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MOVIMENTOS DE MASSA E EVOLUÇÃO MORFOSSEDIMENTAR DO MEGADESLIZAMENTO DO CHUÍ, BACIA DE PELOTAS

Dissertação submetido ao Programa de Pós-graduação em Oceanografia Física, Química e Geológica da Universidade Federal do Rio Grande, como requisito para a obtenção do Grau de Mestre em Oceanografia

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Dissertação

MOVIMENTOS DE MASSA E EVOLUÇÃO MORFOSSEDIMENTAR DO MEGADESLIZAMENTO DO CHUÍ, BACIA DE PELOTAS

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“Is this the real life?
Is this just fantasy?
Caught in a landslide
No escape from reality”
(Queen, 1975)

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Sumário

Resumo

Processos de deslizamento de massa em ambientes marinhos ocorrem a partir de grandes pacotes sedimentares que se movem talude abaixo após a ruptura da estabilidade sedimentar, resultando em depósitos de transporte de massa (MTD). Esses depósitos apresentam diferentes fácies sísmicas de acordo com o grau de deformação durante o processo de deslizamento. O Complexo de Megadeslizamentos do Chui estende-se por 650 km a partir do talude continental até a planície abissal na Bacia da Argentina e representa uma extensa feição morfossedimentar encontrada na margem continental sul brasileira. O objetivo deste estudo foi caracterizar as estruturas geomorfológicas resultantes do processo de movimentação de massa do Complexo do Megadeslizamento do Chui, utilizando dados de sísmica de reflexão de fonte sísmica do tipo *Airgun*. A interpretação dos refletores foi possível por meio do software IHS Kingdom, com o objetivo de delimitar e interpretar a geometria, continuidade, amplitude e formas externas de grupos de horizontes sísmicos. Os depósitos recentes representam dois deslizamentos provenientes de porções adjacentes da margem a partir da escarpa de cabeceira definida pelo falhamento principal. Macroondulações de sedimentos e canais submarinos com diques marginais (levees) situam-se entre os depósitos de movimentos de massa (MTDs). A presença de levees é normalmente associada a fluxos hiperpicnais ou correntes de turbidez, frequentes e contínuas o suficiente para haver o extravasamento dos canais formando os diques marginais. A presença de macroondulações de sedimentos (mudwaves) sugere o retrabalhamento por correntes de contorno. Os MTDs representam uma grande desestabilização do talude, envolvendo parte do Cone do Rio Grande, que representa o principal depocentro da Bacia de Pelotas. Unidades sísmicas semitransparentes representam a sedimentação

hemipelágica e apresentam quebras em sua continuidade, representando falhas normais, sugerindo forças distensivas nas áreas laterais do principal depocentro. Escarpas no talude superior representam áreas potenciais de instabilidade que podem induzir futuros eventos de deslizamento do flanco sul do Rio Grande Cone. Os gatilhos que podem ter causado os episódios de deslizamento podem estar associados à presença de hidratos de gás, alta sedimentação e erosão por correntes de contorno.

INTRODUÇÃO GERAL

A Bacia de Pelotas é a bacia sedimentar mais ao sul da Margem Continental Brasileira, seus limites são definidos pelas feições conhecidas por Alto de Florianópolis (limite norte) e Alto do Polônio (limite Sul). De acordo com Asmus e Porto (1972), a Bacia de Pelotas é definida como uma bacia marginal subsidente preenchida por sedimentos clásticos continentais e transicionais. Sua origem está relacionada ao rifteamento que marcou a abertura do Atlântico Sul a partir do Jurássico, iniciando a formação das bacias marginais brasileiras. Existem registros da Bacia de Pelotas com evidências de preenchimento desde a fase Rifte e possivelmente também da fase pré-rifte. Contudo, por se tratar de uma margem vulcânica, estas fases são preenchidas principalmente por basaltos. Não se confirma, no entanto, se há intercalações de sedimentos junto com as lavas, pois não foram realizadas sondagens nestes intervalos na bacia (Stica et al., 2014).

O Cone do Rio Grande é uma feição deposicional situada na borda da margem continental sul Brasileira. Caracterizada por consecutivos sistemas progradacionais provenientes do aporte de sedimentos fluviais e terrígenos influenciados pela variação do nível do mar (Castillo et al., 2009), avançando a partir da quebra da plataforma até a região do sopé continental, entre as cotas batimétricas de 100 m até 3.600 m (Zembruscki, 1979). A formação sedimentar do Cone do Rio Grande tem sua origem atribuída a uma alta sedimentação a partir do Mioceno (Bassetto et al., 2000). Segundo Razik et al.(2013), a região do Cone do Rio Grande também apresentou um elevado aporte de sedimentos entre o final do Pleistoceno e a metade do Holoceno (14.000 - 4.000 anos atrás), oriundos da bacia de drenagem La Plata, reconhecidamente a segunda maior do mundo (Berbery and Barros, 2002).

Em decorrência da sedimentação ocorre a presença de hidratos de gás na região, associados a nódulos carbonáticos. A presença dos nódulos é possivelmente associada ao aumento da alcalinidade no sedimento resultante da oxidação anaeróbica do metano. Por essa razão, recentemente, a região despertou o interesse para a exploração de hidratos de gás (Miller et al., 2015).

Nas adjacências do Cone, o talude continental sofre grande influência das correntes de contorno que atuam transportando a Água Intermediária Antártica, Água de fundo circumpolar superior, Água de Fundo do Atlântico Norte e a Água de Fundo Circumpolar Inferior, além disso, a Corrente do Brasil que à medida que alcança maiores latitudes se torna mais profunda e forte (Stramma and England, 1999). Essa influência acaba transportando sedimentos, causando uma quebra na estabilidade do talude. A erosão por correntes de fundo pode ser um fator condicionante de instabilidades do talude continental, propiciando a ocorrência de eventos de transporte de massa.

