 ± 140 (7960/7680)	concha	BETA 360370	Santos-Fischer *et al.* 2016
Mo 11 (3,7 m)	7865 ± 115 (7980/7750)	concha	BETA 298208	Weschenfelder *et al.* 2014
Mo 13 (5,7 m)	8040 ± 120 (8160/7920)	concha	BETA 294869	Weschenfelder *et al.* 2014
Pa (-6 m coluna d'água)				
Pa 21 (15 m)	> 43.500	concha	BETA 305998	Weschenfelder *et al.* 2014
Pa 23 (17 m)	> 43.500	concha	BETA 305999	Weschenfelder *et al.* 2014
Pa 26 (20 m)	> 43.500	concha	BETA 298209	Weschenfelder *et al.* 2014
PT-08 (-6 m coluna d'água)				
PT-08 (0,60 m)	4747 +- 98 (4845/4649)	concha	BETA 453296	Presente trabalho

Ao longo da monografia adotou-se a recomendação da IUPAS- *International Union of Pure and Applied Chemistry e IUGS – International Union of Geological Sciences*, expressando os valores em anos com a letra "a" como em ka e Ma. A sigla BP/AP (Before Present/Antes do Presente) é aplicada para idades obtidas por radiocarbono onde a precisão é estabelecida com relação ao ano de 1950.

CAPÍTULO 2 - INCISED VALLEY PALEOENVIRONMENTS INTERPRETED BY SEISMIC STRATIGRAPHIC APPROACH IN PATOS LAGOON, SOUTHERN BRAZIL

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Incised valley paleoenvironments interpreted by seismic stratigraphic approach in Patos Lagoon, Southern Brazil

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ABSTRACT

The Rio Grande do Sul coastal plain area (33.000 km^2) had its geography modified several times along Quaternary, responding to allogenic and autogenic forcings. The Patos Lagoon represent a significative area of RS coastal plain (10,000 km^2), where incised valleys were identified in previous works. About 1000 km of high resolution (3.5 kHz) seismic data, radiocarbon datings, SPT and gravity cores were analysed to the interpretation of the paleoenvironmental evolution along incised valleys infilling. Seismic facies were recognized by seismic parameters. The sedimentologic cores were used to attest the seismic interpretations and help in the paleoenvironmental identification. Key surfaces were established aiming to detail the stratigraphical framework, seismic facies were grouped in four seismic units, which were classified in respectives system tracts within three depositional sequences. The older preserved deposits are predominantly fluvial and estuarine facies, representing the falling stage and lowstand system tracts. The Holocene transgressive records are dominated by muddy material, mainly represented by estuarine facies with local variations. The transgression culminated in Late Holocene deposits of Patos Lagoon, representing highstand system tract. The stacking pattern of the vertical succession was controlled by eustatic variations, while the autogenic forcings (paleogeography and sediment supply) modulated the local facies variation.

Keywords: incised valley; seismic facie; Quaternary; system tracts.

1. INTRODUCTION

The response of coastal environments to sea-level variations has received much attention (Schumm 1993; Shanley and McCabe 1994; Blum and Törnqvist 2000). River incision across the subaerially exposed continental shelf was followed by drowning during transgression (Dalrymple et al. 1994, 2006; Blum et al. 2013).

The Patos Lagoon is the biggest barrier lagoon in the world (~10.000 km^2), with a single permanent tidal inlet at Rio Grande (Kjerfve 1994; Toldo Jr. et al. 2006). Initial studies using high-resolution seismic data investigated Late Quaternary paleo-environments in the Patos Lagoon (Weschenfelder et al. 2006, 2010a, 2014), whose results established a general and regional geological framework.

This study provides an individualization of seismic units, with a more detailed facies description, allowing the interpretation of system tracts and correlation with the sea level curve. The aim is to understand the palleovalley formation and subsequent evolution, and to investigate their role in postglacial evolution of the Patos Lagoon system.

1.1. Regional setting

Rio Grande do Sul State is located between 29º and 34º south (Fig. 1). It has a wide and low relief coastal plain (0,03º - 0,08º slope). During the Quaternary, transgressive-regressive cycles reworked alluvial fans and shelf sediments, creating four barrier/lagoon systems that are preserved on the coastal plain. These sandy barriers are named from oldest to youngest as Barriers I, II, III, and IV (Villwock et al. 1986); Barrier III is the youngest Pleistocene barrier, Marine Isotope Stage (MIS) 5 and it, together with the Holocene barrier (IV), encloses the contemporary Patos Lagoon.

The Patos Lagoon is oriented NE-SW. It is about 240 km long, with an average width of 40 km and the surface area is ~10,000 km^2 (Kjerfve 1986; Toldo Jr. et al. 2006). The single permanent connection with the ocean is the Rio Grande channel and the tidal range average in the lagoon is about 0.22 m (DHN, 2014). The lagoon receives freshwater of two main drainage basins: Jacuí/Guaíba Rivers in the north and Camaquã River in the south (Marques 2005). These rivers are the main sources of sediment into the lagoon. Several morphologic and hydrodynamic cells, partially separated by sandy spits, are present in the Patos Lagoon. The segmentation process, as proposed by Zenkovitch (1959), is believed to be incomplete because of currents associated with freshwater influx (Toldo Jr. 1991). The submerged relief of each cell comprises two sections: the margins (< 5 m water depth) are mainly sandy deposits, over which grow sandy spits in water depths of circa 1 meter depth; the central portion of the cells have an average depth about 6 meters and the deposits are mainly muddy sediments (Toldo Jr. 1991; Toldo Jr. et al. 2006).

Paleodrainage systems and related features were identified in the lagoon during a seismic reflection survey (Weschenfelder et al. 2010a), as well on the adjacent continental shelf (Abreu and Calliari 2005). The upper paleodrainage systems recognized formed during sea level fall of the Last Glacial Maximum (LGM) when the sea level was 120 m below the actual position. From 18,000 years BP, postglacial sea level rise caused paleovalleys drowning and infilling (Corrêa 1986; Weschenfelder et al. 2008a, 2008b, 2010a, 2014, 2016).

2. MATERIAL AND METHODS

About 1,000 km of high-resolution (3.5 kHz) seismic profiles was collected in the Patos Lagoon (Fig. 1), aboard the research vessel LARUS. Positioning was by DGPS. The data was acquired by a Geopulse sub bottom profiler, from GeoAcoustics™ and was processed in SonarWiz (Chesapeake Technology). Average velocities applied were 1,500 m/s for the water and 1,650 m/s for sediments (Jones, 1999).

The concepts established by Mitchum et al. (1977) were applied to limit the depositional sequence, to define the seismic units and to describe the parameters of each facies. Throughout this work, the generic term “discontinuity” is applied to the surfaces, which represent a break in the continuity of the physical character, either by contrast in acoustic impedance or the geometric relationship between strata. The term “unconformity” is applied to the sequence boundaries, specifically when a hiatus or erosion is identified.

The criteria used to differentiate seismic units are the same as those used to separate the depositional sequence in stratigraphic units (system tracts): stacking patterns (strata succession), position within the sequence, and types of bounding surface (Catuneanu et al. 2006, 2011). Therefore, in this work seismic units are relative to a specific system tract.

Seismic facies were identified by seismic parameters, such as amplitude, frequency, continuity of the reflections, internal configuration, external geometry, irrespective of position in the depositional sequence. Seismic facies were used as a tool to interpret the paleoenvironment based on James and Dalrymple (1992). Accordingly, a specific seismic facies (paleoenvironment) could occur in distinct system tracts (stratigraphic/seismic units).

Contrasting acoustic impedance surfaces were minutely described, care was taken to disregard multiples and also “bottom simulating reflectors” (Emery and Myers 1996), which can be produced in zones with gas in the sediment. The continuity of some seismic surfaces was obliterated by gas-related acoustic anomalies in some locations.

A stratigraphic calibration was carried out with sediment cores after the seismic interpretation. Three SPT boreholes (Standard Penetration Test), located exactly on the seismic profiles were analyzed. In addition, 8 gravity cores of 3 m average length were collected. Shells were selected for radiocarbon dating (C^{14}), to establish the age of some units and correlate them with the stratigraphic framework.

3. RESULTS

The acoustic signal penetrated about thirty meters of sediment, encompassing the upper sedimentary package underneath the Patos Lagoon bottom. Three depositional sequences were identified, limited by subaerial unconformities (SU and SU1). The lowest sequence (S1) reveal multiple events of incision and subsequent infilling of the valleys, occurred during Early/Mid Quaternary. The upper sequences (S2 and S3) reflect evolution from the peak of the Last Full Interglacial (LFI), isotope stage 5e (about 120 k.y. B.P.), to the present. The figure 2 synthesizes the stratigraphic framework.

3.1. Discontinuity Surfaces

The discontinuity surfaces represent a switch in strata stacking pattern, beyond which a new group of facies with distinct patterns of reflectors occurs. They are generated by contrasts in acoustic impedance or changes in the geometric relationship between the strata, which are perceivable regionally and allow the identification of seismic units.

The Subaerial Unconformity (SU) is the best defined in the Patos Lagoon records, it underlines the depositional sequence S2, or S3 in case of hiatus of S2. It is evidenced seismically by an irregular reflector, with high amplitude, continuous for tens of kilometers, underlying the incised valleys. It is marked by the truncation of older reflectors and its upper limit is characterized by the onlap/downlap of aggrading flooding reflectors. The cores that penetrated the SU surface (Mo core) show it as a stiff sandy substrate, likely formed under subaerial conditions, such as pedogenesis and fluvial process. The deepest SU segments are located at the central portions of the valleys, more specifically at the substrate of the fluvial channels. On the other hand, the shallowest portions are located on valley interfluves and are thinly covered by sediment.

The SU1 is a high amplitude, irregular reflector, continuous for tens of kilometers which occur on the top of U1 fluvial/estuarine deposits.

The Transgressive Surface (TS) marks the transition from the fluvial and early estuarine facies, to the Post-LGM transgressive facies. It is recorded as a high amplitude and continuous reflector, conformably overlying the fluvial/early estuarine facies or the subaerial unconformity. It appears juxtaposing the SU segments where the fluvial facies are not present.

The Maximum Flooding Surface (MFS) is distinguished by a continuous, high-amplitude reflector, conformably overlying the earlier deposits and is located about 50 cm depth. It represents the complete drowning of the interfluvial areas and the establishment of the geomorphological pattern of the modern Patos Lagoon.

3.2. Seismic Units

The sequences (S1, S2 and S3) were defined by Weschenfelder et al. (2014). In the current work each sequence will be individualized in seismic units which will be interpreted as a specific system tract, following the stratigraphic concepts proposed by Catuneanu et al. (2011). The seismic facies will be interpreted as a specific depositional environment (Figs. 2 to 6).

3.2.1. Unit 1 (U1)

Grouped in the Unit 1 are the early fluvial channel facies (A and B) and early estuarine facies (C). The Unit 1 is underlined by the SU surface, capped by the SU1 surface and is interpreted as the Falling-Stage System Tract (FSST).

There is no clear evidence of subaerial exposition on the top U1 records. However, a theoretical surface was determined as SU1 in the most probable position, because during the FSST the sea level was continuously falling and likely exposed such coastal areas.

3.2.2. Unit 2 (U2)

This unit is the record of the fluvial channel facies (facies A and B) formed during the LGM (Figs. 2, 3), such channels reached the lowest depths recognized in the Upper Sequence (> 25 m), in agreement with the lowest sea level position, around 120 m lower than the current level. It was reached by only one core (Fig. 3). The samples collected are fine to medium sands, with shell fragments.

The stacking patterns of this unit show the same characteristics as the fluvial facies of Unit 1, hence they are interpreted as the same seismic facies (A and B). However, despite having the same physical characteristics, they are in distinct positions in the sequence and therefore represent different system tracts.

Weschenfelder et al. (2006, 2016) associated gas accumulation with the lowest topographic portions of paleovalleys in Patos Lagoon. Therefore, the gas accumulation provides an indirect indication of the position of Unit 1 and 2 channels, especially if declining or chaotic reflectors and truncation of the S1 sequence deposits are associated with the gas signal.

3.2.3. Unit 3 (U3)

U3 exhibits mainly aggradational reflectors, secondarily progradational or mixed pattern, grouping estuarine (C), bay-head delta (D), inlet (E) and overspilling (F) facies. The base of U3 is marked by the TS and the top is delimited by the MFS surface; it therefore comprises the Transgressive System Tract (TST). The cross sectional geometry of this Unit is typical of U-shaped valley infilling (Gibling 2006) (Fig. 3), which has high width/depth ratios and increasing width oceanward. The valley widths are 35 km on average; the depths are variable, peculiar to each lagoon morphologic cell, but usually around 30 m.

3.2.4. Unit 4

Unit 4 caps all the previous deposits and is recognized in all seismic lines. Its basal limit is the MFS and the top is limited by the lagoon floor. One single facies (G) composes this Unit; it has an average thickness of 50 cm, hampering the visualization in the figures, therefore the MFS and Unit 4 are represented together. Facies G represents the deposits when all the interfluves were flooded and the current back-barrier lagoon was formed.

3.3. Seismic Facies

Seismic facies were identified by seismic parameters, such as amplitude, frequency, continuity of the reflections, internal configuration and external geometry. Sedimentologic samples were tied to seismic data. Besides the classic parameters, the presence of gas also can be used to suggest the presence of some paleoenvironments (Weschenfelder et al. 2016).

Facies A (Figs. 2, 5, 6) comprises a 6 m-thick package of confined channel infilling reflectors, whose cross-sectional shape is concave upward. The reflectors are semi-transparent, with low amplitude, low layering, inclined, low continuity and high frequency. Sometimes a switch of pattern is distinguishable around the middle portion of the fluvial sedimentary package. This change determines the beginning of Facies B (Figs. 2, 5, 6) in which high-amplitude reflectors of medium continuity and low frequency, onlap the subaerial unconformities surfaces. Facies A and B are interpreted as V-shaped fluvial incisions, located at the base of U-shaped incised valleys.

Facies A and B are recognized mainly by the external geometry of channel filling type and forming together a total package of 10 m thickness on average. The vertical accretion is symmetric, concentric and confined in a V-shaped fixed channel (Gibling 2006) with no lateral migration. The reflectors downdip toward the channels center and onlap the subaerial unconformity surfaces. One feature stands out in both facies: the reflectors have a geometric shift from concave upward to almost horizontal towards the top. This is particularly evident in Facies B. Two SPT cores (Bo and Pa; Figs. 2 and 5) reached these facies showing an almost homogeneous package, with alternation between fine and medium sands and no fossils available for dating.

Facies C (Figs. 2 to 6) consists of a homogeneous succession with aggradational sediments. It shows reflectors with external sheet forms, low amplitude (rare exceptions), high continuity (kilometrical scale), high frequency and with well-formed parallel layering. The layers are horizontal in the central portion of the valleys and tend to be inclined when onlaping the valleys axes, where they form a wedge shape.

Some reflectors of facies C show high amplitude and trap the gas accumulated in older deposits. Such trapping layers are interpreted as stiff muddy sediments and are mappable for long distances. The cores Mo and Pa reached this facies (Figs. 3 and 5), revealing a sucession of muddy layers. This facies is interpreted as estuarine sediments or deposits of evolving lagoons.

Facies D (Fig. 2 and 5) is a package in a mounded geometry, reaching more than 15 meters thick, comprising bidirectional and progradational reflectors. It is covered in a toplap by the MFS, that “touch” the contemporary bathymetry. An alternation between high and low amplitude reflectors is corroborated in cores, reflecting intercalated sandy and muddy layers, what offered a resistance to gravity core penetration. Northward the reflectors are more continuous and less inclined in comparison with the southward portion of the mound form (Fig. 5). The age of 4,747 +/- 98 cal yr BP was revealed to these deposits by radiocarbon dating carried out in sample shells at 0.60 meters depth. This is interpreted as a bayhead delta.

Facies E (Figs. 2, 3) occurs within the remaining inlet channels and presents mixed aggradational/progradational reflectors characterized by low amplitude, parallel to sub parallel, wavy, filling channel geometry, high frequency and high continuity. In the upper portion some scour created by reactivation of the channels are present. This facies is interpreted as an inlet infilling.

Facies F (Fig. 2, 3) shows a progradational/aggradational packing. It is typified by high-amplitude, low-frequency, medium continuity, oblique and the external geometry in bank. Facies F occurs next to a paleotopographic high, which is onlaped (from southwest to northeast) until the over-spilling, forming a bank geometry on the northeast side. Younger layers of facies C conformably overlie the bank, indicating that facies F was formed during an earlier stage of Holocene sea-level rise. This facies is interpreted as a sandy bank, generated by the sands eroded during the overspilling suffered by a topographic high.

Facies G (Figs. 2 to 6) represents the thin (0.5 m) layer of modern sediments, deposited since the interfluves were flooded and the current back-barrier lagoon was established. This facies is the single one of Unit 4, whose lower limit is the MFS and the upper limit is the lagoon floor. It is characterized by high amplitude reflectors, with lateral continuity, capping all the previous deposits. The cores Bo, Mo and Pa show it as a muddy layer on the top of the sequence.

4. DISCUSSION

Like other lagoons with non-migrating barriers (Benallack et al. 2016), the Patos Lagoon favors the preservation of the Late Pleistocene/Holocene geologic records, because the stable sandy coastal barriers minimize transgressive ravinement by ocean waves and tides. The microtidal range likewise limits tidal ravinement. Moreover, the majority of the deposits in the lagoon are transgressive mud, allowing a satisfactory acoustic signal penetration and facilitating gravity coring.

The subaerial unconformities (SU and SU1) are evidences of the subaerial exposure of the Rio Grande do Sul continental shelf. This surfaces can be interpreted as regional unconformities, because of its continuity through the adjacent morphologic cells of Patos Lagoon. They were generated during the Pleistocene glaciations, eroding the previous deposits, which were formed during the Last Full Interglacial (LFI), MIS 5e (Imbrie et al. 1984; Fig. 7).

These previous deposits probably were generated during a period of high sea level, likely are cohesive mud or cemented sandy barriers from paralic environments. This substrate can be very resistant to erosion, also can inhibit the lateral migration of early fluvial channels, generating the V-shaped channels (Facies A and B), which incised vertically (Gibling 2006).

The rivers lose transport competence during subtle relative sea level rises or stillstands occurred since MIS 5e (Fig. 7A), adjusting their equilibrium profile by depositing bedload. Rivers unable to migrate laterally have to adjust their equilibrium profile vertically, aggrading symmetric and concentric bedload layers, forming Facies A and B, which are recognized within the FSST and LST.

4.1. Falling-Stage System Tract (FSST)

Sea level fall started after the LFI, MIS 5e. The package of deposits accumulated from the onset of sea level fall until the LGM are grouped in the FSST. The Unit 1 is representative of this system tract and is composed of the following Facies: A, B and C. Weschenfelder et al. (2014) associated these deposits with the period between 120-18 ky BP and named them S2.

Paleochannels excavated the S1 during the early process of sea level fall, between MIS 5e and MIS 5d (Fig. 7). Subsequently, a gentle sea level rise occurred, forcing the rivers to accumulate bedload in their channels, Facies A and B of Unit 1. In topographically lower areas, the increase in water level formed early estuarine deposits, Facies C of U1.

Clear evidence of subaerial exposition was not recognized on the top of FSST deposits, therefore the surface (SU1) is marked by a dashed line in the most coherent position (Fig. 6), which is a high amplitude reflector likely indicating pedogenesis. However, FSST deposits were formed during the early stages of sea level fall, probably they were subaerially exposed several times, mainly during the most expressive regression (LGM). A hiatus of deposition is recorded on the top of these deposits, because the LST deposits were not recorded over FSST, probably because the river migrated to a new drainage line. This suggests that the FSST sediments were completely flooded again during the Holocene sea level rising, when they were covered by the TST deposits (Figs. 2, 3).

4.2. Lowstand System Tract (LST)

The LST includes the package of deposits accumulated after the LGM, during the onset of the Post-Glacial sea level rise. Unit 2 is representative of this system tract and is composed of Facies A and B.

According to Corrêa (1986) sea level was at -120/130 m during the LGM, explaining why the LST fluvial channels are deeper than the FSST fluvial channels. During the LGM, the Camaquã River would have promoted scouring of the new route northward, around the Bojuru region (Weschenfelder et al. 2010b, 2014).

4.3. Transgressive System Tract (TST)

The beginning of the TST is marked by the TS surface, over which a succession of aggradational/progradational layers accumulated. The Holocene flooding increased accommodation space vertically and laterally, with stepwise onlap of interfluves. The TST comprises the deposits of Unit 3, which are overlain by the MFS and includes Facies C, D, E and F.

The rates of muddy estuarine deposition were very high in some packages of the TST, reaching ~18 mm/year at some locations. This may be associated with periods of rapid sea level rise (Melt Water Pulses; Gornitz 2007; Smith et al. 2011) and are recorded in our data by C-14 dating (Figs. 2, 3).

Facies C in the TST represents a succession of layers deposited in a low energy environment, filling up the incised valley depressions. The sediment did not offer strong resistance to gravity coring and its geotechnical characteristic indicates that it is not consolidated. This facies is interpreted as estuarine deposits or from evolving lagoons.

Facies D represents a sucession of layers deposited in an environment with variable energy, attested by PT-08 core, which show alternation between clays, silts, sands and gravel. This facies is interpreted as a bay-head delta, because of the external geometry of the facies in mound form, the internal configuration in bidirectional progradational clinoforms, alternation between coarse and thin sediments, indicating as consequence of pulses of increased river discharge.

It is common the existence of bay-head deltas in the landward portion of wave dominated estuaries (Dalrymple et al. 1992; Zaitlin et al. 1994). The most probable streams to develop this deposit were Contagem, Corrientes and Turuçu, southward from Camaquã River (Manzolli 2016). Based on radiocarbon dating, the top (last 0.60 m) was deposited around 4,747 +/- 98 cal yr BP, elucidating that these facies finished its sedimentation during the end of the transgressive system tract.

Facies E can be interpreted as an infilled inlet, because of the external geometry in channel fill type, wavy reflectors (suggesting wave influenced environment), which are organized in an aggradational/progradational stacking pattern with recurrent erosional scouring during Holocene. Santos-Fischer et al. (2016) analyzed diatom assemblages, selected from samples of the SPT boreholes performed in paleochannel locations, concluding that these facies were strongly influenced by marine conditions during the Holocene. These inlet channels remained active in depressions coinciding with former rivers, where the fluvial incision was more prominent (FitzGerald et al*.* 2012), likely the paleo-courses of rivers during the LGM (Weschenfelder et al. 2010b; 2014).

The Holocene coastal barrier was developing ~2 Km seaward of its present position during the Late Holocene in the Bojuru region, creating an interbarrier paleolagoon, between Pleistocene and Holocene coastal barriers (Dillenburg et al. 2004). In this area, Facies E is likely related to a former connection between the Patos Lagoon, the interbarrier lagoon and the ocean. There is a similar example of interbarrier lagoons currently connected each other and with the ocean in Wilderness coastline, South Africa (Cawthra et al. 2014). Coastal ponds or marshy swales can be indicative of relict inlets (FitzGerald et al. 2012); such affirmation resembles the Barra Falsa feature in the Bojuru locality (Toldo Jr. et al. 1991; Weschenfelder et al. 2014).

Facies F is interpreted as an episodic overspilling of an interfluve. The direction of the overspilling process is consistent with winter wind directions, when the strongest storms are expected from the SW (Toldo Jr. et al. 2006b). Two paleodepressions were joined after the overspilling of the gentle interfluve (Fig. 3), forming a remarkable reflector of high continuity and moderate amplitude. This represents a rapid flooding of a large area, elucidating how single events can change dramatically the geography of an area.

4.4. Highstand System Tract (HST)

The MFS marks the onset of the HST deposits, which are classified as Unit 4. These deposits started to accumulate after the flooding of the interfluves, unifying the adjacent incised valley systems and creating a back-barrier lagoon with morphology similar to the current Patos Lagoon configuration. These deposits began to accumulate after the maximum sea level (+5 m), around 5 ky BP (Corrêa 1986; Dillenburg et al*.* 2004; Angulo et al. 2006), during a period of stabilization of the Holocene coastal barrier.

The Holocene coastal barrier stabilized since the onset of a gentle sea level fall, following the Holocene maximum sea level (Corrêa 1986; Dillenburg et al. 2004; Angulo et al. 2006). During this period the Unit 4 (Back-barrier deposits) accumulated in conditions of low energy. In addition, freshwater input starts to be more influential in the salinity, as recorded by the diatom assemblages (Santos-Fischer et al. 2016).

5. CONCLUSION

The incised valleys infilling did not occurr only during the sea level rising periods, it also happened during the falling of sea level (FSST). However, during the sea level risings the accommodation space created was more representative.

The vertical variability of facies was due the sea level oscillations, while the lateral variability was due autogenic forcing factors.

The occurrence of a type of seismic facies is not limited to a specific system tract, however it represents the sea level trend. Facies A and B occur in sea level fallings and lowstands, when rivers drained the exposed coastal plain. Facies C were deposited during pulses of sea level rise, when the river channels were flooded. Facies D, E and F were recorded during flooding events. Facies G was deposited since the maximum flooding was reached.

The fluvial systems active during Last Glacial Maximum are deeper than the fluvial channels of FSST, because the sea level reached the lowest levels.

The V-shaped geometry of facies A and B was due the stiff substrate, constituted of cohesive mud or pedogeinised sandy barriers, deposited during previous highstands. The confined pattern of facies A and B made impossible the lateral adjustment of rivers, which were forced to adjust their equilibrium profile by vertical accretion, accumulating bedload by lose of transport competence.

The Pleistocene drainage basins became continental depositional basins; which the main infilling deposits are transgressive muds of estuarine paleoenvironment.

The accommodation space increased both vertically and laterally with the flooding of continental areas.

The Patos Lagoon reached its current configuration after the flooding of the adjacent incised valleys.

6. ACKNOWLEDGMENTS

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Figure captions:

Fig.1 - Regional setting with geological mapping, seismic profiles and core locations.

Fig. 2 – Stratigraphical framework, with system tracts and seismic facies interpretations.

Fig. 3 – Seismic line 2 with the seismic facies identified, tied to Bo core and system tracts individualization (Bo core and seismic line 2 are modified from Weschenfelder *et al.*, 2014).

Fig. 4 – Seismic line 7 with the seismic facies identified, tied to Mo core and system tracts individualization (Mo core and seismic line 7 are modified from Weschenfelder *et al.*, 2014).

Fig. 5 – Seismic line 12 with the seismic facies identified, tied to PT-08 core and system tracts individualization.

Fig. 6 – Seismic line 22 with the identified seismic facies, tied to Pa core and system tracts individualization. (Pa core and seismic line 22 are modified from Weschenfelder *et al.*, 2014).

Fig. 7 – A: sea level curve and system tracts classification since MIS 5e; B: Detailed sea level curve for the area and sorroundings, since LGM.

Fig. 1

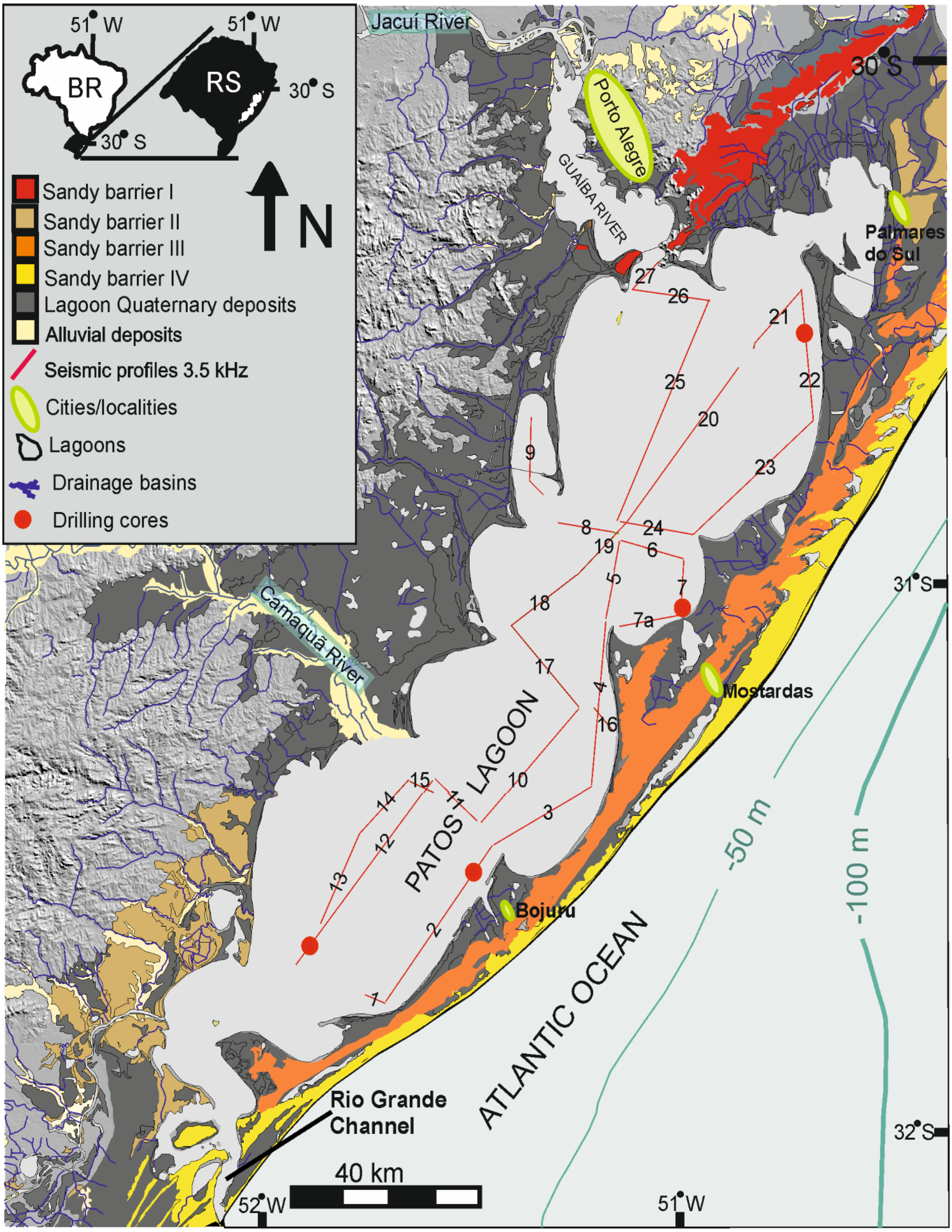

51° W
51° W
BR
RS
30° S
30° S
Sandy barrier I
Sandy barrier II
Sandy barrier III
Sandy barrier IV
Lagoon Quaternary deposits
Alluvial deposits
Seismic profiles 3.5 kHz
Cities/localities
Lagoons
Drainage basins
Drilling cores
N
Jacuí River
Porto Alegre
GUAÍBA RIVER
30° S
Palmares do Sul
Camaquã River
Mostardas
31° S
PATOS LAGOON
Bojuru
ATLANTIC OCEAN
-50 m
-100 m
Rio Grande Channel
40 km
52° W
51° W
32° S

Fig. 2

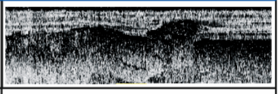
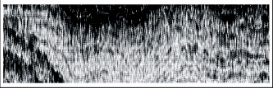
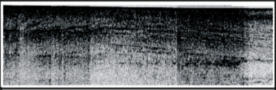
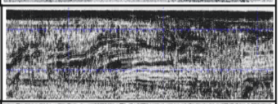
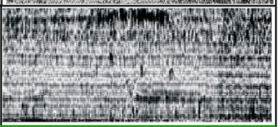
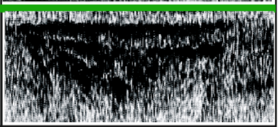
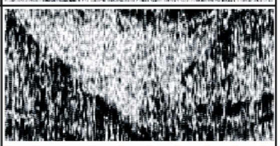
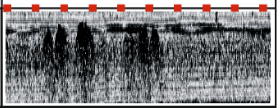
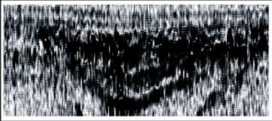
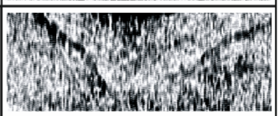
Unit	System tract	Seismic facies	Sediment and thickness	Depositional environment	Main diagnostic criteria	Seismic image
S3	HST U4	G	Mud/ 0,7 m	Back- barrier lagoon	High lateral continuity; high amplitude reflectors capping the MFS;	
	MFS TST U3	F	Sand ? +- 4m	Overspilling	High amplitude reflectors; bank external geometry; near to paleointerfluve;	
		E	Mud and sand +- 12m	Inlets	Infilling geometry; aggradational/progradational wavy reflectors;	
		D	Mud and sand alternation +- 12m	Bay-head delta	Mounded geometry; progradational and bidi-rectional reflectors;	
		C1	Sand +- 6m	Estuary mouth-bar	Progradational reflectors deposited over estuarine deposits (facies C).	
		C	Mud/ +- 10m	Estuarine	Homogeneous sucession of aggradational reflectors; sheet external geoemtry;	
	TS LST U2	B	Sand/ +- 5m	Fluvial	Channel infilling geometry; high amplitude reflectors; symmetrical and concentric infilling, tending to horizontality;	
		A	Sand/ +- 5m	Fluvial	Channel infilling geometry; low amplitude reflectors; symmetrical and concentric infilling;	
S2	SU1 FSST U1	C	Mud/ +- 10m	Estuarine	Homogeneous sucession of aggradational reflectors; sheet external geoemtry;	
		B	Sand/ +- 5 m	Fluvial	Channel infilling geometry; high amplitude reflectors; symmetrical and concentric infilling, tending to horizontality;	
		A	Sand/ +- 5m	Fluvial	Channel infilling geometry; low amplitude reflectors; symmetrical and concentric infilling;	
SU	**S1**					

Fig. 3

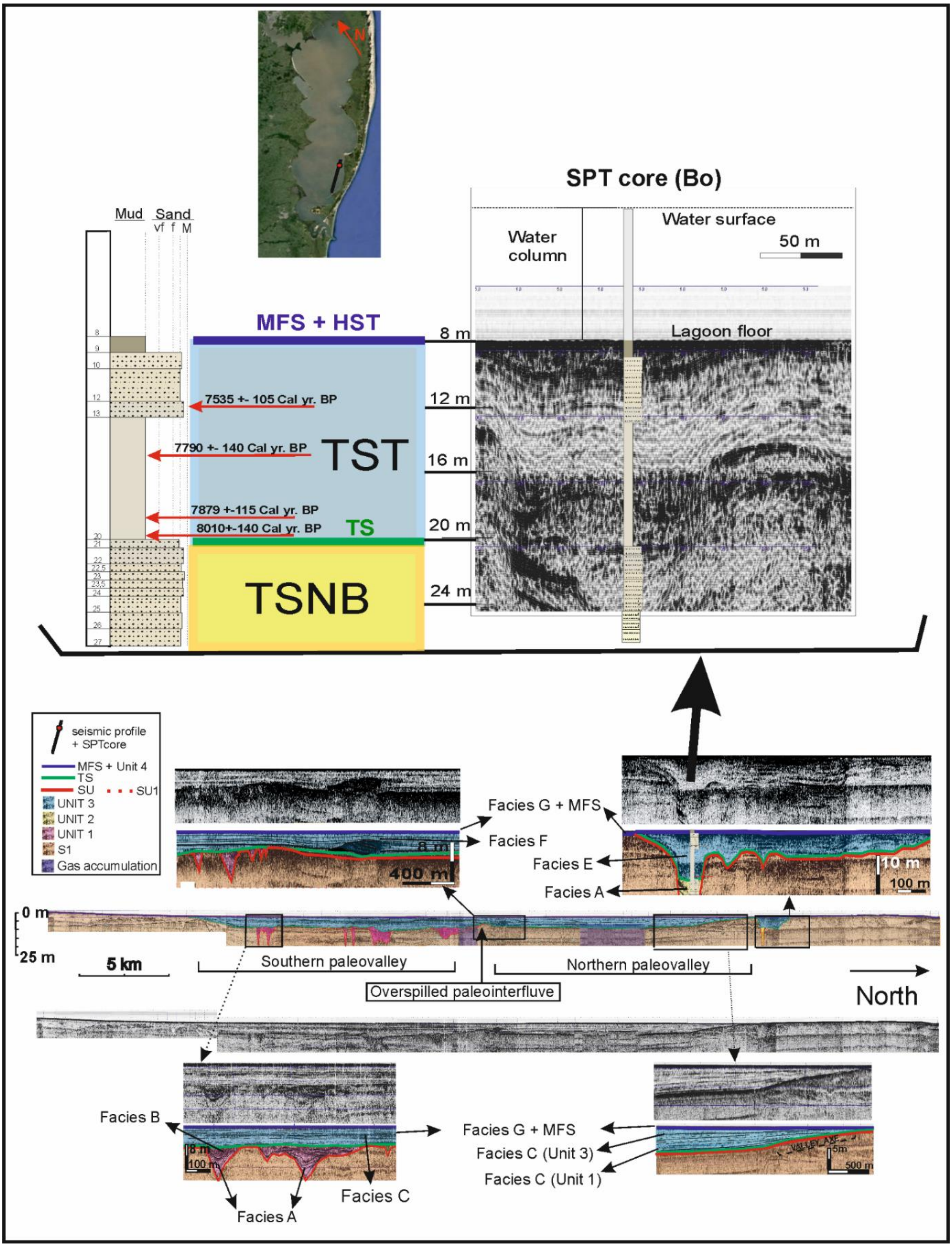
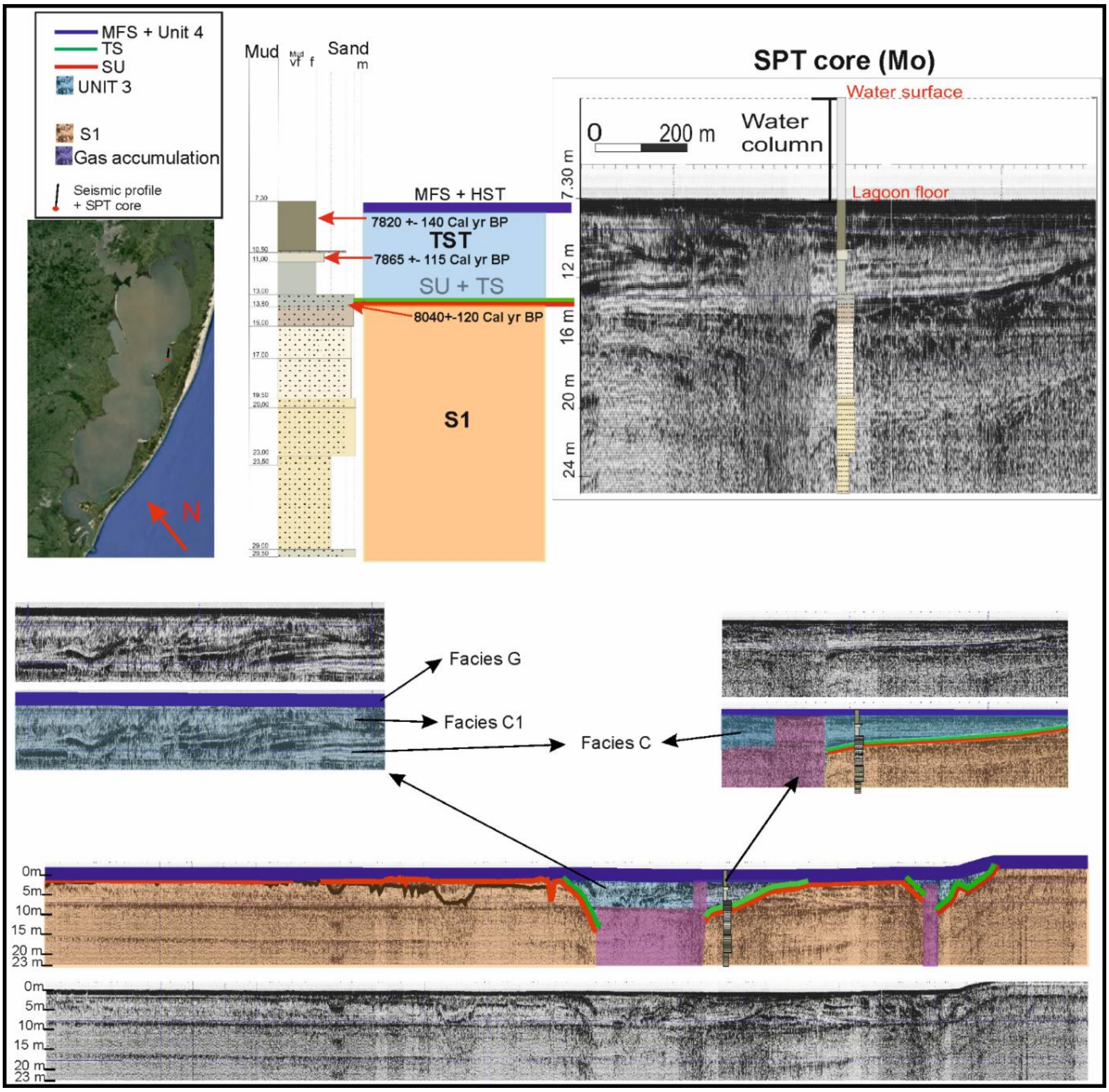

N
SPT core (Bo)
Mud
Sand
vf f M
Water surface
Water column
50 m
MFS + HST
8 m
Lagoon floor
7535 +- 105 Cal yr. BP
12 m
7790 +- 140 Cal yr. BP
TST
16 m
7879 +-115 Cal yr. BP
8010+-140 Cal yr. BP
TS
20 m
TSNB
24 m
seismic profile + SPTcore
MFS + Unit 4
TS
SU
SU1
UNIT 3
UNIT 2
UNIT 1
S1
Gas accumulation
8 m
400 m
Facies G + MFS
Facies F
Facies E
Facies A
10 m
100 m
0 m
25 m
5 km
Southern paleovalley
Northern paleovalley
Overspilled paleointerfluve
North
Facies B
8 m
100 m
Facies C
Facies A
Facies G + MFS
Facies C (Unit 3)
Facies C (Unit 1)
500 m

Fig. 4



MFS + Unit 4
TS
SU
UNIT 3
S1
Gas accumulation
Seismic profile
+ SPT core
N
Mud
Sand
MFS + HST
7820 +- 140 Cal yr BP
TST
7865 +- 115 Cal yr BP
SU + TS
8040+-120 Cal yr BP
S1
SPT core (Mo)
Water surface
0
200 m
Water
column
Lagoon floor
7.30 m
12 m
16 m
20 m
24 m
Facies G
Facies C1
Facies C
0m
5m
10m
15 m
20 m
23 m