Desta forma, o preenchimento das bacias sedimentares é o resultado da combinação da ação de processos gravitacionais, talude abaixo e de processos erosivos e deposicionais associados à ação das correntes de fundo, paralelas à margem continental (correntes de contorno). Os processos gravitacionais são a principal forma de transporte de sedimento para regiões profundas. Esse transporte ocorre quando a tensão de cisalhamento é maior do que a força de resistência ao cisalhamento do sedimento, assim, a massa que se encontra estática entra em movimento (Einsele, 2000).

Movimentos de massa submarinos são processos de re-sedimentação causados por transporte gravitacional dos sedimentos da margem em direção à bacia profunda. São classificados de acordo com o comportamento reológico da massa e com a natureza do mecanismo de suporte dos grãos durante o transporte. De acordo com Booth et al. (1993), os mecanismos de transporte gravitacional de massa podem ser classificados de acordo com o grau de desagregação interna da massa transportada. Os processos de queda de blocos, deslizamentos e escorregamentos envolvem deslocamento de rochas e pacotes de sedimentos, sobre superfícies de escorregamento, mantendo a coerência interna. Os fluxos gravitacionais envolvem transporte de uma mistura de sedimentos e fluido, onde a coerência interna e acamamento deposicional são destruídos e os grãos em movimento pela ação da gravidade são responsáveis pelo fluxo fluido. Quatro tipos de fluxos gravitacionais de sedimentos são reconhecidos: 1) fluxos de detritos (clastos suportados pela matriz); 2) fluxos de grãos (clastos suportados pelo contato grão a grão); 3) fluxos fluidos ou liquefeitos (grãos suportados pelo escape de fluidos de poro) e 4) fluxos turbidíticos (clastos suportados pela turbulência do fluido).

Os locais mais propensos são aqueles com espessas camadas de sedimento, talude íngreme e elevado aporte de sedimento. Essas características são encontradas principalmente em fiordes, deltas progradantes, cânions submarinos e no talude continental. Os principais fatores que desencadeiam esses eventos são a intensa acumulação de sedimento, erosão, atividade tectônica (terremotos), ondas de tempestades (águas rasas), vulcanismo, gases e hidratos de gás, diapirismo e, ocasionalmente, atividade humana (Lee et al., 2007).

Os movimentos de massa podem causar danos a estruturas fixas no fundo submarino, como por exemplo, cabos de telecomunicações e plataformas de petróleo. Podem também gerar *tsunamis* causando destruição na linha de costa, sendo objeto de constantes revisões bibliográficas (Bull et al., 2016).

A medida que o fluxo percorre o talude e alcança a região do sopé, o movimento perde velocidade, devido ao atrito com o fundo e a diminuição na declividade. O material deposita em partes, o fluxo mais denso (detritos) disposto primeiro enquanto que a parte menos densa acaba formando uma franja de detritos na borda do deslizamento. A partir desse momento, as correntes de contorno de fundo passam a transportar os sedimentos paralelamente às linhas batimétricas. O transporte resulta em sedimentos bem selecionados, com elevada porosidade e permeabilidade. Além disso, as correntes se mantém por longos períodos, permitindo que os depósitos, ocasionalmente, registrem condições de oscilações energéticas (Shanmugam, 2008).

Os depósitos de fluxo de detritos são caracterizados pela sedimentação do fluxo mais denso, sendo formado por clastos grossos mal selecionados em uma matriz de areia média a fina ou lama, dependendo da área fonte (Lamarche et al., 2016). Os depósitos de corrente de turbidez são gerados pelo fracionamento decorrente da diminuição de energia e da granulometria do material transportado pelo fluxo turbulento durante a sedimentação, resultando na chamada Sequência de Bouma (1962). Correntes de contorno atuam sobre o material depositado previamente, gerando depósitos chamadas de contornitos (Fig 1) (Heezen et al., 1966; Stow and Lovell, 1979). Estes depósitos são decorrentes da inter-relação da velocidade e variabilidade das correntes de fundo; contexto morfológico; disponibilidade e tipo de sedimento; e o período de tempo que a corrente atua sobre o fundo. Essa interação resulta na vasta diversidade morfológica dos depósitos e das feições contorneias (Faugères et al., 1999; Rebesco et al., 2014). Alterações em depósitos podem indicar variações sutis em correntes profundas que são evidências em variações de longo prazo nos padrões de paleocirculação e condições climáticas pretéritas (Rebesco and Stow, 2001).