Fig. 5

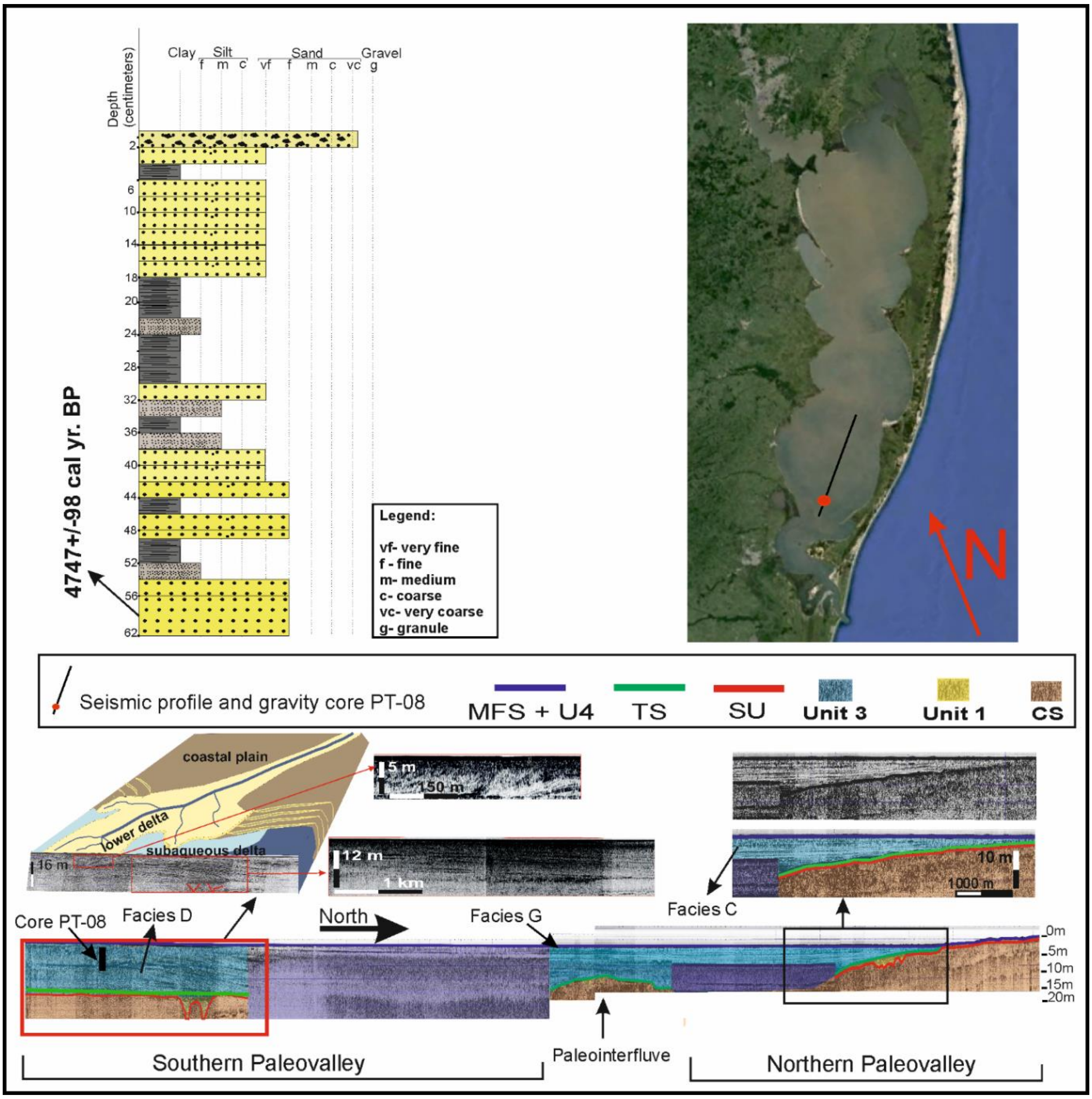

Depth (centimeters)
Clay
Silt
f m c
Sand
vf f m c vc
Gravel
g
4747+/-98 cal yr. BP
Legend:
vf- very fine
f - fine
m- medium
c- coarse
vc- very coarse
g- granule
N
Seismic profile and gravity core PT-08
MFS + U4
TS
SU
Unit 3
Unit 1
CS
coastal plain
lower delta
subaqueous delta
16 m
5 m
150 m
12 m
1 km
10 m
1000 m
Core PT-08
Facies D
North
Facies G
Facies C
0m
5m
10m
15m
20m
Paleointerfluve
Southern Paleovalley
Northern Paleovalley

Fig. 6

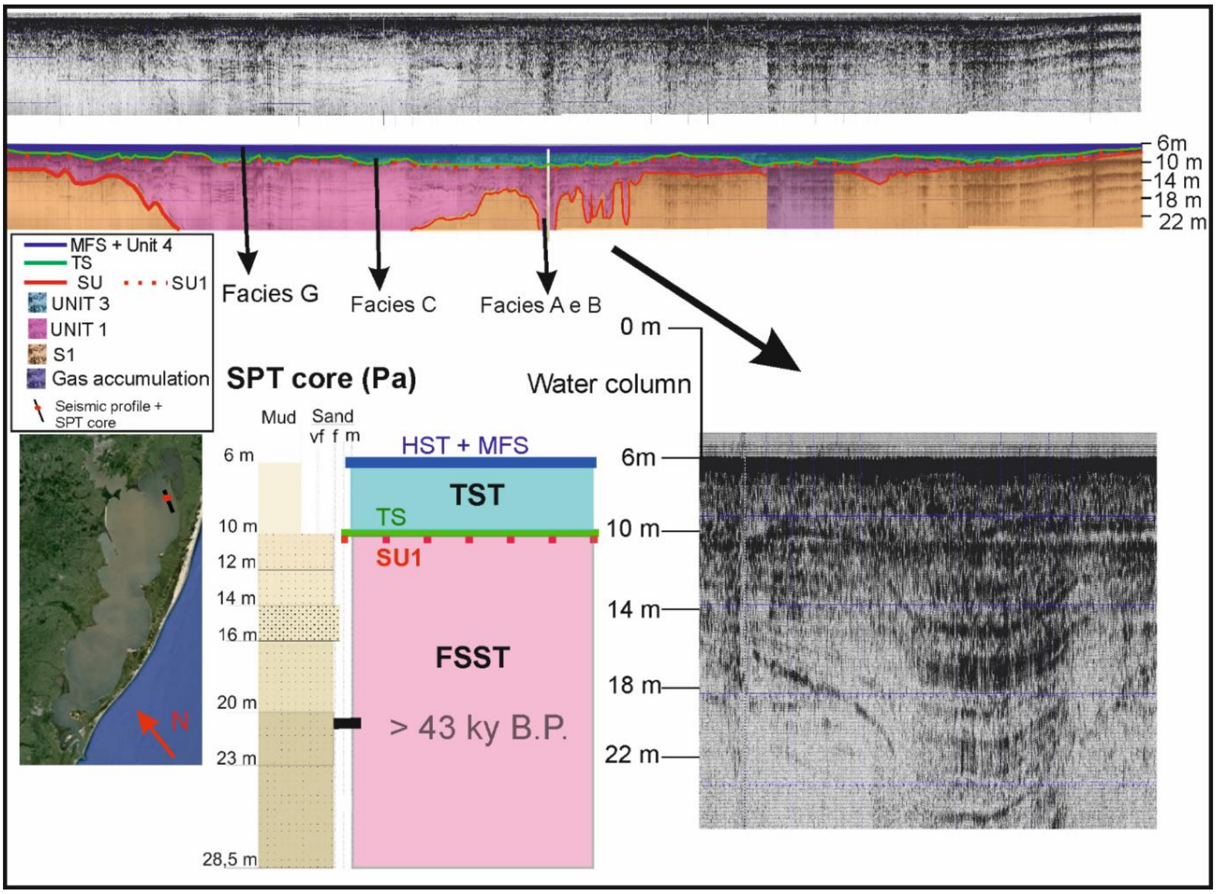
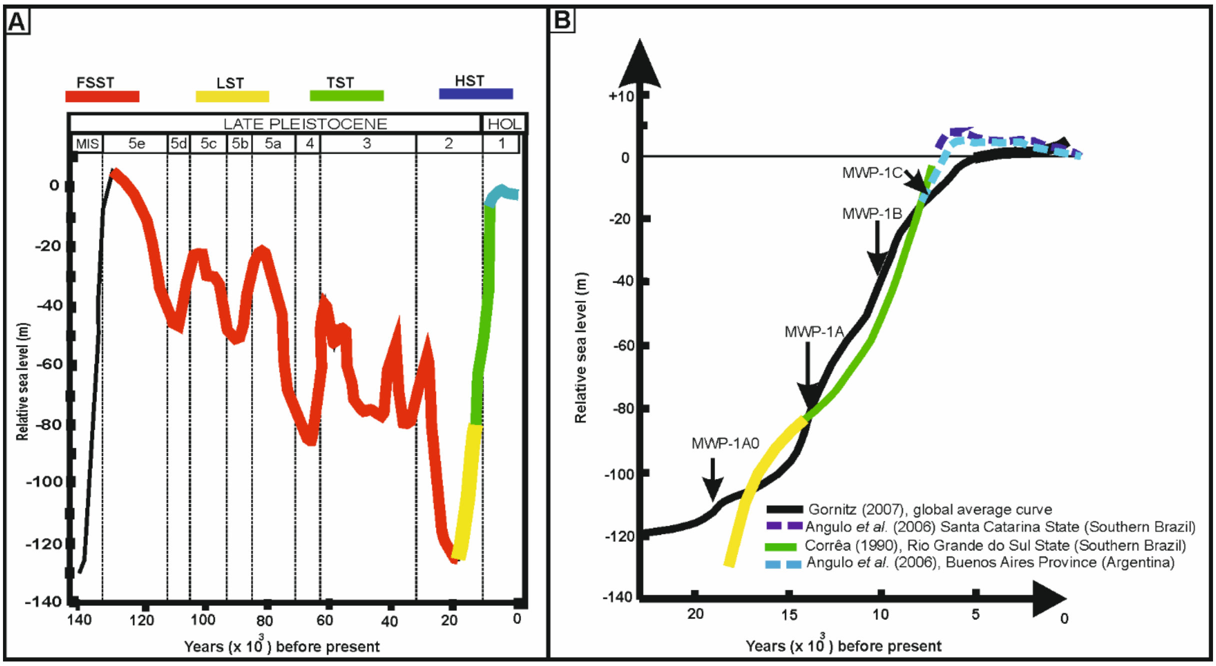

6m
10 m
14 m
18 m
22 m
MFS + Unit 4
TS
SU
SU1
UNIT 3
UNIT 1
S1
Gas accumulation
Seismic profile + SPT core
Facies G
Facies C
Facies A e B
0 m
SPT core (Pa)
Water column
Mud
Sand
vf f m
HST + MFS
TST
TS
SU1
FSST
> 43 ky B.P.
6 m
10 m
12 m
14 m
16 m
20 m
23 m
28,5 m
N

Fig. 7


A
FSST
LST
TST
HST
LATE PLEISTOCENE
HOL
MIS
5e
5d
5c
5b
5a
4
3
2
1
Relative sea level (m)
Years (x 10³) before present
B
MWP-1C
MWP-1B
MWP-1A
MWP-1A0
Gornitz (2007), global average curve
Angulo et al. (2006) Santa Catarina State (Southern Brazil)
Corrêa (1990), Rio Grande do Sul State (Southern Brazil)
Angulo et al. (2006), Buenos Aires Province (Argentina)
Relative sea level (m)
Years (x 10³) before present

CAPÍTULO 3 - HOLOCENE EVOLUTION OF PATOS LAGOON, BRAZIL: THE ROLE OF ANTECEDENT TOPOGRAPHY

Gmail **Eduardo Bortolin <edubortolin@gmail.com>**

Submission Confirmation for HOLOCENE EVOLUTION OF PATOS LAGOON, BRAZIL: THE ROLE OF ANTECEDENT TOPOGRAPHY

1 mensagem

The Journal of Coastal Research <em@editorialmanager.com> 11 de novembro de 2017 13:08
Responder a: The Journal of Coastal Research <cfinkl@cerf-jcr.com>
Para: Eduardo Bortolin <edubortolin@gmail.com>

Dear Mr. Bortolin,

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

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Journal of Coastal Research

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HOLOCENE EVOLUTION OF PATOS LAGOON, BRAZIL: THE ROLE OF ANTECEDENT TOPOGRAPHY

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LRH: Bortolin, Weschenfelder, and Cooper

RRH: Antecedent topography control in lagoon evolution

ABSTRACT

The Patos Lagoon in Rio Grande do Sul, Brazil, is part of the largest barrier lagoon system in the world. It is enclosed by a 400 km-long composite Late Pleistocene/Holocene sandy barrier and has a single tidal inlet. The modern lagoon is shallow (average <5 m) and is dominated by silt deposition. Over 1000 line kilometres of shallow seismic data (3.5 kHz) indicate that the lagoon is underlain by several shore-normal incised valleys separated by interfluves. Each incised valley existed as an individual estuary since their first flooding during the mid Holocene. The infill of these valleys contains a basal fluvial unit, a central estuarine mud unit and locally developed tidal sand bodies associated with former tidal inlets. The contemporary lagoonal sediments form a blanketing upper unit. Ultimately the interfluves were drowned and the contemporary lagoon was formed by the coalescence of the incised valley estuarine systems in the late Holocene. This expansion of accommodation space coincided with a dramatic reduction in vertical sedimentation rates. Seismic profiling reveals the contemporary sandy spits and their subaqueous extensions coincide with the location of former interfluves, indicating that inherited topography exerts a major control on the location and development of lagoon-marginal spits.

ADDITIONAL INDEX WORDS: *Paleotopography; paleovalleys; coastal plain.*

INTRODUCTION

The depositional sequence framework of Patos Lagoon sub-bottom is influenced by the interplay of allogenic and autogenic forcing factors. Allogenic controls (eustatic fluctuations, tectonism and climate changes) are external to the sedimentary basin and are the major influence in the generation of accommodation space (Blum and Törnqvist, 2000; Catuneanu, 2006; Catuneanu *et al*., 2011; Dalrymple, 2006; Dalrymple, Boyd, and Zaitlin, 1994; Posamentier and Vail, 1988; Shanley and McCabe, 1994). Autogenic factors contribute to local forcing in the depositional sequence. They are modulated by the influence of inherited topography and variations of sediment input, which may differ in each sector of the depositional basin and thus control the facies distribution along strike within the depositional system (Catuneanu *et al*., 2011).

Sea level oscillation is the main allogenic control acting in the Rio Grande do Sul (RS), Southern Brazil coastal plain (Tomazelli and Villwock, 2000). The RS coastal plain has been sub-aerially exposed and dissected by drainage systems since the Last Interglacial Maximum (LIM) around 120 ky BP. Responses of the RS coastal depositional systems to sea level changes have been studied by several researchers using various approaches (Corrêa, 1986, 1996; Dillenburg, Tomazelli, and Barboza, 2004; Toldo Jr. *et al.*, 2006; Tomazelli and Villwock, 2000; Weschenfelder *et al*., 2014). The Patos Lagoon which dominates the RS coastal plain is 240 km long and 50 km wide. It formed through flooding of a complex of adjacent incised valleys, during the postglacial marine transgression (Weschenfelder *et al*., 2014). Each morphological cell of the Patos Lagoon can be interpreted as a flooded paleovalley and consequently should be analysed as a discreet basin responding to the respective local forcing factors.

The autogenic forcing factors act locally to influence sedimentation in response to sea level changes. The paleotopography can be considered the main autogenic forcing factor regulating the Patos Lagoon evolutional and depositional processes. The accumulation thickness of the sediment can be considered a secondary autogenic control. This study aims to investigate the relationship between incised paleovalley systems and the Holocene to contemporary deposition in Patos Lagoon, as the lagoon evolved during both the infilling and later filled phase of the incised valley evolution. It furthermore investigates how drainage systems can influence the generation of accommodation space and back-barrier sedimentation.

Physical setting

The Rio Grande do Sul (RS) State (Southern Brazil) contains an extensive coastal plain (Figure 1), encompassing around 33,000 km^2, which developed during major sea level fluctuations of the Quaternary (Angulo, Lessa and Souza, 2006; Corrêa, 1986, 1996; Dillenburg, Tomazelli, and Barboza, 2004; Tomazelli and Villwock, 2000). Four lagoon-barrier depositional systems have been recognized in the RS coastal plain (Tomazelli and Villwock, 2000). Four Quaternary barriers (Barrier I, II, III and IV from oldest to youngest) have been correlated with Pleistocene and Holocene highstands (Tomazelli and Villwock, 2000). The contemporary Patos Lagoon is enclosed by a Late Pleistocene and Holocene barrier complex (Barriers III and IV) at the modern coast. The RS continental shelf average width is 125 km, with a gentle gradient (1.3 - 1.4 m/km) (Tomazelli and Villwock, 2000).

Incised paleochannels have been reported in several studies of the RS coastal zone (Baitelli, 2012; Weschenfelder *et al*., 2008 a, b, 2010, 2014, 2016). They include multiple valleys systems incised during forced regressions (Weschenfelder *et al*., 2014). These Pleistocene deposits were excavated during sea level fall from isotope stage 5e (about 120 ky BP), generating younger valleys that have since been infilled. The last main regressive-transgressive event recorded in the RS coastal plain began in the Late Pleistocene, reaching the maximum regression during the Last Glacial Maximum (LGM) around 18 ky BP (Corrêa, 1986, 1996; Angulo, Lessa and Souza, 2006; Weschenfelder *et al*., 2014).

The subsequent transgression happened in pulses; sandy terraces recorded on the RS continental shelf were interpreted as stabilizations of paleocoastlines, generated during still- or slowstands of sea level (Angulo, Lessa and Souza, 2006; Corrêa, 1986; Smith *et al*., 2011), separated by pulses of fast sea level rise (Cooper *et al*., 2016). The maximum of Post-LGM transgression (SL = + 2-3 m) occurred around 5.1 ky BP in the RS coastal plain, flooding large continental areas and developing the extensive sandy barrier IV (Angulo, Lessa and Souza, 2006; Corrêa, 1986; Smith *et al*., 2011).

The coastal barrier is 5 to 25 km wide and over 10 m in elevation. Currently, there is only one permanent connection between the Patos Lagoon and the Ocean, the Rio Grande channel. This reduces even the effects of the microtidal open ocean tidal oscillation (< 0.45 m) (Tomazelli and Villwock, 2000).

The Patos Lagoon is the dominant geomorphological feature of the RS coastal plain, covering an area around 10,000 km^2. It is 240 km long with an average width of 40 km and average depth around 6 m and its long axis is oriented coast-parallel (NE-SW) (Toldo Jr. *et al*., 2006). The lagoon is partially segmented by marginal sandy spits and can be divided into several morphological cells. According to Toldo Jr. (1991), these spits are Holocene features developed on stable banks.

Stabilization of the barrier took place in the Late Holocene, after the maximum flooding (Dillenburg, Tomazelli, and Barboza, 2004; Lima *et al*. 2013). Toldo Jr. *et al*. (2006) estimated that Holocene sedimentation in the Patos Lagoon basin began around 8 ky BP. Santos-Fischer *et al*. (2016) analyzed diatom assemblages for the Late Pleistocene/Holocene in Patos Lagoon, reporting that two freshwater taxa (*Aulacoseira veraluciae* and *Aulacoseira sp.2*) that were absent since the LGM, returned ages of around 2.4 ky BP.

METHODS

The paleotopography and sediment thicknesses in Patos Lagoon were estimated using about 1,000 km of 3.5 kHz seismic profiles (Figure 1). Data were acquired aboard the research vessel LARUS of FURG (Universidade Federal do Rio Grande). Positioning was by DGPS. The data were acquired by a Geopulse sub bottom profiling system from GeoAcousticsTM and were processed using the SonarWizTM software (Chesapeake Technology). The acoustic wave velocities in water and sediment were assumed to be 1,500 m/s in water and 1,650 m/s respectively (Jones, 1999). A chronologic and stratigraphic calibration was established by coring by Standard Penetration Test (SPT), gravity cores and C-14 dating carried out in sample shells. The granulometry of core material was assessed by sieving and this assisted in interpretation of seismic facies.

The individualization of Pleistocene/Holocene deposits and stratigraphic sequences was based on Weschenfelder *et al.* (2014). The paleoenvironments were interpreted based on the architectural elements of each seismic facies and by the diatoms assemblage reported by Santos-Fischer *et al.* (2016).

RESULTS

Although the modern lagoon is a shallow (<6 m deep) system with surface sediment dominated by muddy sediments (Toldo Jr *et al.*, 2000), seismic profiles reveal it to be underlain by a markedly variable and high relief paleotopography. This comprises shore-normal incised valleys separated by topographic highs (former interfluves) (Figures 2, 6). Interfluves and incised valleys have been blanketed by transgressive sediments to varying degrees. The position of the former interfluves accords with contemporary sandy spits that extend into the lagoon. Incised valleys are up to 30 m deep and 40 km wide. The former interfluves increase in elevation landwards and their upper surfaces are recorded in seismic profiles at elevations between -25 m and a few metres above the contemporary lagoon floor. The submerged banks on the western margins of Patos Lagoon are contiguous with these paleointerfluves and are their shallow subaqueous subaerial extensions (Figures 1, 2, 6).

Incised valley morphology

The valleys are 20 km wide and 10 m deep on average, with deepest incisions reaching more than 30 meters. The width/depth ratios (W/D) are high (Gibling, 2006), characterizing them as U – shaped valleys (Dalrymple, 2006; Simms *et al.*, 2006).

There is often a 30 m difference in elevation from the top of the interfluves and the lowest portion of the valleys. Although the incised valleys are largely infilled, their position is marked by bathymetric lows (>5m deep) in the contemporary lagoon. The paleointerfluves are more prominent on the western margin of Patos Lagoon (Figures 1, 2, 6).

Four semi-parallel seismic lines from the southern morphological cell of Patos Lagoon are shown in figure 2. A topographic high evident in the bathymetry (intersection between Line 13 and Line 14) can be traced offshore in the seismic data (Line 12 and Line 2) where it is blanketed by estuarine/lagoonal sediments. This represents one of the several paleointerfluves evident in the western margin of Patos Lagoon.

The eastern margin shows buried incised valleys and interfluves underneath the Patos Lagoon floor. The channel-associated paleovalley in seismic profile 2, where Bo core was carried out (Figures 1, 2) aligns with a contemporary blind channel (Barra Falsa). Similarly, in the northern section of the lagoon (Figure 6), a narrow infilled incised valley on line 7 (core Mo) is adjacent to a contemporary isolated water body (do Rincão).

Pre-LGM incised channels highlighted by a black dashed line in profiles 22 and 23 (Figure 6) align with enclosed ponds (dos Gateados; da Reserva) on the adjacent barrier eastern lagoon margin, suggesting that they too may represent former channels in Barrier III (last interglacial).

Seismic lines 20, 21, 25 and 27 (Figure 6) cross the deepest part of the entire lagoon (> 7 m deep). This is underlain by an incised valley evident in lines 27, 25 and 20. The adjacent Pleistocene high in the north-eastern segment of profile 20 is an area of contemporary shallow water. In the highlighted segment of profile 21, two paleochannels can also be noted in the deepest parts of the contemporary lagoon.

Seismic lines 7 and 7a (Figure 6) also show a close correlation between bathymetry and ancestral topography. The eastern segment of profile 7a records Pleistocene substrate under a bathymetric high.