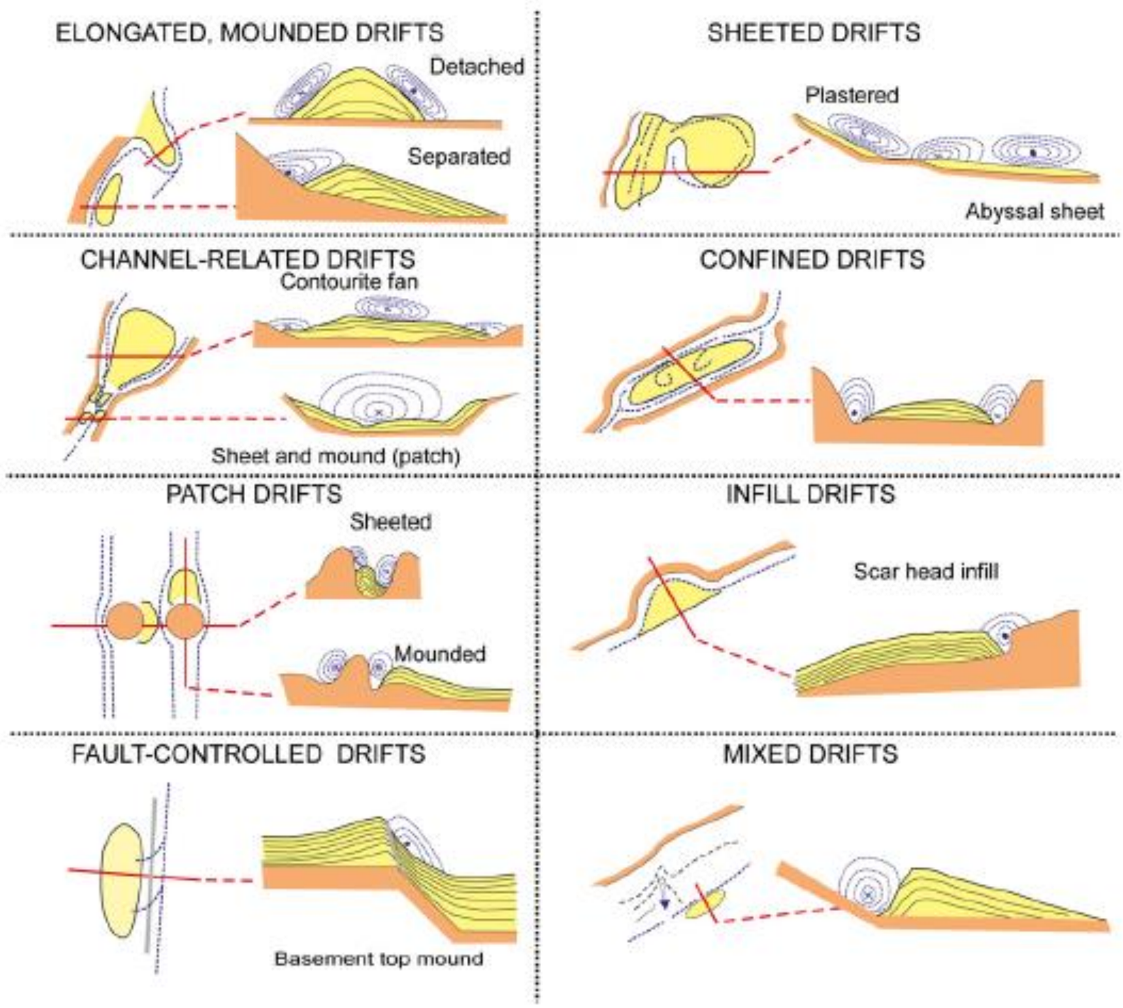

Figura 1. Diversas morfologias geradas pela ação das correntes junto a depósitos gerando depósitos de correntes de contorno (contornitos) (Rebesco et al., 2014).

Movimentos de massa são fenômenos de difícil observação direta, os registros encontrados foram reconhecidos pelos impactos causados na atividade humana. Outros registros indiretos são os depósitos associados a deslizamentos. Na margem continental brasileira, na região do Cone do Amazonas, foram identificados inúmeros megadeslizamentos (Reis et al., 2016; Silva et al., 2010). Em estudos realizados nos Estados Unidos, Booth et al. (1993) observaram que cerca de 47% dos casos ocorreram no talude continental. A inclinação mostra ser fator importante, pois os locais que o fundo marinho apresenta declividades entre 3° e 4° representaram 27% dos casos.

Área de estudo

A feição de interesse desse estudo chamada Megadeslizamento do Chuí foi identificada por Reis et al., 2016, sendo reconhecida como um conjunto de escorregamentos submarinos de larga escala localizados na face Sul do Cone do Rio Grande. O depósito é dividido em setores morfológicos, que caracterizam a morfologia e estruturas deposicionais (fig. 2). A região do talude é caracterizada por uma vasta zona de remoção, limitada lateralmente por escarpas com largura estimada entre 50 – 85 km, com extensão talude abaixo de cerca de 180 km. As escarpas laterais variam entre 400 m, na região proximal, até 100 m na parte mais distal. A extensão total do depósito apresenta 650 km talude abaixo e uma área de 150.000 km² com espessura de 400 m.