Incised valley infilling

The post-LGM incised valleys preserved under the Patos lagoon contain an infill that records changes in sea level and sedimentation rates during the Holocene. The history of infilling is relevant to the Holocene evolution of Patos Lagoon and its geomorphological evolution towards its present configuration.

For the purposes of this paper, Pre-LGM deposits are regarded as the base of the stratigraphic framework, represented by S1 and S2 sequences (Figure 3). The Post-LGM valley infill is referred as S3 (Figures 2, 3, 5 and 6), the base of which is a subaerial unconformity surface (SU1).

Unit 1 (U1) represent the early infilling deposits, accumulated since LIM and until the LGM. These records are described as channel infilling sediments deposited between subaerial unconformities SU and SU1 (Figure 3). The deposits thickness can reach 20 meters, summing fluvial and estuarine deposits.

Unit 2 (U2) deposits are the Post-LGM early infill of the paleovalleys. U2 is represented by the fluvial deposits accumulated during the onset of sea level rise (Figure 3), their top is marked by the Transgressive Surface (TS). U2 can be distinguished by stratigraphic position (Late Pleistocene/ Early Holocene), channel geometry with sandy deposits, usually concentric infilling, high amplitude and inclined seismic reflectors (Figures 3, 5). The nature of the sandy material is proven from cores (Figures 5).

Unite 3 (U3) is usually a thick (about 8 m) muddy package (cores PT-05, PT-01 and Mo; Figures 4 and 5), with layers that extend laterally for tens of kilometres (estuarine facies, Figure 3). These deposits have parallel to semi-parallel reflectors and that were dated from the corresponding core unit as having been deposited during the Holocene transgression. These laminated silts and muds represent the main valley infilling material (Figures 2, 3).

Core PT-08 (a 0.62 m-long gravity core) penetrates U3 and contains an intercalation of clay, silty and sandy deposits topped by a granule layer (Figure 4). These coincide with a seismic signature which shows progradational, bidirectional reflectors with an overall mound geometry, with high amplitude and variable continuity. These are interpreted as bay-head delta deposits, of which the uppermost 60 cm accumulated since 4,747 +/- 98 cal yr BP (Figure 4).

Overspilling deposits are recognized by inclined reflectors of high amplitude, in a bank geometry, next to a paleotopographic high (Figure 2, 3) and by stratigraphic position. These deposits are topped by the Maximum Flooding Surface (MFS).

Unit 4 (U4) represents Patos Lagoon deposits generated during and since the Holocene highstand (Figure 3). They are represented in seismic record by a high amplitude reflector of high lateral continuity and high amplitude (Figures 3, 5). Gravity core PT-01 shows a fining upward facies association of this unit (Figures 4). It contains a 0.10 m sandy package at the base (Pre-LGM substrate), covered by a 0.60 m silty package (Holocene sedimentation). PT-01 was acquired next to an interfluve, against which a thin (0.60 m) package of Holocene sediment accumulated. Gravity core PT-05 (Figures 4), contains 1.5 meters of homogeneous unconsolidated fine silt.

The incised valleys comprise a distinctive Post-LGM infilling sequence. The Pleistocene substrate is influential on the depositional process that have occurred since the LGM. Typical fluvial facies are only recognized in the basal portion of the deepest segments of these valleys (U1 and U2), with limited lateral extension.

Accommodation rates

Figure 5 illustrates seismic profiles 2 and 7, in the southern and northern cells of the lagoon, respectively. Seismic profile 2 represents a valley of ~ 40 km width between two Pleistocene interfluves, and a smaller adjacent paleochannel that is 1 km wide and 20 m deep (Figure 5). Sediment core Bo in the small paleochannel reveals basal deposits (U2) topped by Holocene sediments that accumulated at rates of 1.7 cm/year, (8,010 +- 140 cal yr BP to 7,535 +- 105 cal yr BP).

Granulometric analysis of Bo (Figure 5) core reveals an intercalation between sandy, silty and muddy sediments. Sand predominates in the basal portion (20-15 m), representative of the inclined and high amplitude reflectors observed in seismic data (U2) (Figure 5). A muddy package in the middle portion (15-6 m) is characterised by parallel/semi-parallel, wavy and low amplitude draped reflectors (U3). Another sandy package occurs in the upper portion (6-1 m), it is coincident with a seismic unit containing high amplitude reflectors with channelized geometry. These sands are topped by 1 m of mud, representing Patos Lagoon sediments (U4).

Profile 7 (Figure 5) shows a 3 km-wide incised valley with a distinctive shelf in its upper portion, cut into interfluves of Pleistocene sediment. SPT core Mo on the margin of the fluvial valley contains 17 meters (22-5 m) of fine and very fine sands with no fossils, showing pedogenesis evidences on the top (Pleistocene substrate). The upper portion comprises 5 meters of mud, with two distinct accumulation rates. The first 4 meters represents an interval of very high accumulation rates of 1.8 cm/year (8,040 +- 120 cal yr BP to 7,820 +- 140 cal yr

BP). This is associated with deposition in an estuarine basin (U3) within the incised valley. The upper 1 m of mud was deposited between 7,820 +- 140 cal yr BP and present (10^{-4} m/yr). This is associated with slow lagoonal sedimentation (U4) in the Patos Lagoon that contrasts with the high accumulation rates of the Middle Holocene.

DISCUSSION

Incised valleys act as depositional basins on the coastal zones. During transgression they are infilled by fluvial and estuarine sediments (Dalrymple, 2006; Dalrymple, Boyd, and Zaitlin, 1994). During sea level highstands incised valley fills may be topped by a variety of nearshore sediments depending on the local geomorphic setting. In the study area, incised valley fills are topped by lagoonal deposits.

The influence of paleovalleys morphology in accommodation rates and current bathymetry

The Patos Lagoon is underlain by a complex of adjacent flooded paleovalleys, each of which functioned as an independent estuarine depositional basin, during much of the Holocene rise in sea level. The incised valleys contain fluvial deposits (U1 and U2) at their base, at depths > 15 meters. These fluvial facies are represented by inclined/chaotic reflectors in seismic records (Figures 2, 6). The U1 and U2 deposits average 10 meters thick.

Sedimentation in the incised channels contrasts markedly with the interfluves. The paleochannels accumulated more than 25 meters of sediment whereas less than 10 m has accumulated on the interfluves (Figures 2 and 6). The interfluves became active sites of sedimentation only when the incised valleys were fully flooded and began to coalesce into a single back-barrier lagoon in the late Holocene. Benallack *et al.* (2016) reported a similar evolutionary pattern in a large African lagoon.

Channels in the base of the valleys afforded limited accommodation space (laterally and vertically) for accumulation of fluvial facies (U1 and U2). The Patos Lagoon incised valleys began to be inundated during the Middle Holocene, when sea level reached about -30 m (Angulo, Lessa and Souza, 2006; Corrêa 1986), flooding the incised valleys behind the Pleistocene barrier remnants.

The channels located at Bo and Mo core are interpreted as Holocene inlet channels. Based on the chaotic/inclined reflectors at the channels base it is possible to admit that they were active as fluvial channels during LGM. These are the easternmost channels recognized, the most vulnerable areas to the Holocene flooding and are aligned with two topographical depressions (Rincão lake and Barra Falsa blind channel). The inlets can remain active in areas where the fluvial incisions were more prominent and can be indicated by coastal water bodies (FitzGerald, Buynevich, and Hein, 2012). Diatom assemblages analysed by Santos-Fischer *et al*. (2016) revealed a marine-dominated paleoenvironment. Bo and Mo channels are interpreted as paleoinlets records. The coastal water bodies “dos Gateados”, “da Reserva”, “do Rincão” and Barra Falsa feature are suggested as paleoinlet channels.

As a consequence of fast drowning, the estuarine facies (U3) occupy an expanded accommodation space and dominate the valley fills, as in the incised valleys of the South Africa continental shelf (Angulo, Lessa and Souza, 2006; Corrêa, 1986; Green *et al*., 2013; Green, Dladla, and Garlick, 2013; Smith *et al*., 2011) and adjacent barrier lagoons (Benallack *et al*., 2016; Wright, Miller, and Cooper, 2000). Unit 3 records the highest Holocene sediment accumulation rates (~ 1.8 cm/year), as the shoreline had transgressed the paleocoastal plain, and the flat gradient encouraged suspension settling of the materials in the transitioning estuarine systems, depositing silts and muds typical of the low energy central basin unit of microtidal estuaries (Cooper, 2001, Green, Dladla, and Garlick, 2013).

In the Patos Lagoon, an average Holocene sedimentation rate of 0.075 cm/year was estimated by Toldo Jr. *et al*. (2000; 2006), based on the thickness of the whole Holocene package (U3+U4). Comparing U3 accumulation rates (1.8 cm/year) with the whole Holocene rates (0.075cm/year), the increase in vertical accomodation space (flooding) was not uniform along Holocene, happening in pulses (Figure 5) (Gornitz 2007). The accumulation rate differences in association with the seismic units signature can be used to individualize system tracts and map key surfaces. In this study case it helped to recognize Maximum Flooding Surface and separate Transgressive System Tract from the Highstand System Tract.

The complete submerging of all paleointerfluves occurred around 5 ky BP, when the sea level reached the maximum elevation in Rio Grande do Sul coast (Angulo, Lessa and Souza, 2006; Corrêa, 1986). At this time, the former individual estuarine systems merged into the Patos Lagoon (U4) and sandy barrier IV was stabilized (Dillenburg, Tomazelli, and Barboza, 2004; Lima *et al*., 2013). Sedimentation rates in the lagoon dropped by 4 orders of magnitude relative to the individual estuarine basins, as a result of the vast increase in size of the sedimentary basin.

In the late Holocene, sea level stabilization and particularly the post 5.1 ky BP ca. 2-3 m sea level fall to the present, would have reduced tidal prisms and led to the closure of former inlets (Bo and Mo channels) by reworked tidal delta and aeolian sediments (Weschenfelder *et al*., 2008), a process documented elsewhere under similar sea level conditions on the South African coast (Benallack *et al*., 2016; Wright, Miller, and Cooper, 2000). This process of barrier sealing and dune accumulation, in turn would have reduced tidal exchange and restricted overwashing. Toldo Jr. *et al*. (1991) dated closure of the Barra Falsa inlet at around 2,080 yr BP, coincident with conditions associated with modern lagoonal diatom assemblages (Santos-Fischer *et al*., 2016).

The morphology of the paleovalleys remain preserved in Patos Lagoon bathymetry (Figure 1). The paleointerfluves are better visible in the western margin of the Patos Lagoon, because the eastern margin was flooded earlier suffering for longer periods with partial wave/tide ravinement during Post-LGM transgression, when Holocene barrier was not completely developed, also wind-generated waves acted on the interfluves erosion along this period.

The central portion of each morphological cell shows the lowest bathymetry (>5m deep), also represent the depocenter of the paleovalleys (Figures 2, 5, 6). These areas accumulated the thickest deposits since LGM event and currently muddy material is deposited (Toldo Jr. 1991). In contrast, the margins are the shallow portions of the morphological cell (<1m depth), represent the paleovalleys interfluvial areas which serve as structure for spits development.

Sandy spits development

Coastal lagoons usually are parallel to the coast (Kjerve, 1994), they occupy shallow coastal depressions (Kjerve, 1986). Usually paleovalleys represent depressions in perpendicular orientation to the coast (Dalrymple, 2006; Dalrymple, Boyd, and Zaitlin, 1994) and are recognizable in lagoons bathymetry (Cooper, Green, and Wright, 2012). Sandy spits in Patos Lagoon margins are perpendicular to the shore orientation. The perpendicularity of remaining interfluves and sandy spits is not coincidence in Patos Lagoon.

The waves typically approach the shore line of Patos Lagoon in an oblique angle. If the bathymetry of the margins is irregular, the approaching waves will change their orientation in reaction to bottom irregularities, following the refraction principle. Several spits are evident which develop on submerged banks in the western margins of Patos Lagoon (Figures 1, 2, 6), the submerged banks were described by Toldo Jr. (1991) as relict structures that are not currently active. Seismic data reveals these features to be the landward remnants of flooded interfluves. The submerged banks are composed of Pleistocene sands and influence the bathymetry of lagoonal margins, and therefore also influence the incoming waves action providing the sandy sediment source that has enabled development of Holocene sandy spits.

Merging of the former isolated basins in the late Holocene created a lagoon with a fetch distance of over 200 km sub-parallel to the dominant E-ENE winds. This created an energetic back-barrier environment in which the relict topographic highs were reworked to form contemporary sandspits along the margins, a situation similar to those documented by Bruno *et al*. (2016) and Raynal *et al*. (2009).

This marked antecedent control on spit location and orientation is absent from the Zenkovich (1959) and Ashton, Murray, and Olivier (2001) models. The theories about the origin of sandy spits in lagoon margins agree that shore line unevenness are necessary to the early development of sandy spits. Future studies should observe paleotopography as a conditioner to spits growing, mainly paleovalleys features.

CONCLUSIONS

The Patos Lagoon originated as a complex of multiple adjacent incised valleys, each of which existed as an individual fluvial/estuarine basin until the late Holocene. Incised valleys under the contemporary lagoon were the first to be drowned (ca. 8,000 yr BP) during the Holocene transgression. Interfluvial areas remained subaerially exposed for variable periods, but were ultimately flooded in the late Holocene when sea level reached its maximum (+ 2-3 m) ca. 5,000 yr BP and the proto-Patos Lagoon was formed. All but one of the tidal inlets that persisted into the late Holocene closed with the fall in sea level to the present by about 2,000 yr BP.

The incised valleys were not completely filled after the maximum flooding, because the sediment input was insufficient. Submerged banks in the western margins of Patos Lagoon are the relict structures of paleointerfluves and influence the current waves and sand distribution on Patos Lagoon margins. As a consequence, the contemporary bathymetry of Patos Lagoon still maintains a surface expression of the paleo-drainage systems formed during the LGM. The segmentation process is dominated by the position of paleo-interfluves and is incomplete because spit growth is limited to the shallow margins where wave energy can penetrate to the lagoon bed, and where sediment is available for transport.

ACKNOWLEDGEMENTS

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List of Figures

Fig. 1

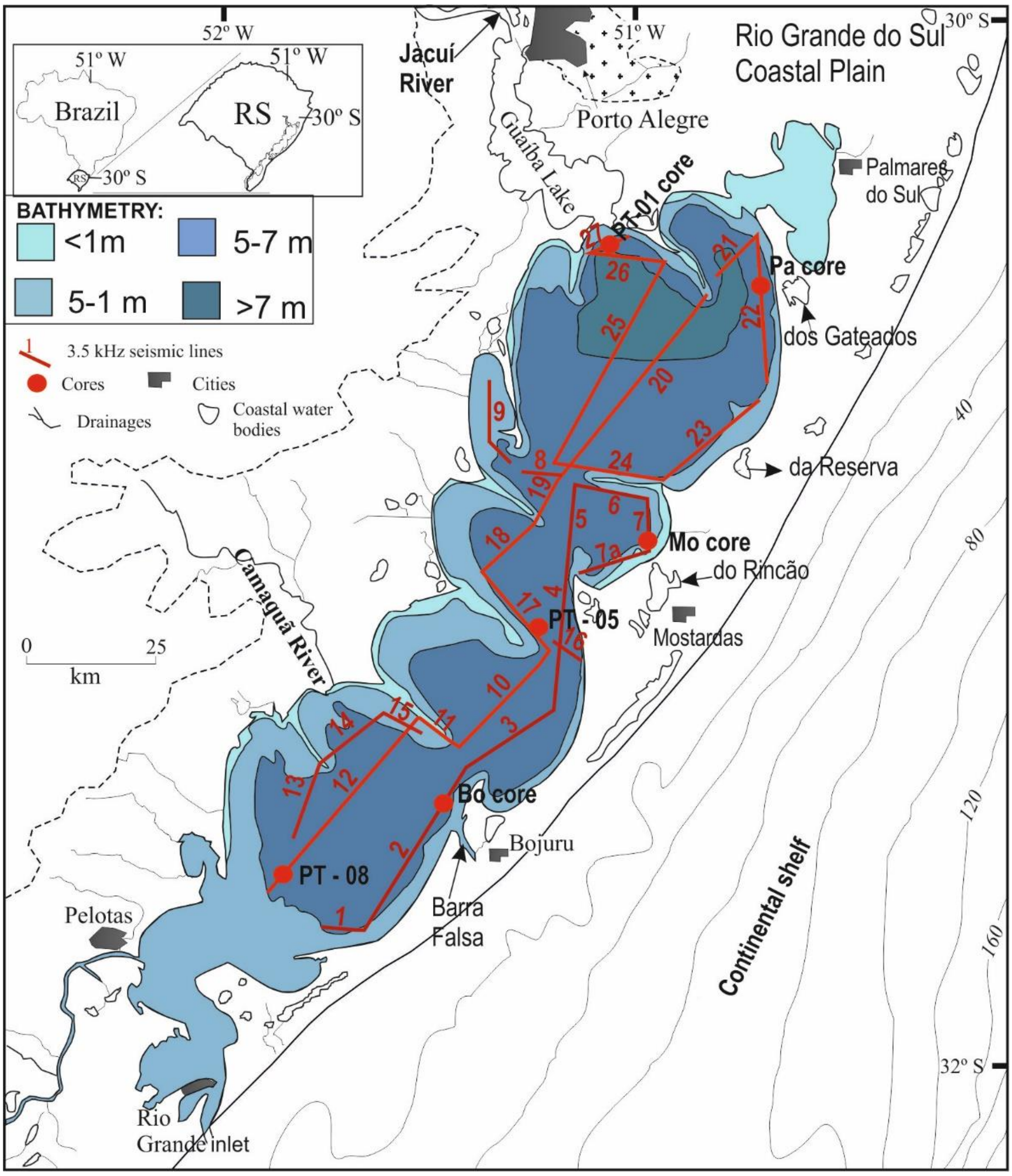

52º W
51º W
30º S
Rio Grande do Sul
Coastal Plain
Jacuí
River
Porto Alegre
Guaíba Lake
PT-01 core
Palmares
do Sul
Pa core
dos Gateados
da Reserva
Mo core
do Rincão
PT - 05
Mostardas
Bo core
Bojuru
Barra
Falsa
PT - 08
Pelotas
Rio
Grande inlet
Camaquã River
Continental shelf
32º S
Brazil
RS
BATHYMETRY:
<1m
5-7 m
5-1 m
>7 m
3.5 kHz seismic lines
Cores
Cities
Drainages
Coastal water
bodies
0
25
km

Fig. 2

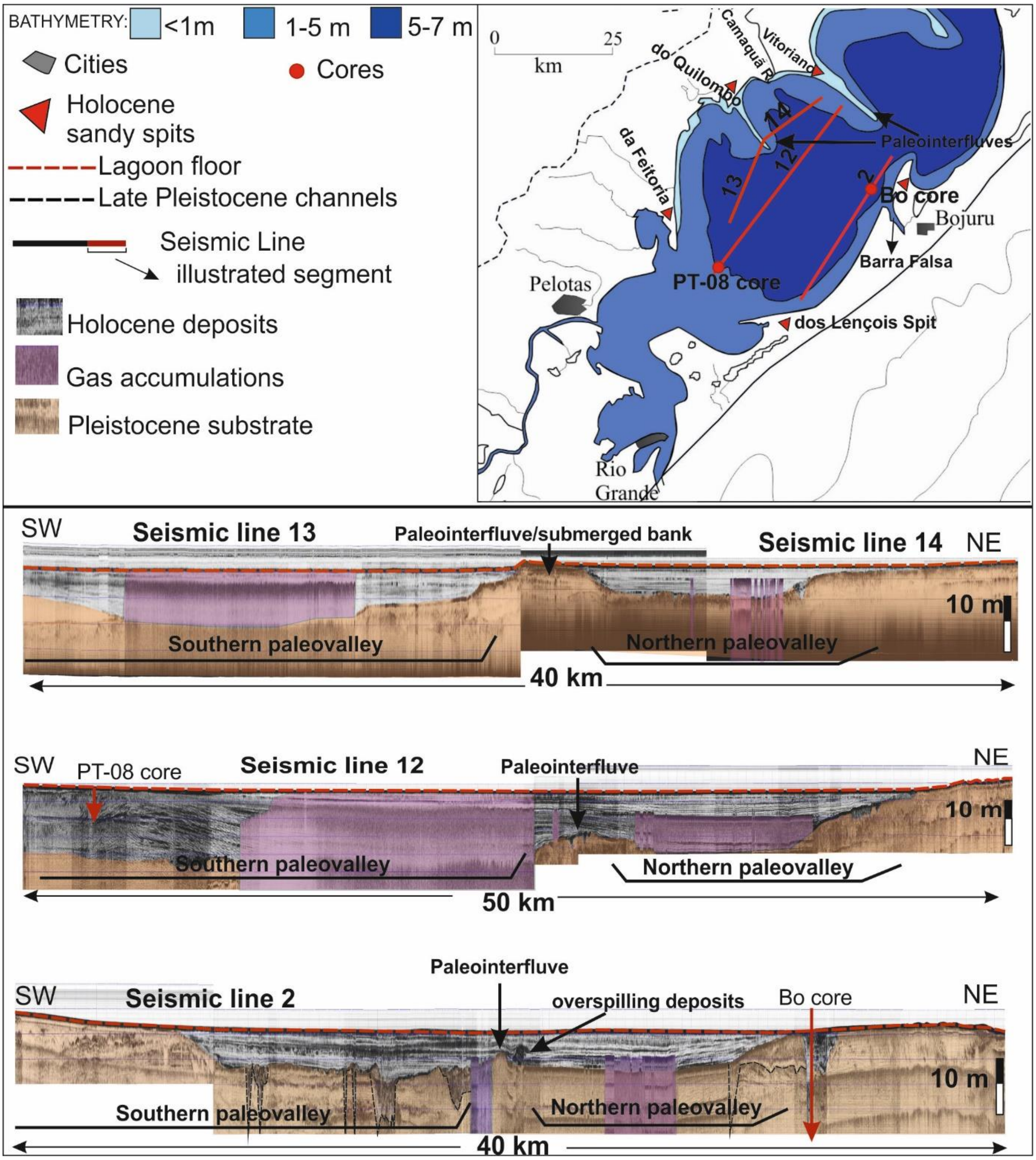

BATHYMETRY: <1m 1-5 m 5-7 m
Cities
Cores
Holocene sandy spits
Lagoon floor
Late Pleistocene channels
Seismic Line
illustrated segment
Holocene deposits
Gas accumulations
Pleistocene substrate
0 25 km
do Quilombo
Camaquã R.
Vitoriano
da Feitoria
Paleointerfluves
Bo core
Bojuru
Barra Falsa
PT-08 core
Pelotas
dos Lençois Spit
Rio Grande
SW
Seismic line 13
Paleointerfluve/submerged bank
Seismic line 14
NE
10 m
Southern paleovalley
Northern paleovalley
40 km
SW
PT-08 core
Seismic line 12
Paleointerfluve
NE
10 m
Southern paleovalley
Northern paleovalley
50 km
Paleointerfluve
SW
Seismic line 2
overspilling deposits
Bo core
NE
10 m
Southern paleovalley
Northern paleovalley
40 km