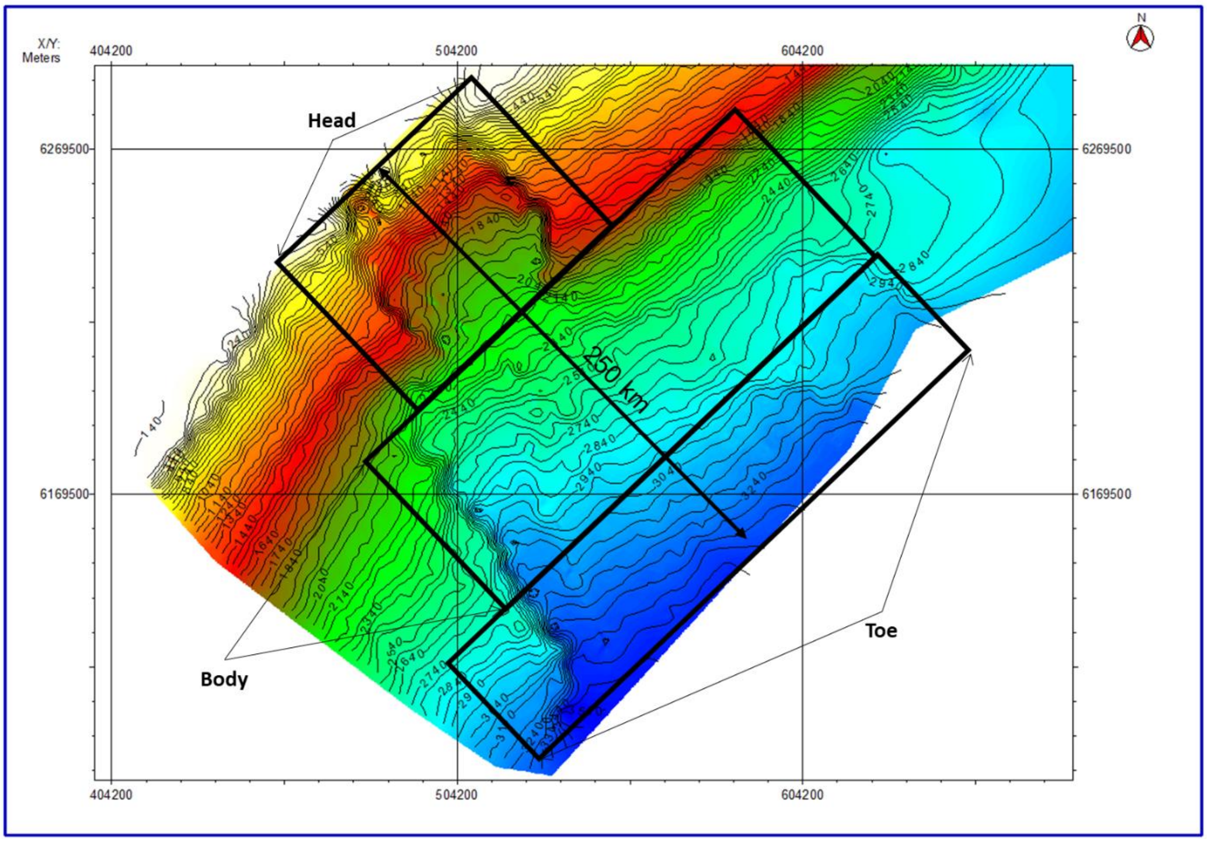

Figura 2. Região do talude em que está localizada a zona de remoção do Megadeslizamento do Chui dividida em setores segundo Reis et al.(2016).

Estes setores foram classificados de acordo com o arranjo e configuração dos depósitos.

De acordo com (Reis et al., 2016), o depósito é composto por escorregamentos translacionais na porção superior. Na região inferior são encontradas camadas plano paralelas classificadas como turbiditos, juntamente com depósitos hemipelágicos. Intercaladamente às camadas de deslizamentos são encontrados contornitos. A identificação dessas estruturas indicou a presença de uma série de deslizamentos, resultantes do falhamento principal que cortam sedimentos do Plioceno ao Quaternário.

OBJETIVOS

Geral

- Estabelecer a relação entre os depósitos de movimentos de massa do megadeslizamento do Chuí, no contexto da evolução sedimentar desta porção da Bacia de Pelotas.

Específicos

- Caracterizar a natureza dos processos sedimentares e o grau de desestruturação interna através da análise das fácies sísmicas da região do depósito;
- Estabelecer a relação entre as feições morfossedimentares presentes no megadeslizamento com os processos de preenchimento sedimentar nesta porção sul da Bacia de Pelotas;
- Caracterizar os depósitos associados à processos de instabilidade do talude e de retrabalhamento por correntes de fundo;

MATERIAL E MÉTODOS

Os dados utilizados nesse estudo foram adquiridos durante o programa sísmico 2D da Bacia de Pelotas Fase II pela empresa Spectrum Geo e registrados na Agência Nacional de Petróleo, Gás Natural e Biocombustíveis – ANP com o nome 0257_PEP2_2015.

Os dados foram gerados através da técnica de Sísmica de Reflexão 2D, com fonte emissora do tipo *Airgun* (10-100 Hz), em que as ondas sísmicas emitidas (pulsos) são geradas artificialmente na superfície e se propagam pela subsuperfície através de meios heterogêneos, sujeitas a reflexão a cada horizonte de contraste com características físicas das rochas e sedimentos. O método de sísmica de reflexão possibilita a identificação e interpretação dos refletores sísmicos. Os dados adquiridos com o uso dessa fonte específica sísmica permitem a exploração de horizontes mais profundos (alta penetração) com significativa resolução.

Ao todo, foram interpretadas 77 linhas sísmicas, cobrindo uma área de 227.300 km^2 da Bacia Pelotas. As linhas possuem espaçamento de 10 km por 10 km, com perfis *dip* e *strike* desde a quebra da plataforma até a elevação continental (Fig. 3). Para este estudo nós tivemos acesso à porção superior dos perfis sísmicos (0,5 s). Perfis sísmicos 2D adicionais foram disponibilizados pela Diretoria de Hidrografia e Navegação, permitindo a visualização de todo o pacote sedimentar até o embasamento da bacia. O foco do estudo é a área do megadeslizamento do Chuí nas imediações do Cone do Rio Grande (Fig. 3).

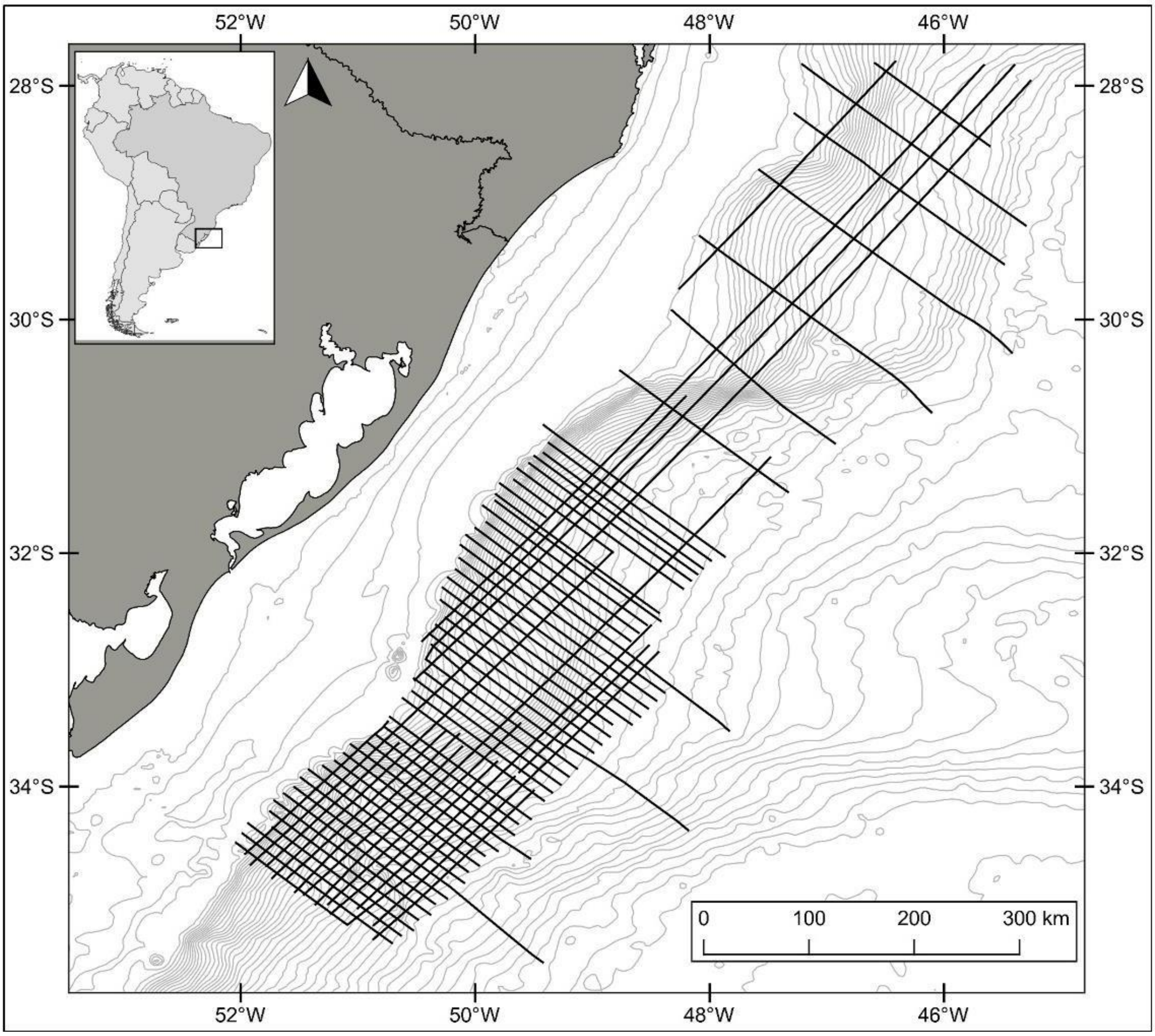

Figura 3. Disposição dos perfis sísmicos (*strike* e *dip*) na porção do talude da Bacia Pelotas.

A descrição e interpretação dos perfis sísmicos 2D de reflexão multicanal foi realizada utilizando-se o software IHS Kingdom®, que permite identificar e destacar os refletores sísmicos de interesse. A análise de fácies sísmicas é composta pela interpretação da configuração, continuidade, amplitude e frequência dos refletores e por sua geometria externa, seguindo os princípios clássicos de estratigrafia sísmica (Mitchum et al., 1977).

ARTIGO

Morphosedimentary evolution of Chui Megaslide: Implications for the southern Brazil margin stability.

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Abstract

Mass sliding processes can disrupt and displace large sedimentary packages that move downslope after the rupture of the sedimentary stability, resulting in mass transport deposits (MTD). These deposits have different seismic facies according to the energy and internal deformation during the sliding process. The Chui Megaslide Complex, extends 650 km from the continental slope into the Argentine Basin abyssal floor leaving a large slide scar bordered by steep lateral escarpments on the southern slope of the Brazilian continental margin, near the border with Uruguay. In this study, we characterized the near-surface geomorphological structures and internal configuration of mass transport deposits of the Chui Megaslide Complex, using 2D reflection seismic images from the upper 0.5 s sedimentary interval (nearly 500 m below seabed). Two mass transport deposits, originated from different areas on the upper slope main failure area indicating. Migrant sediment waves and submarine channels occur between the MTD's. The formation of channels with well-developed levees are normally associated to hyperpycnal flows or turbidity currents, which indicate continuous processes, long enough to build the channel levees. The MTD's represent large destabilization of the slope, involving part of the Rio Grande Cone, which is the main depocenter of the Pelotas Basin. Hemipelagic, semi-transparent units are affected by normal faults, related to extensional forces in the southern side of the Rio Grande Cone. Escarpments at the upper slope are potential areas for further collapse in the southern flank of the Rio Grande Cone. The triggering mechanisms can be associated to high sedimentation rates; to the presence of gas hydrates, as confirmed by the presence of bottom-simulating reflectors (BSR); and by the action of contour currents eroding the foot of the slope.

Keywords: continental slope processes; submarine morphology; stratigraphic evolution; seismic interpretation; contourites; mass transport deposits

1. Introduction

Submarine landslides formed by gravity-driven movements are important agents of sediment transport from the continental shelf to ocean basins. The combination of gravity transport and other processes, such as contour current reworking, shapes the ocean basin morphology and represents important re-depositional features (Hampton et al., 1996). Chaytor et al. (2009) presented statistical information about submarine landslides distribution, indicating greater occurrence on open continental slope with gradients of 5° or less. The distribution is associated to thick sediment bodies and environmental loads. The accumulation of large volumes of sediment changes the slope stability and causes mass movement and transport. The triggers of submarine landslides are associated to multiple factors: rapid sediment accumulation, erosion, earthquakes, volcanoes, waves, gas and gas hydrates, groundwater seepage, diapirism and human activity (Lee et al., 2007).

The study region is located in Pelotas Basin, an offshore marginal basin in the southern passive Brazilian margin, where large input of clastic sediments resulted in a thick depocenter known as Rio Grande Cone (Martins, 1984). This morphosedimentary feature extends from the shelf break to water depths nearly 2,900 m, having 10 km thick, deposited from Late Miocene (Bassetto et al., 2000) to Late Holocene, when the area received large amounts of sediment from La Plata River. Changes in the wind-driven ocean circulation increased the sedimentation rates for the last 14 Kyr (Razik et al., 2013). As a consequence of high sedimentation rates, the region is prone to gas hydrates formation, occurring in water depths from 200 to 600 m (Paull et al., 1994). Recently, the interest on exploration of natural gas hydrates has grown due to the presence of large areas of gas hydrates in the cone area (Miller et al., 2015).