Fig. 3

	Unit	System tract	Seismic facies	Sediment and thickness	Depositional environment	Main diagnostic criteria	Seismic image
S3	HST U4		G	Mud/ 0,7 m	Back- barrier lagoon	High lateral continuity; high amplitude reflectors capping the MFS;	
S3	MFS TST U3		F	Sand ? +- 4m	Overspilling	High amplitude reflectors; bank external geometry; near to paleointerfluve;	
S3	TST U3		E	Mud and sand +- 12m	Inlets	Infilling geometry; aggradational/progradational wavy reflectors;	
S3	TST U3		D	Mud and sand alternation +- 12m	Bay-head delta	Mounded geometry; progradational and bidi-rectional reflectors;	
S3	TST U3		C1	Sand +- 6m	Estuary mouth-bar	Progradational reflectors deposited over estuarine deposits (facies C).	
S3	TST U3		C	Mud/ +- 10m	Estuarine	Homogeneous sucession of aggradational reflectors; sheet external geoemtry;	
S3	TS LST U2		B	Sand/ +- 5m	Fluvial	Channel infilling geometry; high amplitude reflectors; symmetrical and concentric infilling, tending to horizontality;	
S3	LST U2		A	Sand/ +- 5m	Fluvial	Channel infilling geometry; low amplitude reflectors; symmetrical and concentric infilling;	
S2	SU1 FSST U1		C	Mud/ +- 10m	Estuarine	Homogeneous sucession of aggradational reflectors; sheet external geoemtry;	
S2	FSST U1		B	Sand/ +- 5 m	Fluvial	Channel infilling geometry; high amplitude reflectors; symmetrical and concentric infilling, tending to horizontality;	
S2	FSST U1		A	Sand/ +- 5m	Fluvial	Channel infilling geometry; low amplitude reflectors; symmetrical and concentric infilling;	
S1	SU						

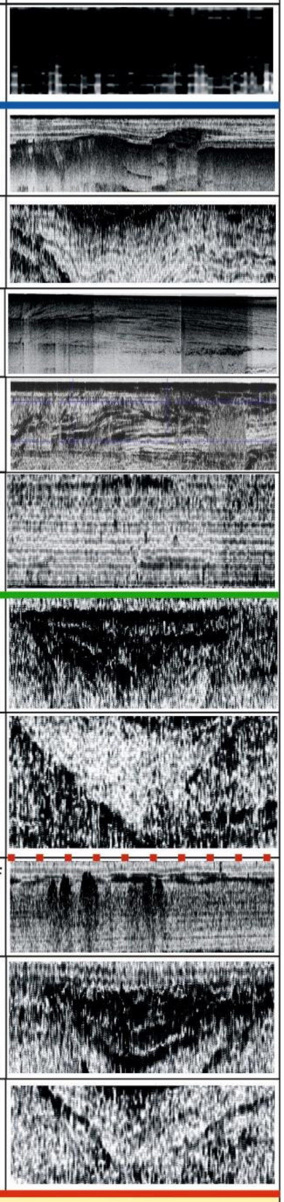


Fig. 4

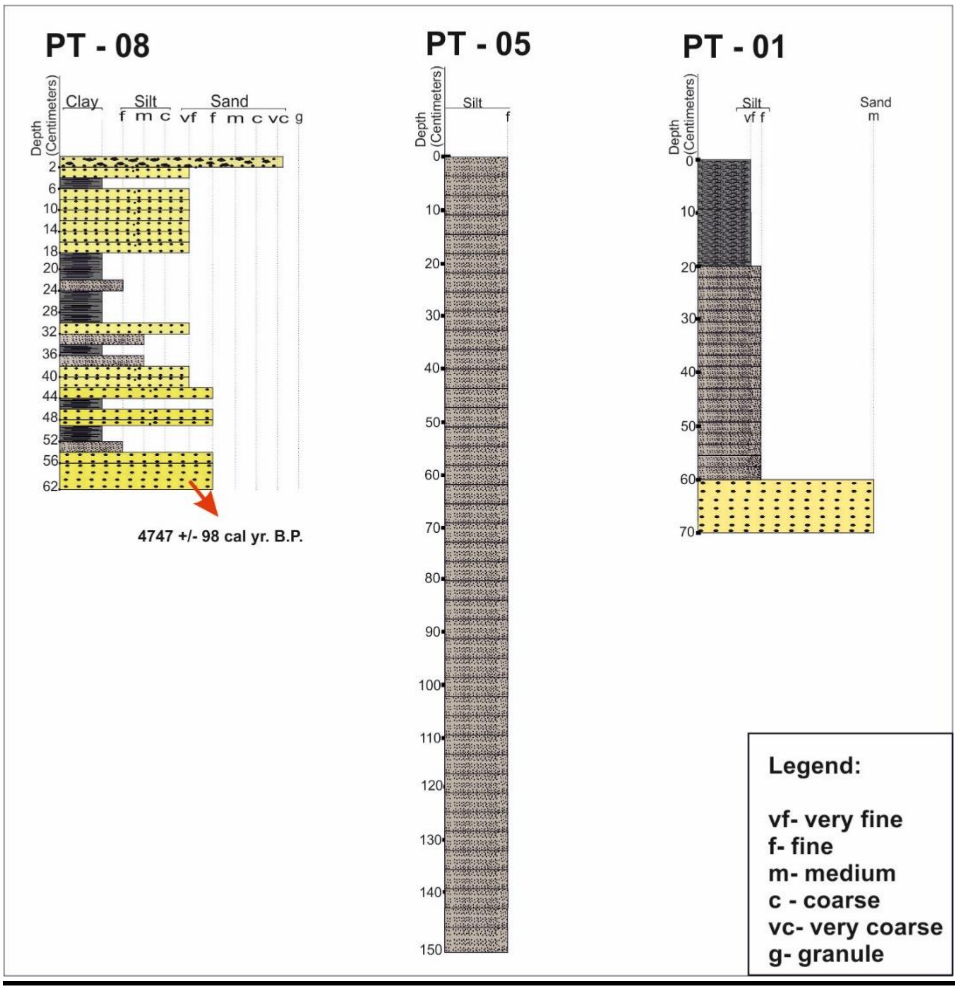

PT - 08
Depth (Centimeters)
Clay
Silt
f m c
Sand
vf f m c vc g
2
6
10
14
18
20
24
28
32
36
40
44
48
52
56
62
4747 +/- 98 cal yr. B.P.
PT - 05
Silt
f
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
PT - 01
Silt
vf f
Sand
m
0
10
20
30
40
50
60
70
Legend:
vf- very fine
f- fine
m- medium
c - coarse
vc- very coarse
g- granule

Fig. 5

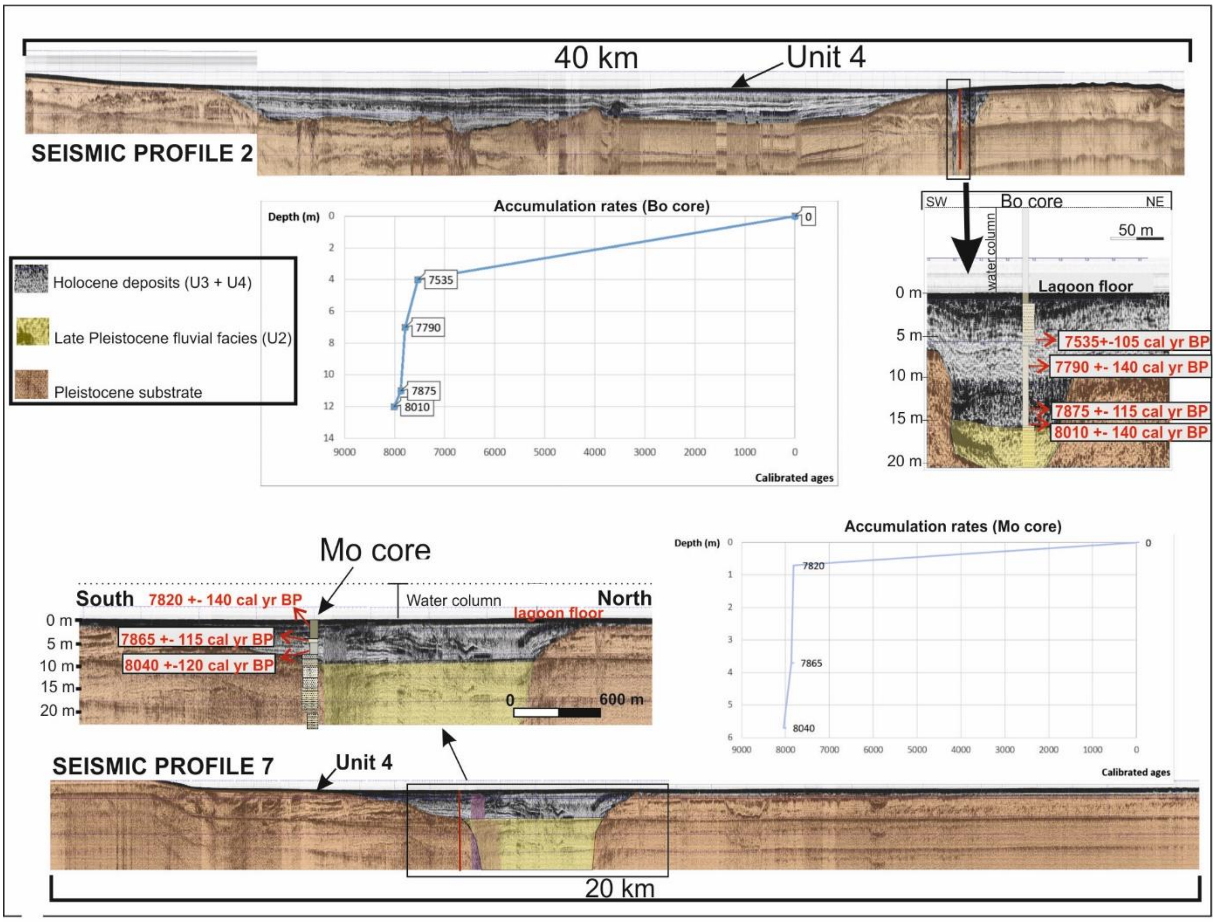
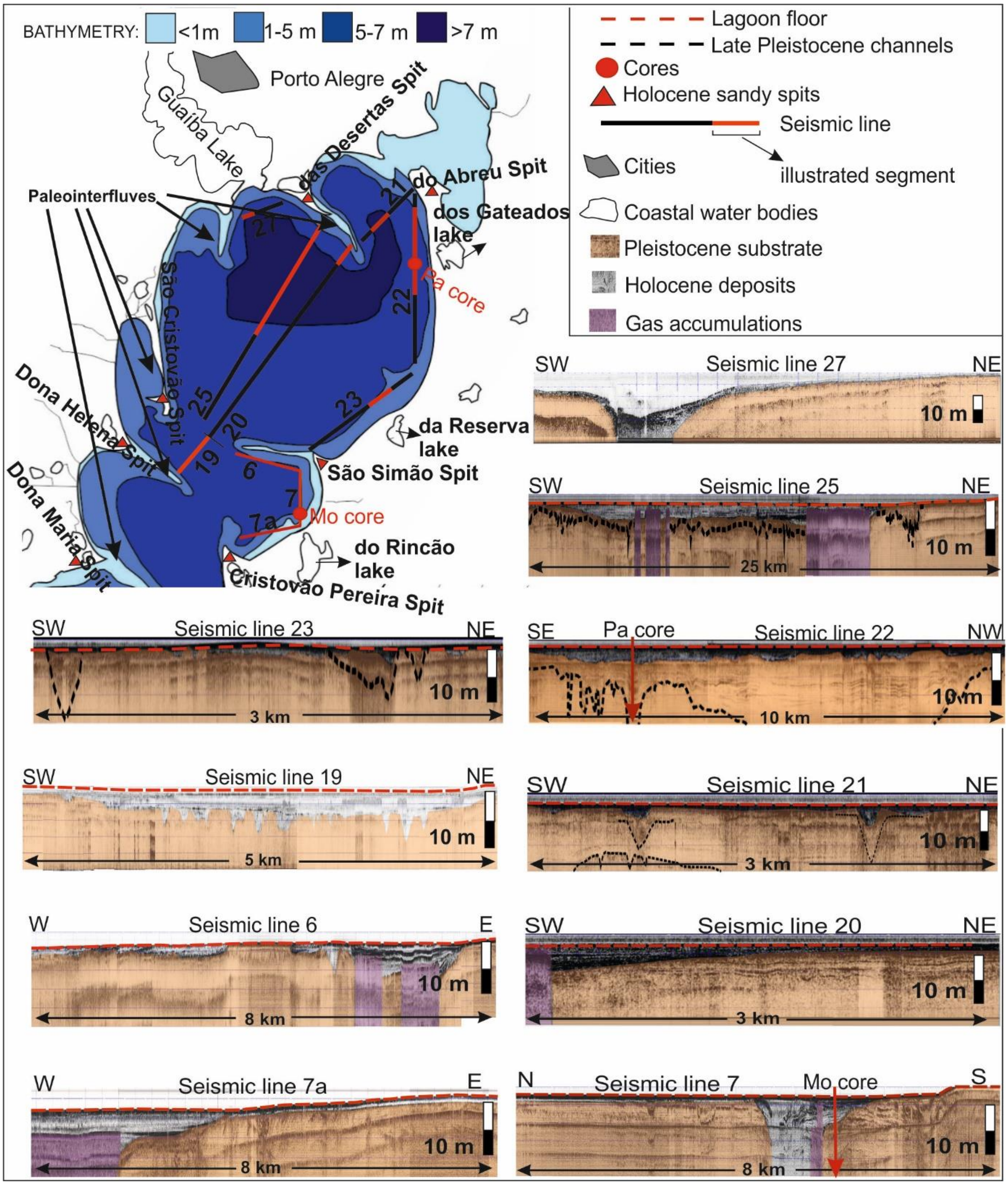

40 km
Unit 4
SEISMIC PROFILE 2
Accumulation rates (Bo core)
Depth (m)
Calibrated ages
7535
7790
7875
8010
Holocene deposits (U3 + U4)
Late Pleistocene fluvial facies (U2)
Pleistocene substrate
SW
Bo core
NE
50 m
water column
Lagoon floor
7535+-105 cal yr BP
7790 +- 140 cal yr BP
7875 +- 115 cal yr BP
8010 +- 140 cal yr BP
Mo core
South
North
Water column
lagoon floor
7820 +- 140 cal yr BP
7865 +- 115 cal yr BP
8040 +-120 cal yr BP
600 m
Accumulation rates (Mo core)
7820
7865
8040
SEISMIC PROFILE 7
Unit 4
20 km

Fig. 6



BATHYMETRY: <1m 1-5 m 5-7 m >7 m
Lagoon floor
Late Pleistocene channels
Cores
Holocene sandy spits
Seismic line
illustrated segment
Cities
Coastal water bodies
Pleistocene substrate
Holocene deposits
Gas accumulations
Porto Alegre
Guaíba Lake
das Desertas Spit
do Abreu Spit
dos Gateados lake
Paleointerfluves
São Cristovão Spit
Pa core
Dona Helena Spit
Dona Maria Spit
da Reserva lake
São Simão Spit
Mo core
do Rincão lake
Cristovão Pereira Spit
Seismic line 27
Seismic line 25
25 km
Seismic line 23
3 km
Seismic line 22
10 km
Seismic line 19
5 km
Seismic line 21
3 km
Seismic line 6
8 km
Seismic line 20
3 km
Seismic line 7a
8 km
Seismic line 7
8 km
10 m

CAPÍTULO 4 - DRAINAGE REORGANIZATION OF SOUTHERN BRAZILIAN COASTAL RIVERS

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Drainage reorganization of southern Brazilian coastal rivers

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ABSTRACT

Drainage readjustments are commonly associated to allogenic forcing factors, mainly tectonism. Quaternary adjacent valleys are recorded in Patos Lagoon sub-bottom, incised by Jacuí and Camaquã drainage systems which shifted laterally during Pleistocene marine regressive-transgressive cycles. Investigate the processes of drainage reorganization is important to understanding the geological evolution of Patos Lagoon, speciation processes, placer development and fossils sites locations. High resolution seismic data (3.5 kHz), SPT core sedimentary samples, radiocarbon datings and diatom assemblage analyses were compiled from previous works to constitute a consistent body of data. In addition, one 10 kHz seismic profile, three gravity cores and one radiocarbon dating were collected. The data revealed at least two Pleistocene regressive-transgressive events, one during Last Glacial Maximum and another earlier, with the main coastal rivers (Jacuí and Camaquã) incising different areas during each event. No evidence of tectonic forcing was recognized. The older valleys were fulfilled by sediment input during the Pleistocene sea level risings, creating a topographical high in comparison with surroundings. During the Last Glacial Maximum, the rivers flowed by gravity to lower adjacent areas, breaching interfluves, helped by groundwater flow. The eustatic fluctuation controlled the thickness accumulation in the valleys and the autogenic controls (sediment input, paleotopography and groundwater flow) forced the rivers to readjust their drainage basin. These interpretations reinforce the importance of autogenic forcing factors in studying Quaternary incised valleys.

Keywords: drainage readjustment, paleovalley, Quaternary, paleotopography.

1. Introduction

The rerouting of drainage lines has been topic of important surveys, despite having few published works describing the detailed processes (Bishop, 1995; Brocard et al., 2011; Willet et al., 2014). Several allogenic and autogenic factors can cause the reorientation of a river into a new route, such as: sea level changes, tectonic adjusts, paleotopography, sediment input, differences in substrate resistence and groundwater flow. The coastal plain most vulnerable areas to sea level changes are the incised valleys, which are regional topographical depressions (Zaitlin et al., 1994). The river flow by gravity through the lowest areas, eroding incised valleys during sea level falls and infilling the valleys during subsequent transgressions (Dalrymple, 2006; Dalrymple et al., 1994).

The evolution of Patos Lagoon and surrounding environments fed discussions along the last decades (Dillenburg et al., 2004; Rosa et al., 2011; Toldo Jr. et al., 1991; Tomazelli & Villwock, 2000; Weschenfelder et al., 2014). Incised valleys were revealed in the Patos Lagoon substrate by high frequency (3.5 kHz) seismic data, providing important clues to the Pleistocene/Holocene evolution of the southern Brazil coastal zone (Weschenfelder et al. 2010, 2014).

Patos Lagoon is the biggest barrier lagoon in the world (~10.000 km^2), which basin receives the discharge of two main rivers: Jacuí and Camaquã (Fig. 1). These rivers shifted their drainage basin along Quaternary, eroding adjacent incised valleys in Rio Grande do Sul (RS) coastal plain (Weschenfelder et al., 2014). The paleovalleys are in a normal angle to the shoreline and were infilled in response to marine transgressions. Diverse depositional facies buried the valleys, controlled by allogenic/autogenic forcing factors and are recorded in the Patos Lagoon substrate.

Previous works carried out by Weschenfelder et al. (2010, 2014) recognised incised valley systems in RS coastal plain and also a general description of the depositional sequence framework. These earlier studies presented possibilities for paleodrainage lines, but did not discussed the reasons for drainage reorientation. This study suggests a cause for drainage basin readjustments ocurred along Quaternary, based on the valley infillings thickness, architectural elements and chronological data.

The reorganization of a drainage into a new route can cause changes in the sediment supply, placer locations, in the aquatic and terrestrial biota (Bishop, 1995). Studies carried out in RS coastal plain analysing such changes will be discussed in this work from the drainage reworking perspective.

1.1. Geological setting

The study area is located in the RS coastal zone, southern Brazil (Fig. 1). The RS continental shelf is a wide (~ 150 km) and low gradient area (1.3/1.4 m/km), with gentle relief (Corrêa et al., 1986; Martins et al., 1972; Tomazelli & Vilwock, 2000). According to Corrêa (1986, 1990), the sea level was 130 m lower than the present level during the Last Glacial Maximum (LGM) and the presence of terraces in the continental shelf attest stabilizations of previous shorelines during the subsequent transgression.

The RS coastal plain is a broad area (33,000 km^2) with low topography (Tomazelli & Vilwock, 2000), in which four extensive (hundred kilometres length) lagoon barrier systems were developed during Quaternary highstands, oriented in NE/SW direction. This extraordinary barrier dimension was reached due the microtidal regime (<0.45m), available sediments and high wave energy. The barriers I, II and III are Pleistocene, named from the oldest to youngest. The barrier IV is Holocene, it is juxtaposed to barrier III and both partially enclose Patos Lagoon from the Atlantic Ocean, currently remaining only a single tidal inlet (Rio Grande channel) (Tomazelli & Villwock, 2000) (Fig. 1).

Patos Lagoon is the biggest chocked lagoon in the world, encompassing 10,000 km^2 (Kjerfve, 1986). It has 240 km long, average width of 40 km and average depth around 6 m (Toldo Jr. et al., 2006). The lagoon is partially segmented by marginal sandy spits, which individualize it in morphological cells (Toldo Jr., 1991). The bottom deposits are muds at the central portion of each cell and sands along the margins, which suffer reworking by the wave energy (Toldo Jr., 1991; Toldo Jr. et al., 2006). Acoording to Toldo Jr. (1991), these spits are Holocene features developed on stable banks.