The Rio Grande Cone observed a gravity collapse, due to its extreme sedimentary thickness, resulting in the formation of normal faults on the upper fan, in an extensional domain, and thrust faults and folds on the lower fan, in a compressive domain. These structures were also responsible for seabed instabilities, considered conditioning elements favoring mass transport events.

Previous studies described the occurrence of gravitational flows in different types of continental margins (Bull et al., 2016). In the Brazilian margin submarine landslides were identified in the following oceanic basins: Santos (Mézerais et al., 1993), Campos (Kowsmann et al., 2015), Espírito Santo (Gamboa et al., 2010) and Amazonas (Perovano et al., 2009; Reis et al., 2010; Silva et al., 2010). Nearby, the Uruguayan (Hernández-Molina et al., 2016) and Argentine (Hernández-Molina et al., 2009) continental slopes have very similar characteristics to the present study region, with a series of submarine landslides, canyons and contourites. In these areas, the interaction between sediments and oceanographic agents resulted in a variety of shapes and deposit configurations.

In the southernmost Brazilian continental margin there are few studies describing mass wasting processes and related deposits. Reis et al. (2016) described the Chuí Megaslide Complex, on the southernmost margin of the Pelotas Basin, to the south of the Rio Grande Cone. The present study provides a detailed description of the upper sedimentary section of the Chui Megaslide Complex, based on new, closely spaced 2D seismic data, illustrating the geomorphogical features and internal seismic facies and structures, on the upper 0.5 seconds (nearly 500 m) below seabed. The interpretation was directed to the recognition of deposits resulted from mass wasting events and the associated features in the oceanographic context of the Pelotas Basin.

2. Regional Setting

2.1. Study area

The study area is located between latitudes 33° S and 36°S in the southernmost Pelotas Basin, 150 km from Brazilian coast, extending from the shelf break (200 m) to the Argentine Basin abyssal plan (4,900 m). The Rio Grande Cone and the Chui Megaslide Complex are the main submarine morphological features on this southern portion of the Brazilian continental margin.

Reis et al. (2016) first described the Chui Megaslide Complex as a series of large-scale submarine slides located in the southern flank of Rio Grande Cone (Fig. 4). A large elongated contourite deposit, named the Chui Drift occurs adjacent to the thrust compressional belt on the lower end of the Rio Grande Cone, to the north of the Chuí Megaslide area (fig. 2). These authors recognized three sectors on the Chuí Megaslide Complex, based on its morphology and depositional processes. Erosive processes dominate the upper region, inside a large corridor, of circa 50 km to 80 km wide, extending for 180 km to approximately 3,000 m water depth. This corridor is bounded by escarpments showing reducing heights from 500 m to 100 m in a downslope direction. Large mass transport deposits (MTD) dominate the lower slope sector, spreading down from 3,000 m to 4,900 m water depth. A combination of deformed failed masses and a series of slides interbedded by plan-parallel contourite layers composes the deposits, extending for 650 km downslope covering an area of approximately 150,000 km^2. Reis et al. (2016) described a series of 8 to 12 large-scale, interbedded MTDs. Considering its regional extent (hundreds of km) and individual thicknesses (hundreds of meters), they classified the entire MTD succession as a megaslide complex.

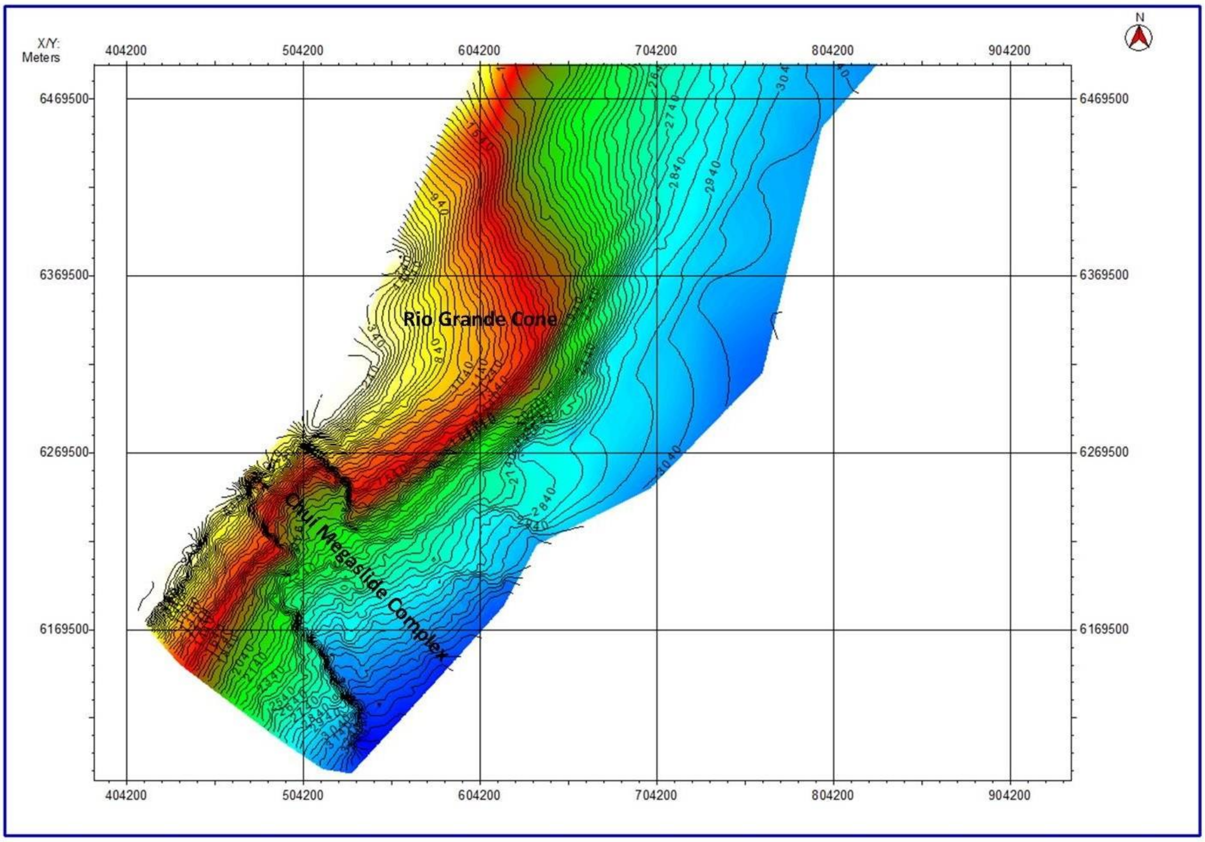


Figure 4. Bathymetric chart of Pelotas Basin showing the Chui Megaslide and Rio Grande Cone.