The Patos Lagoon receives the outflow of two main drainage basins, with the respective annual average discharges: Jacuí (1,253 m^3/s) and Camaquã (307 m^3/s) (Vaz et al., 2006). Jacuí rivers create a delta into Guaíba river, near Porto Alegre city. The delta of Camaquã River is located at the western margin of Patos Lagoon (bay-head delta) near to São Lourenço city (Fig. 1) (Toldo Jr. & Almeida, 2009; Vaz et al., 2006).

Quaternary paleochannels were identified in the Patos Lagoon sub-bottom by high resolution seismic data (Weschenfelder et al., 2010). These rivers occupied incised valleys in the RS coastal plain during Quaternary regressions and buried the valleys during the subsequent transgressions (Weschenfelder et al., 2010, 2014). Quaternary stratigraphic sequences were individualized by Weschenfelder et al. (2014) using subaerial unconformities as limit.

The Patos Lagoon reached its present configuration in Late Holocene (Dillenburg et al., 2004; Toldo Jr. et al., 2006). The Holocene barrier began to stabilize from the maximum flooding (seal level= + 2-3 m), around 5 k.y.B.P. (Angulo et al., 2006; Corrêa, 1986, 1990; Lima et al., 2013).

2. Material and methods

About 1000 km of high resolution (3.5 and 10 kHz) seismic data were collected in Patos Lagoon and analysed in this study. The seismic data was acquired by a Geopulse sub bottom profiler from GeoAcousticsTM and was processed in SonarWiz sotware (Chesapeake Technology). Positioning was by DGPS. The average velocities applied to acoustic signal in the substrate were 1,500 m/s for the water and 1,650 m/s for sediments (Jones, 1999).

Some segments of these seismic lines were analysed by previous works (properly referenced in the figures) aiming to represent a generical stratigraphic framework and estimate the previous drainage lines. These seismic records are reinterpreted here approaching the topic of drainage readjustments along Quaternary.

Three Standard Penetration Test (SPT) cores (Bo, Mo and Pa) were carried out in previous works for faciologic calibration (Weschenfelder et al. 2010, 2014) (Fig. 1, 3). The SPT core samples were sieved following the intervals of: 0.062, 0.088, 0.125, 0.177, 0.25, 0.35, 0.5, 0.71 and 1 millimetres. Three gravity cores were also carried out for faciologic calibration, their particle sizes samples were analyzed using the "HORIBA Laser Scattering Particle Size Distribution Analyzer LA-950".

Radiocarbon datings carried out in Bo, Mo and Pa cores were published in previous works and compiled in Table 1. A new radiocarbon dating was carried out in this work, by a shell collected in PT-08 gravity core.

To reach the results presented in this work was necessary an earlier analysis of facies recognition based on the concepts stablished by Mitchum (1977), using seismic and core data. Changes in physical character, either by differences in impedance contrast or in strata architecture, are named discontinuities. The term "unconomity" is used for discontinuities which show hiatus or erosion in a regional scale, representing the limits of sequences.

The bathymetric map was compared with the seismic data to analyse the paleotopography and Pleistocene/Holocene deposits thickness. The radiocarbon dating made possible to know which channels were active during LGM and which ones were before.

3. Results

The general stratigraphical framework of the Quaternary deposits recorded in Patos Lagoon substrate was determined by Weschenfelder et al. (2014), by determining three seismo-depositional sequences (S1, S2 and S3), limited by two subaerial unconformities (Fig.2).

3.1. The general stratigraphical framework

The subaerial unconformity surfaces (SU and SU1) are recorded in the seismic data by an irregular reflector of high amplitude, continuous for tens of kilometres, underlying seismic valleys of regional scale. These surfaces also are marked by the truncation of older reflectors. They represent fluvial erosion and subaerial exposition at interfluves, occurred in RS coastal plain as consequence of Wisconsin glaciation.

The lowest sequence was named S1 by Weschenfelder et al. (2014), it encompasses several infilled channels, representing several events of incision and infilling ocurred during Quaternary with inaccurate dating, it is topped by the SU.

The Sequence 2 (S2) is topped by the SU1 and underlined by the SU (Fig. 2). The S2 is characterized by chaotic and inclined reflectors deposited in channel infiling geometry. The reflectors have concavity up, with variable continuity, high frequency, trending to horizontality upward. The Pa core provided shells for radiocarbon datings, which recorded an age over 43 k.y. B.P. to these deposits, exceeding the limit of C^{14} dating method.

The Sequence 3 (S3) encompasses the LGM and Post-LGM deposits, is the last infilling sequence, topped by the Patos Lagoon floor, it is underlined by the SU1. The deposits accumulated during LGM are mainly represented by chaotic/inclined reflectors of variable amplitude, fulfilling a confined channel in “filling type” external geometry. The samples collected show fine to medium sands, with shell fragments. These paleochannels reached the lowest depths (-30m from the current lagoon surface).

The Post-LGM deposits are represented by the flooding of confined fluvial channels, prevailing reflectors with aggradational stacking patterns, infilling U-shaped (cross-section) incised valleys with high width/depth ratios (Gibling, 2006). The flooded incised valleys had widths of 35 Km on average, variable depths around 30 m. Radiocarbon datings carried out in shells revealed Holocene ages to these deposits (table 1).

Reflectors in a mounded geometry, reaching more than 15 meters thick, with bidirectional progradational reflectors were interpreted as Holocene bay-head delta deposits. The alternation between sandy-muddy reflectors is attested by PT-08 core and also by the alternation of high-low amplitude reflectors. These deposits are topped by a granule layer. A shell was collected at a depth of 0.60m for radiocarbon dating, it revealed the age of 4747 +/- 98 yr BP to these deposits.

The top of S3 is composed by a muddy layer (facies G) (Fig.3), which caps all previous deposits, it has an average thickness of 0.5 m. deposited since the maximum flooding, when all the interfluves were flooded and the current back-barrier lagoon was stablished.

No evidence of tectonism was recognized in the entire seismic records analyses.

Table 1: Radiocarbon dating with references.

Core/ samples/ depths	calibrated ages BP	Material	Sample	Publication
Bo core(-8 m water clomun)				
Bo 12 (4m)	7535 +- 105 (7640/7430)	Shell	BETA 294867	Weschenfelder et al. 2014
Bo 15 (7m)	7790 +- 140 (7930/7650)	Shell	BETA359870	Santos-Fischer et al. 2016
Bo 19 (11 m)	7875 +- 115 (7990/7760)	Shell	BETA 294868	Weschenfelder et al. 2014
Bo 20 (12 m)	8010 +- 140 (8150/7870)	Shell	BETA 359871	Santos-Fischer et al. 2016
Mo core (-7.30 m water column)				
Mo 8 (0.70 m)	7820 +- 140 (7960/7680)	Shell	BETA 360370	Santos-Fischer et al. 2016
Mo 11 (3.7 m)	7865 +- 115 (7980/7750)	Shell	BETA 298208	Weschenfelder et al. 2014
Mo 13 (5.7 m)	8040 +- 120 (8160/7920)	Shell	BETA 294869	Weschenfelder et al. 2014
Pa core (-6m water column)				
Pa 21 (15 m)	> 43,500	Shell	BETA 305998	Weschenfelder et al. 2014
Pa 23 (17 m)	> 43,500	Shell	BETA 305999	Weschenfelder et al. 2014
Pa 26 (20 m)	> 43,500	Shell	BETA 298209	Weschenfelder et al. 2014
PT-08 (-6 m water column)				
PT-08 (0.60 m)	4747 +- 98 (4845/4649)	Shell	BETA 453296	Current work

3.2. Paleodraiange lines

The Jacuí and Camaquã rivers are the main drainage systems which drained Patos Lagoon area, during Quaternary sea level falls. The seismic lines were correlated with the bathymetric map (Fig. 4) to estimate the paleoroutes. The Jacuí River paleovalleys were recognized in 3 seismic lines: 22, 7 and 7a (Fig. 4). Camaquã paleovalleys were recognized in seismic lines 2, 12, 13 and 14 (Fig. 4).

3.2.1. Northern morphological cell

The seismic lines, cores and radiocarbon datings analysed in the northern cell of Patos Lagoon were published in previous works (Baitelli, 2012; Weschenfelder et al., 2014). The paleovalley recognized in seismic line 22 (Fig. 4) has about 10 km width, more than 30 m depth, infilled with chaotic/inclined reflectors with medium to high amplitude and moderate lateral continuity increasing upward simultaneously with the infilling. Pa core was carried out in seismic profile 22 paleovalley. Three shell samples were collected in S2 sediments of Pa core (Fig. 4) at depths 21, 23 and 26 meters, revealing an age older than 43.5 ky BP to these deposits (Weschenfelder et al., 2014).

The cross-section of seismic line 7 shows a paleovalley about 3 Km wide and more than 30 meters depth, infilled with S3 deposits. At the base the channel is confined, with chaotic/inclined reflectors. The channel increased vertically and laterally the accomodation space upward; the upper portion is represented by aggradational reflectors with local inclined reflectors. The SPT core Mo was carried out in the southern portion of seismic line 7 (Fig. 4), reaching the southern margin of the valley.

An interval of very high accumulation rates (1.8 cm/year) is recognized in the uppermost 4 meters of Mo core, measured by three radiocarbon datings: 8,040 +- 120 cal yr BP, 7865 +- 115 cal yr BP and 7,820 +- 140 cal yr BP. These muddy deposits were associated with Holocene estuarine deposits (U3). The last one meter of mud at the top was deposited between 7,820+-140 cal yr BP and present (10^{-4} m/yr). This is associated to modern lagoonal sedimentation in Patos Lagoon (U4), contrasting with the high accumulation rates of the Middle Holocene (Figs. 4, 3).

3.2.2. Southern Morphological cell

The southern morphological cell presents seismic lines with great image resolution (Fig. 4). The seismic profiles 13/14, 12, and 2 are parallel to the lagoon margins. They reveal important clues about paletopography and geometry of Camaquã River paleovalleys. The bathymetry also helps in the paleovalleys mapping.

The seismic profiles 13/14 were collected in line and unified for better visualization and description (Figs. 4, 6). These profiles show the landward portion of two paleovalleys, associated to Camaquã drainage system. These paleovalleys have a well preserved cross-sectional geometry, also evident in the bathymetry. These paleovalleys are separated by a paleotopographic high, recognized in the central portion of profile 13/14 and also notable in the bathymetry as a submerged bank. In these profiles, the paleotopographic high represent a large structure, about 10 meters high and 5 Km wide. The paleovalleys were named northern and southern (Fig. 6). In this profile both paleovalleys show gas curtains and were infilled by S3 deposits, mainly aggradational parallel layers.

The seismic line 12 (Figs. 4, 6) is in the central portion of southern morphological cell. Northern and southern paleovalleys are distinguishable. However, the paleointerfluve between them is less prominent, 7 meters high and 2 Km wide, it is covered by S3 aggradational deposits and is not marked in the bathymetry. On average, both paleovalleys have about 12 km width and 15 meters thickness of infiling deposits, these measures are subtly larger oceanward.

The seismic line 2 was already published by Weschenfelder et al., (2014). This line enables the individualization of northern and southern paleovalleys, but the interfluve suffered erosional process and is notable as a relict feature, 300 meters wide and 3 meters high. In seismic line 2 both valleys show fluvial paleochannels on their bases. The paleochannels are covered by agradational, locally progradational reflectors (Figs. 2, 4, 6).

The SPT core Bo was carried out in the largest paleochannel located at the northern portion of profile 2, both core and channel were described in Weschenfelder et al., (2014). This paleochannel has about 1.5 km wide, reaching more than 25 meters depth. Inclined and chaotic reflectors were identified in core basal portion (27-20 m), constituted of inclined layers of fine sand within a confined channel. These facies are covered by a seven meters thick (20-13 m) muddy package, genetically associated with the enlargement of the channel and increasing in accommodation space. The upper package (13 – 9 m) is constituted by fine sands, showing channel scour, eroding previous deposits. All previous deposits are topped by a lagoonal muddy package of 1 meter thick (9-8 m) (Figs. 2, 4, 6).

4. Discussion

Several works have been carried out studying paleorivers in RS coastal plain. The understanding of the paleoenvironment evolution is crucial to the understanding of the current geography of RS coastal plain. Study the river avulsion processes occurred during Quaternary can help to detail the understanding of RS coastal plain topography, current Patos Lagoon bathymetry, placers locations, available sediments for coastal barriers and speciation processes.

4.1. Drainage rearrangement rivers paleoroutes

Reorganization of river`s palocourses have been documented, but only few authors approached the causes and processes involved (Bishop, 1995; Brocard et al., 2011). Rivers avulsion of the Jacuí and Camaquã Rivers was already reported by Baitelli (2012) and Weschenfelder et al. (2014). In the current study will be exposed an interpretation of the probable causing process of the drainage reorganization.

The RS coastal plain has a gentle morphology and small differences in topography can be enough to force a change in drainage route. In this study, it is interpreted that the readjustment mechanism occurred in Jacuí and Camaquã rivers was “diversion by top-down”, this process was described by Bishop (1995) and Brocard et al. (2011).

The process recognized was the sediment infilling of an earlier drainage line until the river flow by gravity to lower adjacent areas, or the water level overcome the interfluve.

The process could be accelerated by groundwater flow. In both rivers the interfluve heights are known, as the amount of transgressive aggradation. The ages of Jacuí and Camaquã paleovalley infillings are also known.

Drainage rearrangements can vary the sediment input of a river, biota, location and amount of provenance placers. Researchers attributed the speciation process of a rodent (*Ctenomys minutus*) to the Jacuí and Camaquã paleorivers; these rodents are not able to swim and the rivers would act as physical barriers to reproduction between populations (Fornel et al., 2010). The paleodrainages of Jacuí and Camaquã rivers were associated as favourable areas to the fossilization of skeletons of terrestrial Pleistocene mammals, in RS coastal zone (Cruz et al., 2016). Heavy mineral placers were recognized by Munaro (1994) and Dillenburg et al. (2004) in the in the southern morphological cell of Patos Lagoon; the placers sources were interpreted as the reworking of Pleistocene deposits of Camaquã river.

4.2. Jacuí River paleodrainage lines

In the current drainage configuration, the Jacuí river flows to Guaíba River, which flows to Patos Lagoon. The Guaíba River has a deep and defined channel (Toldo Jr. & Almeida, 2009), which is the most probable paleoroute of Jacuí River during sea level falls. The lowest bathymetric depressions (>7m) in northern cell of Patos Lagoon are next to Guaíba River mouth area (Fig. 4). In front of Guaíba River mouth area there is a depression in Patos Lagoon bathymetry, limited by stable banks (Fig. 4). These banks are ancestral features and are interpreted as paleointerfluves of Jacuí river.

This depression in bathymetry was mapped until the point where the paleochannel was recognized in profile 22 (Figs. 4, 5), indicating an earlier drainage line of Jacuí River which bypass the position of seismic line 22 (Northern paleovalley, Fig. 4 A). The paleochannel recognized in profile 22 was interpreted as S2 deposits, because of the age (> 43,500 yr. BP) revealed by three radiocarbon datings carried out in shell samples of Pa core (table 1) (Weschenfelder et al. 2014). Eastward from the paleochannel recognized in profile 22, in the lagoon margin there is a lake named dos Gateados, which can indicate paleoroute of Jacuí River.

The seismic parameters described for S2 deposits of profile 22 revealed a channel infilling configuration typical of estuarine succession, with inclined/chaotic reflectors, variable amplitude, trending to horizontality upward as the infilling was completing. The infilling may have completed during subtle sea level risings which occurred since Marine Isotope Stage (MIS) 5e (Imbrie et al., 1984).

The marine transgression in the area is attested by diatom samples collected deeper than 16 meters in Pa core, which revealed a marine-dominated paleoenvironment with rare and uncommon freshwater (Santos- Fischer et al. 2016). The diatoms also show strong evidences of freshwater from 16 meters to 10.5 meters depth, evidencing river infilling during Mid-Late Pleistocene. The diatoms in the top of Pa core show a marine dominated paleo environment with influence of freshwater, what probably reflects an esturine/lagoonal Holocene environment (Santos- Fischer et al., 2016).

The paleovalley recognized in profile 22 was partially infilled before the LGM, creating a relative high area, more than 20 meters of S2 deposits (Weschenfelder et al., 2014), forcing Jacuí paleoriver to flow by adjacent depressions during the LGM event (Fig. 5). In addition, this valley was infilled mainly by very fine sands with mud (Pa core - Fig. 3), which are very cohesive, resistant to erosion and minimize the reoccupation possibility.

The valley recognized in seismic line 7 is interpreted as the paleodrainage of Jacuí River during the LGM, classified as S3 deposits by Weschenfelder et al. (2014). The infilling material is recorded from the depth of 13.80 m to the top (Mo core – Fig. 3), is composed mainly by muddy sediments, with Holocene ages (table 1) (Weschenfelder et al., 2014). This paleochannel reached one of the lowest depths (-30m from the current lagoon surface), in concordance with the sea level curve lowest position (-120/130 m lower than current levels). In front of the channel identified in profile 7 there is a lake named do Rincão which suggest the paleoroute of Jacuí River during LGM.

The lowest depths of Mo core are composed mainly by sands and do not provided diatoms samples. However, from 13.80 m depth to the top the diatoms revealed a marine dominated environment with rare and uncommon freshwater, with ages younger than 8040+- 120 years BP (Santos-Fischer et al., 2016). Probably during Holocene this was an estuarine paleoenvironment with strong marine influence, evolving to a lagoon by shallowing the channel and increasing its lateral extension, as the Holocene barrier was been juxtaposed to Barrier III (Pleistocene). This interval is associated to the high accumnulation rates (1.8 cm/year) described in Mo core samples.

4.3. Camaquã River paleodrainage lines

Two paleovalleys recognized in southern morphological cell of Patos Lagoon are interpreted as been drained by Camaquã River in distinct moments (Figs. 4, 6), these valleys were recognized by seismic data images and still notable in the Patos Lagoon bathymetry, because were not completely infilled. A paleochannel with similar dimensions to the current Camaquã River channel was not recognized in seismic profiles of southern paleovalley, difficulting the estimative of when Camaquã River occupied this valley. However, placers mapped by Munaro (1994) were interpreted as reworking of Pleistocene depoists of Camaquã River and suggest that this paleovalley was occupied by Camaquã River during any time along Pleistocene.

The Southern paleovalley probably was occupied by Camaquã River thereafter MIS 5e, during the early stages of falling in sea level, accumulating on average 7 meters of S2 deposits (Weschenfelder et al., 2014). The readjust of drainage lines from the Southern to the Northern paleovalley occurred due the partial infilling of Southern paleovalley by sediments, before the LGM, creating a relative topographical high in comparison with the adjacent area. The gravity action forced the river to flow by the modern valley (northern paleovalley); the process was accelareted by groundwater flow (Fig. 6).

Deltaic sediments were recognized on the top of southern paleovalley in southern morphological cell (Fig. 4). A radiocarbon dating was carried out on the top of these deltaic sediments, revealing a Late Holocene age (4747 +/- 98 cal yr. B.P.). The Patos Lagoon had a morphology similar to modern days from the maximum flooding (5 k.y.

B.P.), minimizing the chances of this delta have been formed by Camaquã River, which the modern delta is 50 km from the paleodelta area. These deltaic sediments are interpreted as deposited by the streams in the western margin of the lagoon, Corrientes, Contagem and Turuçu (Manzolli, 2016) during the Holocene flooding (bay-head delta).

A channel recognized in Northern paleovalley, around Bojuru region, reached deeper depths in comparison with the channels of Southern paleovalley, what indicates that this channel was active during the Last Glacial Maximum, when the sea level reached the lowest position, -120/130 m (Corrêa, 1990; Weschenfelder et al., 2010, 2014). Radiocarbon datings carried out in Bo core sample shells revealed that this channel was active during early Holocene. Previous studies interpreted the Camaquã River flowing by the channel recognized in Bojuru region and following through Barra Falsa feature (Toldo Jr. et al., 1991; Weschenfelder 2010, 2014).

The diatoms samples analysed by Santos-Fischer et al. (2016) revealed a strong marine dominance through the whole channel of Bo core, this probably is due the nearby position to the coast. The ocean waters likely entered the riverine/estuarine system easily during Holocene transgression, due the late juxtaposing of Holocene coastal barrier to Pleistocene relict coastal barrier (III) (Dillenburg et al., 2004).

The mouth of modern Camaquã river is limited by two stable banks, which are interpreted as the paleointerfluves of Camaquã River during the LGM, as occur in northern morphological cell into Guaíba River mouth (Fig. 4). The limits of the northern paleovalley in the lagoon southern morphological, the paleovalley identified in Bojuru region and the Barra Falsa feature indicate the path of Pleistocene/Holocene paleovalley occupied by Camaquã River (Weschenfelder et al., 2010, 2014).

5. Conclusions

The investigations about coastal paleodrainages evolution in RS can help in the understanding of coastal zone geography, coastal water bodies evolution, speciation processes, sediment sources, placers location and fossil sites.

Autogenic factors as paleotopography, sediment input and groundwater flow can force drainage readjustments. Rivers flowing by gentle relief coastal plains respond to little differences in topography that can be originated by sediment input.

The sediment input of Jacuí and Camaquã rivers along Pleistocene was enough to infill the paleovalleys and overcome the interfluves. Forcing the shift to adjacent depressed drainage basins, during subsequent sea level falls.

The paleoroutes of Jacuí and Camaquã rivers remain notable in Patos Lagoon bathymetry despite the partial paleovalleys infilling. Coastal water bodies existent in eastern margin of Patos Lagoon should be investigated as paleodrainages.

The landward (western margin) paleointerfluves are better marked in the Patos Lagoon bathymetry, because were flooded later, suffering less with marine/estuarine erosional processes.

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FIGURE CAPTIONS

Fig. 1 – Study area locality, with seismic profiles and cores positioning.

Fig. 2 – Representation of the stratigraphical framework based on Weschenfelder et al. (2014), with facies interpretation.

Fig. 3 – SPT and gravity cores columnar sections.

Fig. 4 - Comparison between bathymetry and seismic line records in northern (A) and southern morphological cells (B).

Fig. 5 – Representation of the Late Quaternary evolution of Jacuí river.

Fig. 6 – Representation of the Late Quaternary evolution of Camaquã river.

Fig. 1

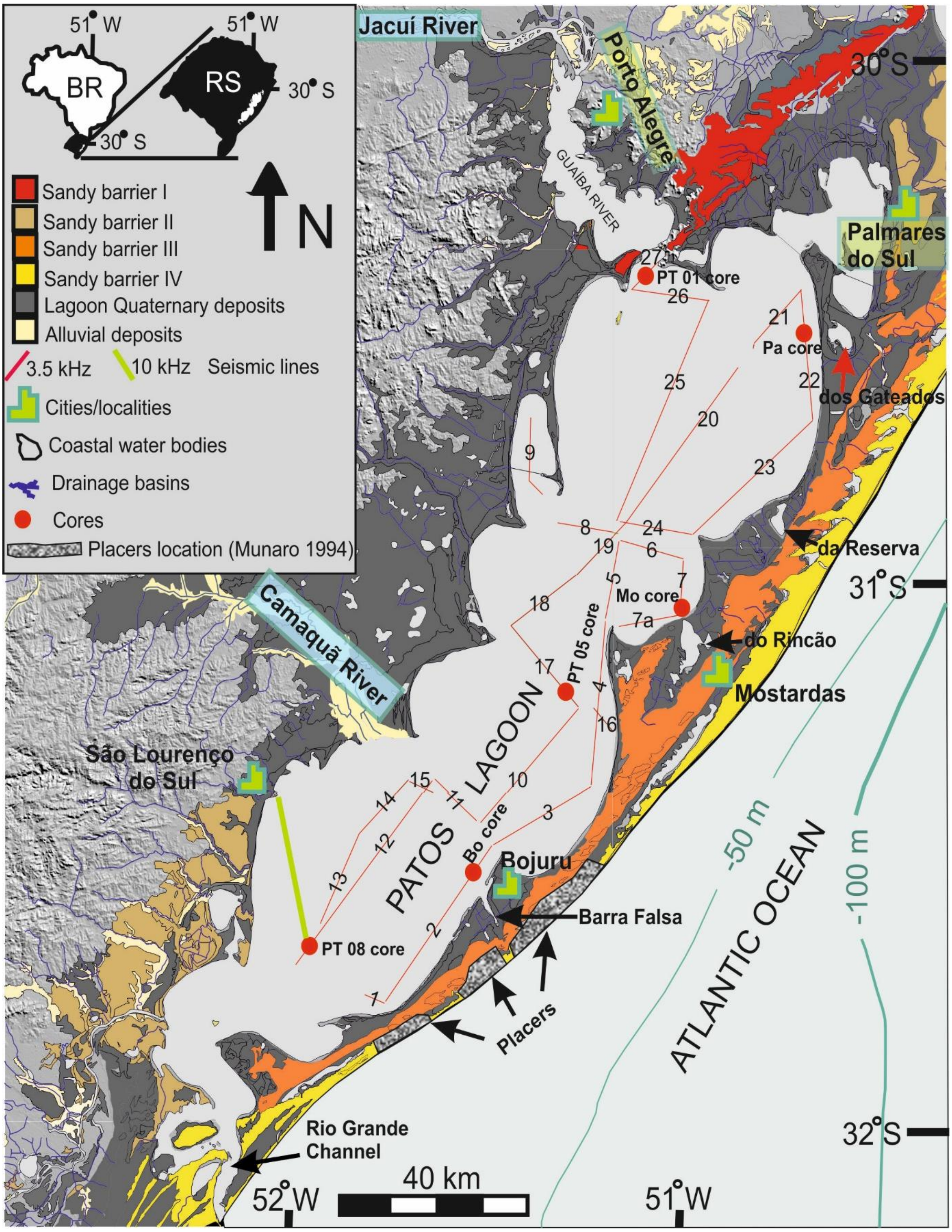

51° W
51° W
BR
RS
30° S
30° S
N
Sandy barrier I
Sandy barrier II
Sandy barrier III
Sandy barrier IV
Lagoon Quaternary deposits
Alluvial deposits
3.5 kHz
10 kHz
Seismic lines
Cities/localities
Coastal water bodies
Drainage basins
Cores
Placers location (Munaro 1994)
Jacuí River
Porto Alegre
GUAÍBA RIVER
Palmares do Sul
30° S
PT 01 core
Pa core
dos Gateados
da Reserva
31° S
Mo core
PT 05 core
do Rincão
Mostardas
Camaquã River
PATOS LAGOON
São Lourenço do Sul
Bo core
Bojuru
Barra Falsa
PT 08 core
Placers
ATLANTIC OCEAN
-50 m
-100 m
32° S
Rio Grande Channel
40 km
52° W
51° W

Fig. 2

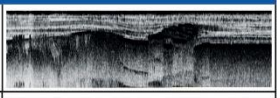
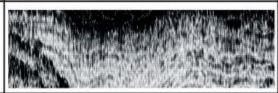
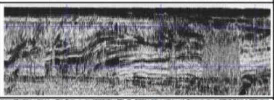
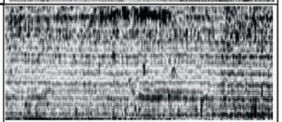
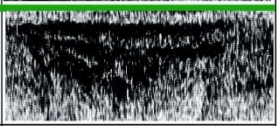
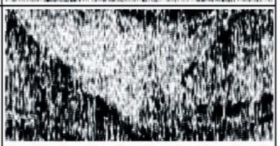
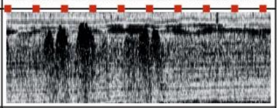
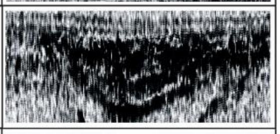
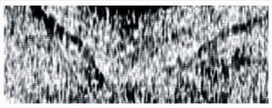
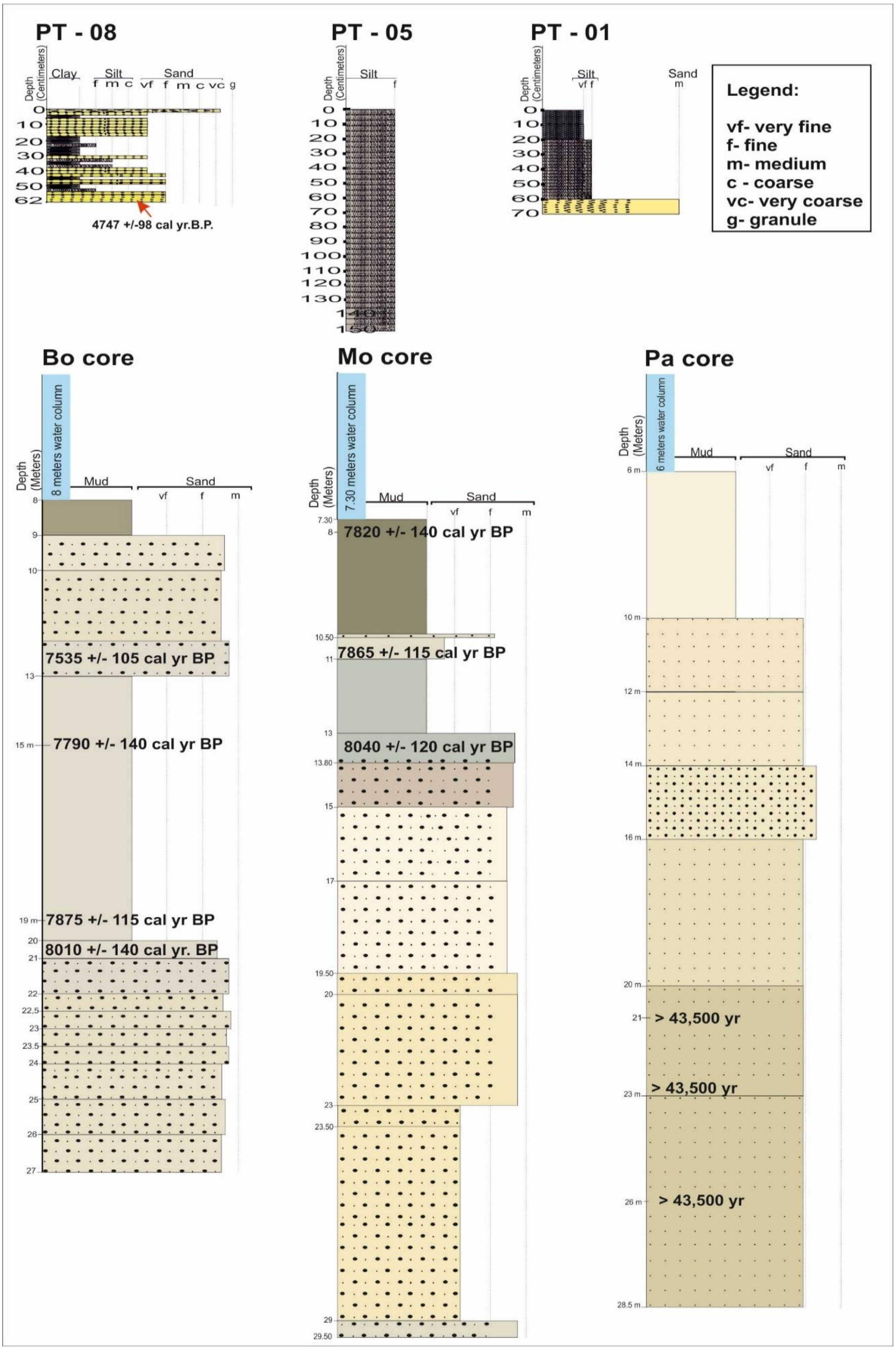
	Unit / System tract	Seismic facies	Sediment and thickness	Depositional environment	Main diagnostic criteria	Seismic image
S3	HST U4	G	Mud/ 0,7 m	Back- barrier lagoon	High lateral continuity; high amplitude reflectors capping the MFS;	
	MFS					
	TST U3	F	Sand ? +- 4m	Overspilling	High amplitude reflectors; bank external geometry; near to paleointerfluve;	
		E	Mud and sand +- 12m	Inlets	Infilling geometry; aggradational/progradational wavy reflectors;	
		D	Mud and sand alternation +- 12m	Bay-head delta	Mounded geometry; progradational and bidi-rectional reflectors;	
		C1	Sand +- 6m	Estuary mouth-bar	Progradational reflectors deposited over estuarine deposits (facies C).	
		C	Mud/ +- 10m	Estuarine	Homogeneous sucession of aggradational reflectors; sheet external geoemtry;	
	TS					
	LST U2	B	Sand/ +- 5m	Fluvial	Channel infilling geometry; high amplitude reflectors; symmetrical and concentric infilling, tending to horizontality;	
		A	Sand/ +- 5m	Fluvial	Channel infilling geometry; low amplitude reflectors; symmetrical and concentric infilling;	
S2	SU1					
	FSST U1	C	Mud/ +- 10m	Estuarine	Homogeneous sucession of aggradational reflectors; sheet external geoemtry;	
		B	Sand/ +- 5 m	Fluvial	Channel infilling geometry; high amplitude reflectors; symmetrical and concentric infilling, tending to horizontality;	
		A	Sand/ +- 5m	Fluvial	Channel infilling geometry; low amplitude reflectors; symmetrical and concentric infilling;	
	SU					
S1						

Fig. 3



PT - 08
PT - 05
PT - 01
Legend:
vf- very fine
f- fine
m- medium
c - coarse
vc- very coarse
g- granule
4747 +/-98 cal yr.B.P.
Bo core
Mo core
Pa core
8 meters water column
7.30 meters water column
6 meters water column
Mud
Sand
7535 +/- 105 cal yr BP
7790 +/- 140 cal yr BP
7875 +/- 115 cal yr BP
8010 +/- 140 cal yr. BP
7820 +/- 140 cal yr BP
7865 +/- 115 cal yr BP
8040 +/- 120 cal yr BP
> 43,500 yr
> 43,500 yr
> 43,500 yr

Fig. 4

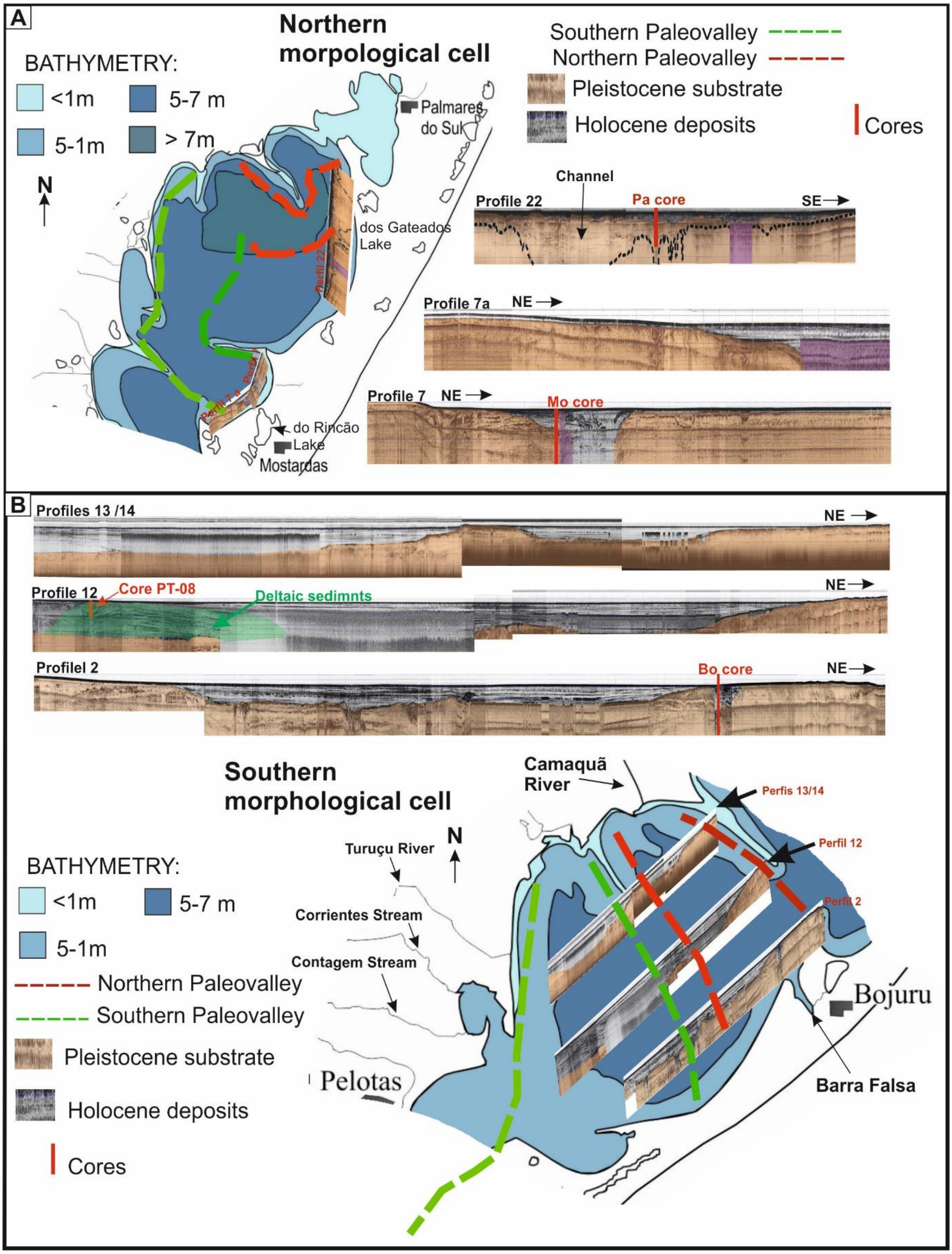

A
Northern morpological cell
BATHYMETRY:
<1m
5-7 m
5-1m
> 7m
N
Southern Paleovalley
Northern Paleovalley
Pleistocene substrate
Holocene deposits
Cores
Palmares do Sul
dos Gateados Lake
Channel
Profile 22
Pa core
SE
Profile 7a
NE
Profile 7
NE
Mo core
do Rincão Lake
Mostardas
B
Profiles 13 /14
NE
Profile 12
Core PT-08
Deltaic sedimnts
NE
Profilel 2
Bo core
NE
Southern morphological cell
Camaquã River
Perfis 13/14
Perfil 12
Perfil 2
Turuçu River
N
BATHYMETRY:
<1m
5-7 m
5-1m
Corrientes Stream
Contagem Stream
Northern Paleovalley
Southern Paleovalley
Pleistocene substrate
Holocene deposits
Cores
Pelotas
Bojuru
Barra Falsa

Fig. 5

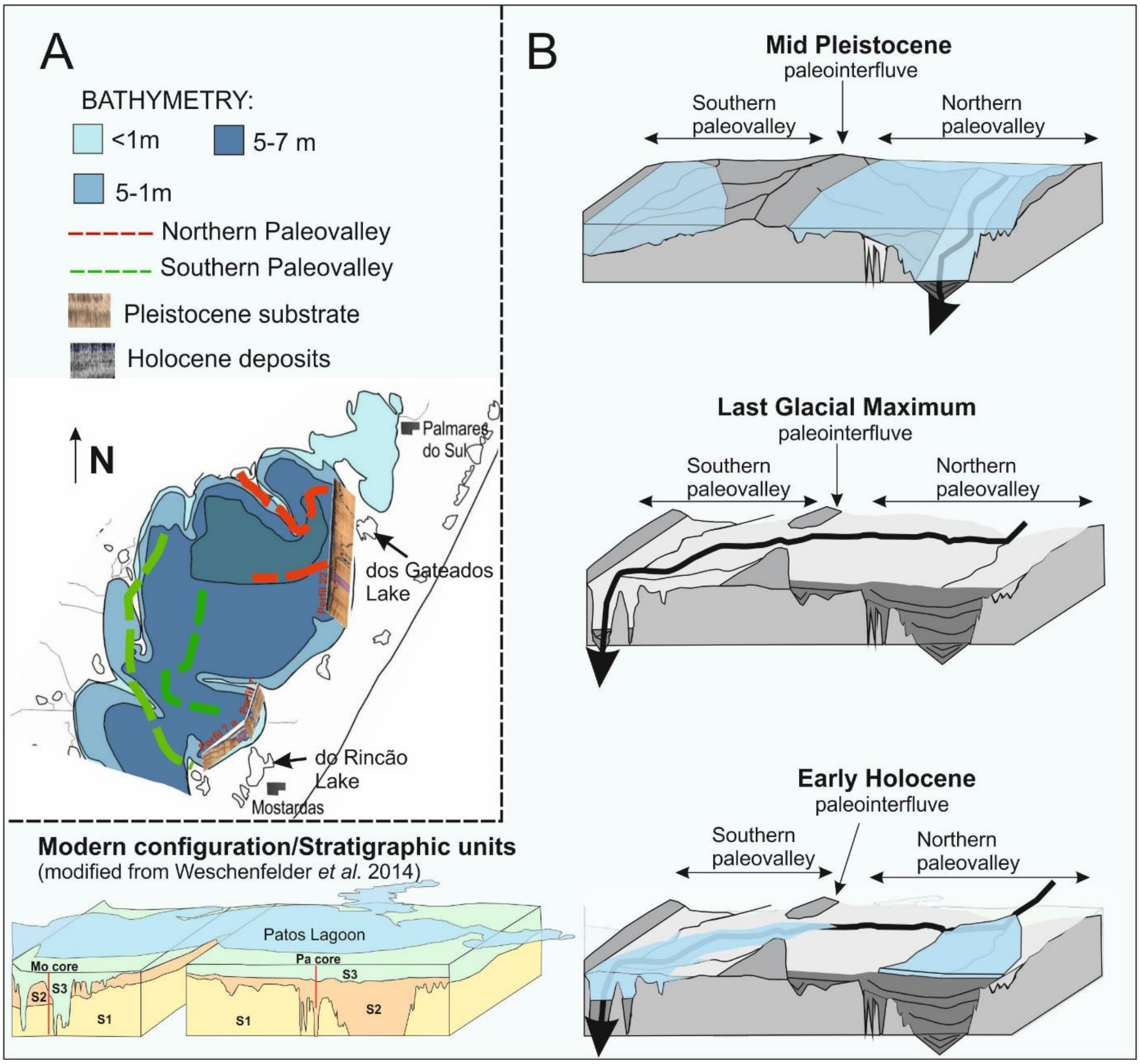
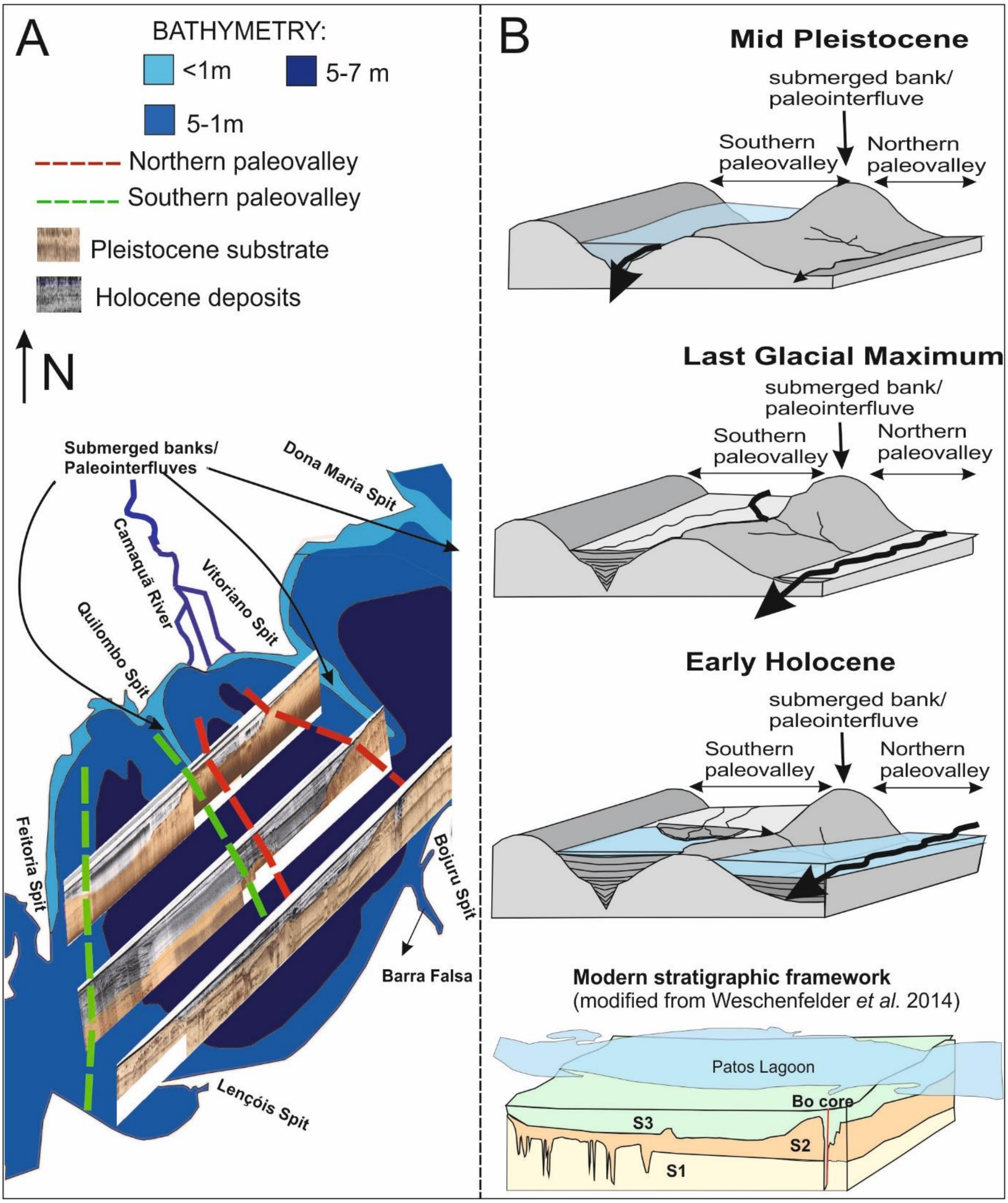