2.2. Oceanography Framework

Along the Brazilian and Uruguayan continental margin the thermohaline circulation of the Antarctic Intermediate Water (AAIW), at depths ranging from 700 to 1200 m, and the Antarctic Deep Water (AAIW), at depths greater than 3,500 represents the currents flowing northwards. The North Atlantic Deep Water (NADW) flows southwards, in depths ranging from 1500 m to 3,500 m (Preu et al., 2013). Brazil Current, flowing southwards along the continental shelf and upper slope, transporting the Tropical Water and South Atlantic Central Water, represents the superficial circulation. The Antarctic Bottom Water dominates the abyssal circulation and is strongly influenced by the bottom topography (Stramma and England, 1999). This circulation pattern transport and re-deposit sediments, becoming a potential conditioner for gravity-driven processes on the continental slope (Gomes and Viana, 2002; Niedoroda et al., 2003).

3. Data and methods

The data used in this study were provide by the company Spectrum and registered in the National Agency of Petroleum, Natural Gas and Biofuels - ANP with the name 0257_PEP2_2015. This data consists of 77 2D multichannel seismic reflection profiles, covering an area of 227,300 km² on the southeastern slope of the Pelotas Basin (Fig. 3). For this work, we had access of the upper 0.5 seconds of the seismic data. Additional 2D seismic sections were provided by the Brazilian Navy (Marine Hydrographic Directorate Center – DHN), including the entire depth of seismic penetration.

The seismic sections have a spacing of 10 x 10 km. To convert metric depths we used an average velocity of 1,500 m/s for water column, to make a bathymetric chart of the area.

The seismic data were interpreted using IHS Kingdom ® software, from IHS Markit Company, to identify the seismic reflectors and analyze seismic facies. The seismic facies analysis involved the interpretation of geometry, continuity, amplitude and external forms of reflection groups, following the classical concepts of seismic stratigraphy (Mitchum et al., 1977). This information enables to recognize the gravitational features and associated deposits as well as to characterize the depositional processes involved. In addition, QGis tools were used to estimate geomorphologic parameters, volumes and to further compile the seismic facies into a map. To calculate the volume of slope erosion we extended a horizon from the adjacent un-affected areas considering a realistic approximation of seabed prior to slope failure.

4. Results

The area investigated in this paper comprehends approximately 22,000 km² of the Chuí Mega-slide Complex, from the slope-break to the upper abyssal plain, extending for 250 km until the 3,600 meters isobath (Fig. 1). To describe the Chui Megaslide, this work follows the morphological sectors division of Reis *et al*. (2016): head, body and toe regions, focusing in detailing its geomorphological and internal facies and features (Fig. 1).

The description of the gravity driven processes and resulting deposits was basically determined by the recognition of the seismic facies. In this work we identified eight seismic facies as illustrated and detailed in figure 5: chaotic facies, transparent to semi-transparent facies, high amplitude parallel to sub-parallel reflectors, irregular and truncated reflectors, wavy shaped high to medium amplitude reflections.

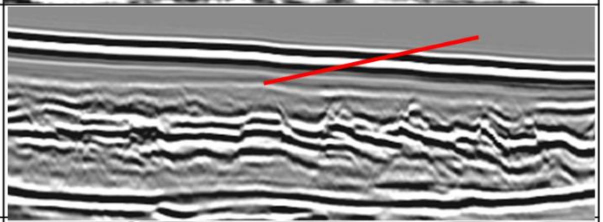
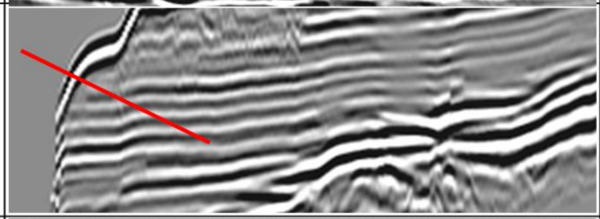
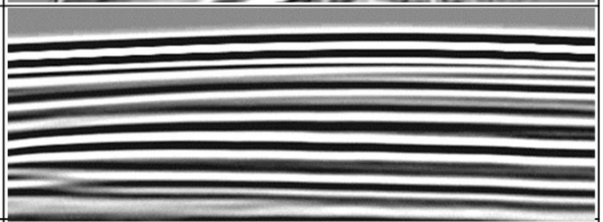
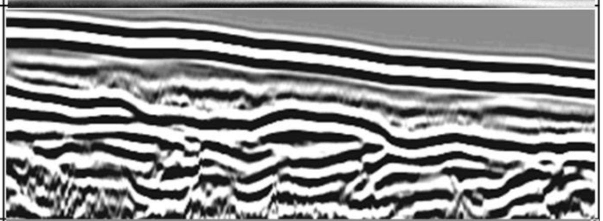
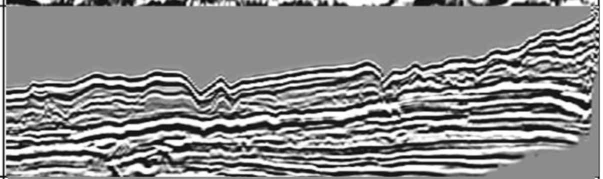
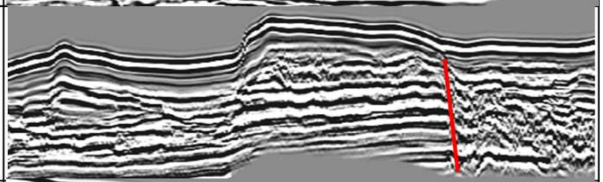
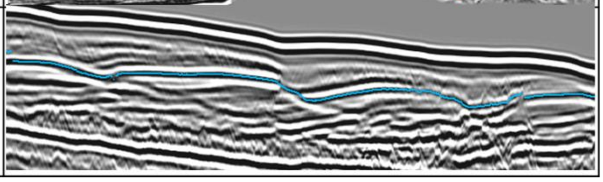
Interpretation	Seismic patterns
Chaotic	
Transparent	
Semi transparent	
Parallel	
Subparallel	
Irregular	
Truncated	
Wavy	