A
BATHYMETRY:
<1m
5-7 m
5-1m
Northern Paleovalley
Southern Paleovalley
Pleistocene substrate
Holocene deposits
N
Palmares do Sul
dos Gateados Lake
do Rincão Lake
Mostardas
Modern configuration/Stratigraphic units
(modified from Weschenfelder et al. 2014)
Patos Lagoon
Mo core
Pa core
S1
S2
S3
B
Mid Pleistocene
paleointerfluve
Southern paleovalley
Northern paleovalley
Last Glacial Maximum
paleointerfluve
Southern paleovalley
Northern paleovalley
Early Holocene
paleointerfluve
Southern paleovalley
Northern paleovalley

Fig. 6


A
BATHYMETRY:
<1m
5-7 m
5-1m
Northern paleovalley
Southern paleovalley
Pleistocene substrate
Holocene deposits
N
Submerged banks/
Paleointerfluves
Dona Maria Spit
Camaquã River
Vitoriano Spit
Quilombo Spit
Feitoria Spit
Bojuru Spit
Barra Falsa
Lençóis Spit
B
Mid Pleistocene
submerged bank/
paleointerfluve
Southern
paleovalley
Northern
paleovalley
Last Glacial Maximum
submerged bank/
paleointerfluve
Southern
paleovalley
Northern
paleovalley
Early Holocene
submerged bank/
paleointerfluve
Southern
paleovalley
Northern
paleovalley
Modern stratigraphic framework
(modified from Weschenfelder et al. 2014)
Patos Lagoon
Bo core
S3
S2
S1

CAPÍTULO 5 – SÍNTESE INTEGRADORA

Os capítulos anteriores, referentes à introdução e aos artigos científicos abordam temas relacionados à evolução de vales incisos e da Lagoa dos Patos. Neste capítulo os resultados serão discutidos de maneira integrada, contextualizando cada conteúdo.

Várias fácies sísmicas foram reconhecidas por meio da análise de dados sísmicos de alta resolução (3,5 e 10 kHz) do interior da Lagoa dos Patos. Os critérios utilizados para descrição e individualização dessas facies foram: geometria externa dos pacotes, e amplitude, configuração interna e terminação dos refletores sísmicos (MITCHUM, 1977).

Os furos de sondagem conferiram maior confiabilidade às interpretações dos dados sísmicos em respeito as facies reconhecidas e individualizadas. As datações por meio do método C-14 atribuíram idade absoluta aos depósitos sedimentares (tabela 1), possibilitando a contextualização geológica e com a curva eustática. Tomando como base este acervo de dados e os respectivos resultados gerados, foi possível interpretar cada paleoambiente registrado e analisar a evolução desses paleovales da Lagoa dos Patos.

Os pacotes sismo-deposicionais foram agrupados em unidades, limitados por superfície-chaves, e associados a tratos de sistema, obedecendo aos critérios da estratigrafia de sequências estabelecidos principalmente no trabalho de Catuneanu *et al.* (2011) (Fig. 2).

As superfícies denominadas de SU e SU 1 (Fig. 2) representam momentos de exposição subaérea ocorridos durante glaciações quaternárias. Rios drenavam a planície costeira do RS nesses períodos de linha de costa recuada, escavando o substrato mais antigo e transportando sedimentos em direção ao oceano. Muitas vezes este substrato era composto de sedimentos lamosos coesivos, barreiras arenosas semiconsolidadas, que dificultam muito a migração lateral, forçando os rios a ajustarem-se seu perfil verticalmente em resposta às forçantes alocíclicas e autocíclicas. Por esta razão, desenvolveram-se os canais em forma de “V” reconhecidos na base dos paleovales.

5.1 – VALES INCISOS PRÉ-LGM

Os rios formaram vales incisos na zona costeira do sul do Brasil (e PCRS) durante os tratos de sistema "Em queda" (FSST) e de "Nível Baixo" (LST), preenchendo parcialmente alguns paleovales pelo próprio aporte fluvial durante sútis elevações do nível do mar (DALRYMPLE; BOYD; ZAITLIN, 1994; SHANLEY; MC CABE, 1994; ZAITLIN; DALRYMPLE; BOYD, 1994; DALRYMPLE, 2006; CATUNEANU *et al.,* 2011; WESCHENFELDER *et al.,* 2014). Estes depósitos foram formados principalmente entre os estágios isotópicos de oxigênio 5 e 2 (MIS 5 e 2; Fig. 3), 120 ka AP e 20 ka AP (IMBRIE *et al.,* 1984).

Avanços nas pesquisas a respeito de paleovales mostraram que durante os Tratos de Sistema em Queda e de Nível Baixo não ocorre um simples transpasse (*bypassing*) de sedimentos em direção ao oceano, mas nestas fases há uma expansão na área da bacia de drenagem, avulsão de canais e, portanto, significativa retenção de sedimentos nas bacias de drenagem (BLUM; TÖRNQVIST, 2000; BLUM *et al.*, 2013).

Durante o longo período de recuo da linha de costa (FSST), os principais rios que drenavam a PCRS (Jacuí e Camaquã) escavaram e preencheram parcialmente vários vales, em latitudes adjacentes (WESCHENFELDER *et al*., 2014). Sutis diferenças topográficas são suficientes para mudar o curso de uma drenagem em uma planície costeira. O vale de um rio parcialmente preenchido pode criar um desnível com relação às adjacências, forçando o curso d'água para regiões topograficamente mais deprimidas (BISHOP, 1995; BROCARD *et al*., 2011). Eventos episódicos de intenso aporte sedimentar podem criar estruturas sedimentares com topografia acentuada, como deltas, cujos depósitos podem atingir dezenas de metros de espessura.

Na ampla planície costeira do RS, alguns destes paleovales mais antigos foram parcialmente preenchidos, preservando depósitos de mais de 20 metros de espessura, como é o caso de um dos paleovales do rio Jacuí reconhecido no perfil 22. Estes depósitos areno-lamosos são coesivos, dificultaram a reincisão e favoreceram o reajuste fluvial para áreas das adjacências. Estes casos de reajuste das linhas de drenagem devido a fatores autocíclicos (aporte sedimentar e paleotopografia) são mais notáveis nos rios cujas bacias drenam grandes áreas e possuem aporte sedimentar significativo.

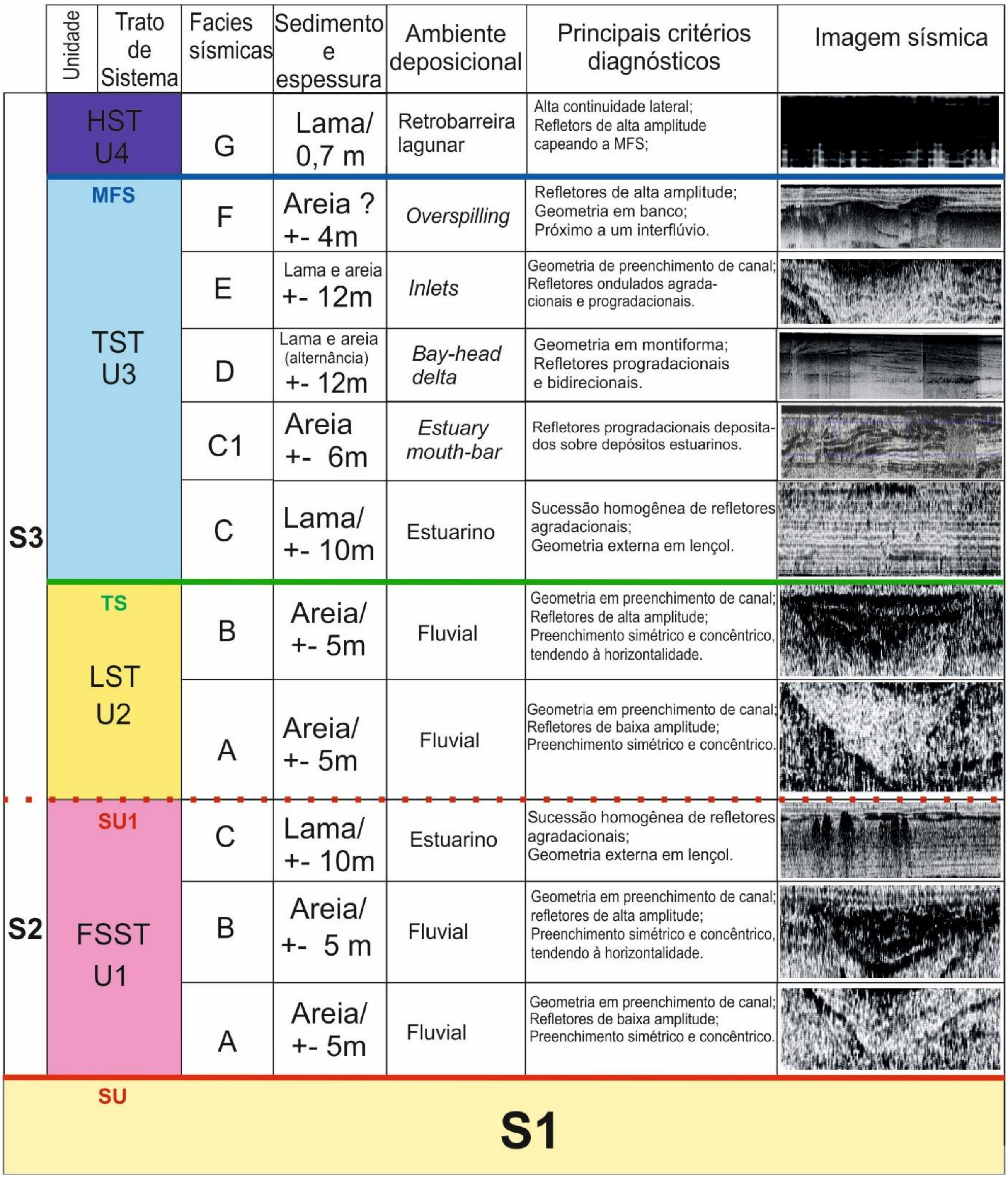


Figura 2: Resumo do arcabouço estratigráfico na Lagoa dos Patos, agrupando depósitos às unidades sísmicas.

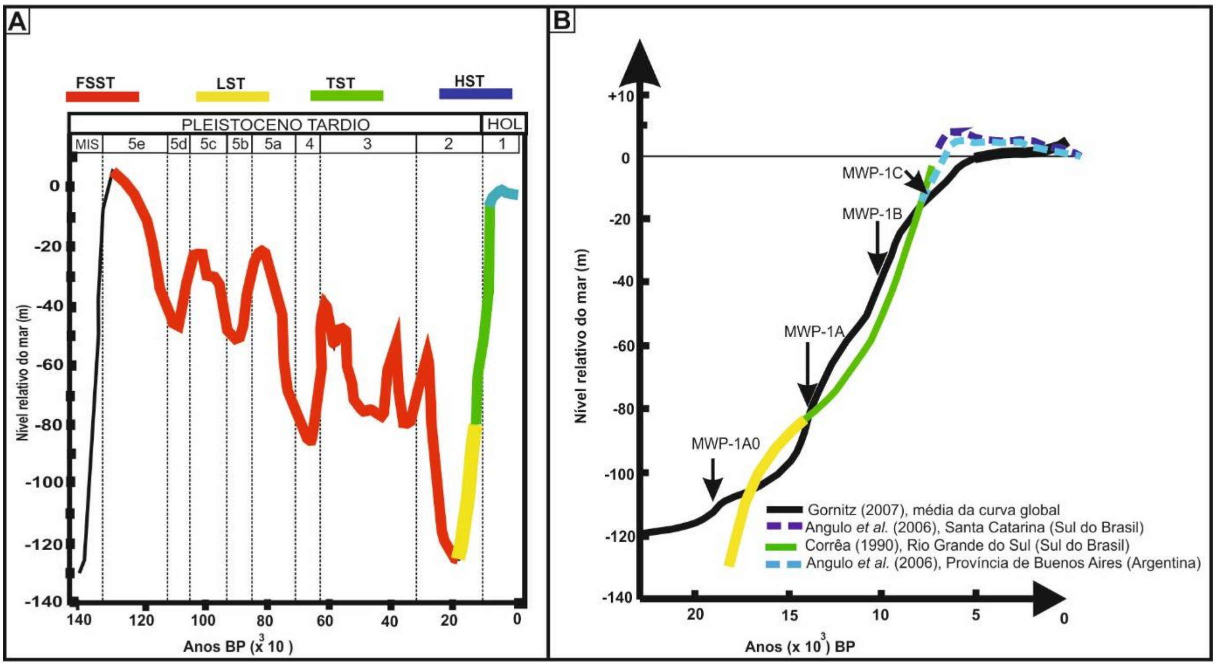


Figure 3: A- Representação dos Tratos de Sitema na curva eustática; B- Representação dos MWP pós-glaciais em curvas de nível do mar regionais e globais.

5.2 – VALES INCISOS PÓS-LGM

Após 20 ka AP a curva global de nível do mar apresenta pulsos transgressivos, também identificados na zona costeira do sul do Brasil (CORRÊA, 1986; GORNITZ, 2007; SMITH *et al.,* 2011). A agradação vertical, assim como o aumento lateral na área de deposição são consequências da progressiva submersão das planícies de inundação fluviais, marcada pela superfície transgressiva (TS). Durante o Trato de Sistemas Transgressivo os depósitos fluviais tornaram-se estuarinos, com significativo aumento do espaço de acomodação lateral e vertical em áreas continentais. O pico da taxa de acumulação de sedimentos registrado atingiu ~ 18 mm/ano em alguns locais, medidos entre 8.010 ± 140 anos cal AP e 7.535 ± 105 anos cal AP, associados a períodos de rápidas elevações do nível do mar (*Melt Water Pulses*; GORNITZ, 2007; SMITH *et al.,* 2011).

Durante a transgressão, a barreira holocênica avançava em direção ao continente, até justapor-se à barreira pleistocênica III durante o máximo transgressivo (CORRÊA, 1986; DILLENBURG; TOMAZELLI; BARBOZA, 2004; LIMA *et al.,* 2013). O represamento culminou na inundação completa das áreas interfluviais e formação da Lagoa dos Patos, cujos depósitos formam a Superfície de Inundação Máxima (MFS).

A sobreposição das duas barreiras fechou *inlets* holocênicos, cujas feições remanescentes permanecem evidentes na margem leste da Lagoa dos Patos. Após o nível de mar máximo holocênico (5,1 ka AP) a barreira holocênica desenvolveu-se e estabilizou-se, simultaneamente a um sutil rebaixamento no nível do mar (CORRÊA, 1986; DILLENBURG; TOMAZELLI; BARBOZA, 2004; ANGULO; LESSA; SOUZA, 2006).

A sedimentação dentro dos vales incisos não preencheu completamente os paleovales, mesmo após o nível máximo do mar máximo. As dimensões e geometria dos paleovales ainda são notáveis na batimetria da Lagoa dos Patos, principalmente na margem lagunar oeste, que por ser mais distante da costa preservou estruturas relictas de processos erosivos e deposicionais costeiros/marinhos.

A morfologia batimétrica da Lagoa dos Patos foi dividida por Toldo Jr. (1991) em duas regiões: margem interna/flanco lagunar (isóbatas entre 0 - 5m) e piso lagunar (isóbatas > 5m). Na margem lagunar, observam-se bancos submersos de batimetria rasa (< 1metro), que não se desenvolvem atualmente, sobre os quais crescem pontais arenosos. Toldo Jr. (1991) intepreta os bancos arenosos como resultado da dinâmica pretérita, que hoje estão submersos e desvinculados da dinâmica que os fez crescer.

As principais paleodrenagens escavaram vales perpendicularmente à linha de costa; não por acaso a orientação dos bancos arenosos da margem oeste da Lagoa dos Patos é perpendicular à costa. Os dados sísmicos permitem correlacionar os bancos submersos aos limites dos vales (interflúvios), enquanto o piso lagunar é coincidente com as porções mais profundas dos paleovales.

A espessura de depósitos transgressivos é contrastante ao comparar os bancos submersos (< 1 metro) e o piso lagunar, no assoalho as porções de sedimentação mais significativa ultrapassaram 20 metros. Este contraste ocorre pois os interflúvios tornaram-se sítios de sedimentação ativos após sua submersão, enquanto as porções mais profundas dos vales acumulam sedimentos desde o Trato de Sistemas em Queda.

A paleotopografia dos vales parcialmente preenchidos é influente na hidrodinâmica atual da Lagoa dos Patos. Os bancos submersos (paleointerflúvios) representam irregularidades na linha de margem lagunar, exercendo influência na incidência de ondas oblíquas à margem, seguindo o princípio de refração. Assim, estas ondas erodem os bancos submersos e desenvolvem sobre eles os pontais arenosos holocênicos (TOLDO Jr., 1991). Nas porções centrais das células lagunares (depocentro dos paleovales), a espessa coluna d`água (> 6 m) inibe a ação das ondas sob o fundo, configurando o piso lagunar como um ambiente de baixa energia e deposição basicamente de silte e argila.

Este controle no desenvolvimento de pontais exercido pela morfologia de paleovales é ausente nos modelos de Zenkovich (1959) e Ashton, Murray e Olivier (2001). Porém, estes modelos concordam na necessidade de irregularidades na linha de costa para desenvolvimento de pontais arenosos. Estudos futuros devem observar a presença de paleovales como condicionantes para crescimento de pontais.

5.3 – CONCLUSÕES

Os vales incisos iniciaram seu preenchimento desde o estágio de queda do nível do mar (FSST), aumentando o espaço e as taxas de acomodação durante estágios transgressivos.

A variabilidade vertical de facies deposicionais ocorreu devido à variação eustática, enquanto a variabilidade lateral é devido às forçantes autogênicas, como: aporte sedimentar, paleotopografia, proximidade do oceano, proximidade da área fonte, energia do ambiente deposicional, etc.

A ocorrência de uma fácie sísmica não é limitada a um trato de sistema específico, entretanto indica uma tendência no nível do mar.

Os canais fluviais escavados durante o último máximo glacial (LGM) são mais profundos do que os formados durante o trato de sistema em queda (FSST), porque durante o LGM o nível relativo do mar baixou mais.

Os canais em forma de V (facies A e B) são formados devido ao substrato rígido, constituído de lama coesiva ou barreiras arenosas pedogeinizadas, depositadas durante estágios de nível de mar alto anteriores. O padrão de confinamento destas drenagens impossibilitou o ajuste lateral dos canais, os quais tiveram que ajustar seu perfil de equilíbrio verticalmente (agradação), acumulando carga de fundo por perda de competência de transporte.

Fatores autogênicos como paleotopografia, aporte sedimentar e fluxo d`água subterrâneo podem forçar reajustes de drenagem. Estes fatores foram os responsáveis pelas reorganizações nas rotas de drenagem dos rios Jacuí e Camaquã, ocorridas durante os tratos de sistema em queda (FSST) e de nível baixo (LST).

As bacias de drenagem pleistocênicas tornaram-se bacias de deposição continental, cujos principais depósitos de preenchimento são lamas transgressivas de paleoambientes estuarinos.

O espaço de acomodação aumentou verticalmente e lateralmente com a inundação de áreas continentais. Este processo de inundação não ocorreu de maneira uniforme, respondendo à pulsos de degelo (MWP). Os vales incisos foram as primeira áreas a ser inundadas, enquanto os interflúvios permaneceram expostos até o máximo transgressivo holocênico. Portanto, o acúmulo de sedimentos nas porções mais profundas dos vales foi mais significativo do que nas zonas interfluviais.

O aporte sedimentar não foi suficiente para preencher completamente os vales. Bancos submersos na margem lagunar oeste representam estruturas relictas das zonas interfluviais e influenciam na incidência de ondas sob as margens lagunares. Como consequência, a batimetria atual da Lagoa dos Patos preserva sutilmente a morfologia das paleodrenagens.

O processo de segmentação lagunar por meio do desenvolvimento dos pontais é incompleto, por causa do jato d`água e também porque as ondas que remobilizam areia atuam apenas sob o fundo da margem lagunar (rasa). O piso lagunar das porções centrais das células não é remobilizado devido a lâmina d`água de 6 metros de profundidade, que impede a ação das ondas sob o fundo. Os bancos submersos são essenciais para desenvolvimento destes pontais lagoa adentro.

A Lagoa dos Patos atingiu sua configuração atual após a inundação de vales adjacentes. O principal fator forçante alogênico controlando a deposição na Lagoa dos Patos é a variação eustática, exercendo influência direta na criação e redução do espaço de acomodação.

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