Figure 5. Seismic patterns and respective interpretation. Red line indicates the seismic section indicated in the interpretation. Blue line in wavy pattern showing the

interpretation.

Large erosional episodes removed portions of the continental slope and Rio Grande Cone and are indicated by several scarps and erosional truncations affecting the Chui Megaslide lateral scarps and leaving a large scar on the slope. The estimated volume of eroded and re-deposited material is approximately 2,400 km³. In the Rio Grande Cone, a strong bottom simulating reflector (BSR) of negative amplitude occurs bellow the seabed at depths from 0.6 s to 0.4 s TWTT (Two Way Travel Time) (~400 to 600 m) (Fig. 6) in an area of 12,500 km². The presence of BSR and consequently gas hydrates is another conditioning element favoring seabed instabilities and mass transport events.

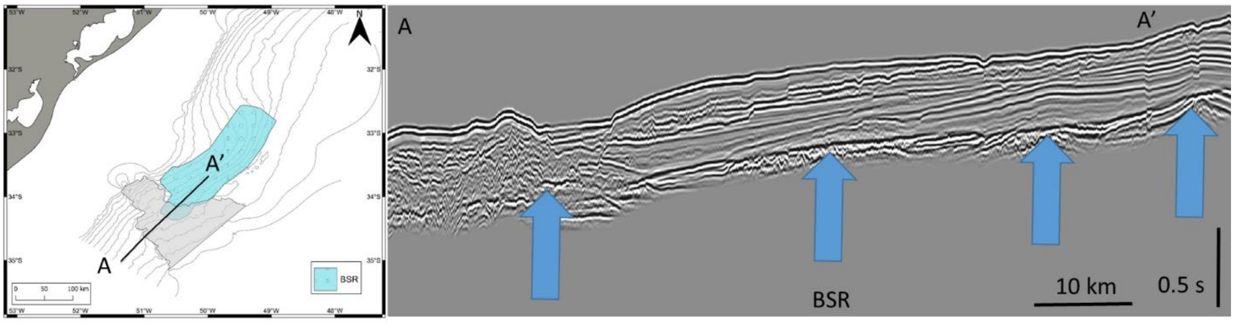


Figure 6. Strike profile indicating the presence of bottom simulator reflector (BSR), represented by high amplitude reflector over the blanking of the seismic signal, indicating the loss of seismic impedance between the different texture of sediment layers (Clennell, 2000). This horizon overlies most of the Rio Grande Cone and partially of the main failure area.

The head region is located on the upper-to-middle slope, in water depths from 400m to 2140 m. It has an amphitheater shape, nearly 50 km wide and 47 km long (Fig. 2) and is dissected on its southwestern side by a narrow, 6 km wide and 480 m deep canyon. In strike oriented seismic sections we observe steep lateral scarps, with reliefs near 300 m and clear erosive truncations (Fig. 7). Hanging slides over the northeastern sidewall escarpments points to receding scars from outside to inside the failure area

(Fig. 7). Scarps and collapsed blocks suggest recent activity over the margins and erosional remnants are present within the corridor (Fig. 7). Mass transport deposits (MTDs) occur inside the corridor limited by the escarpments. The MTD's are recognized in seismic data by the chaotic seismic facies, eventually with contorted to subparallel reflectors indicating the internal deformation related to the mass wasting processes. Rough irregular bottom surface suggests erosion and displaced blocks resulting from submarine slides with small deformation (Fig. 8).

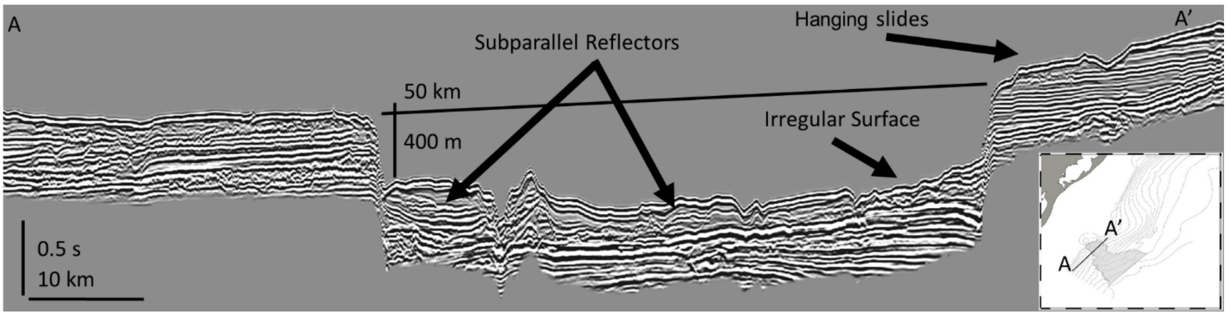


Figure 7. Strike oriented seismic profile of body region indicating the presence of low amplitude seismic reflectors, subparallel reflectors characterizing the irregular seabed surface. The main corridor is 50 km wide and 400 m deep, indicating a major erosion of the slope.

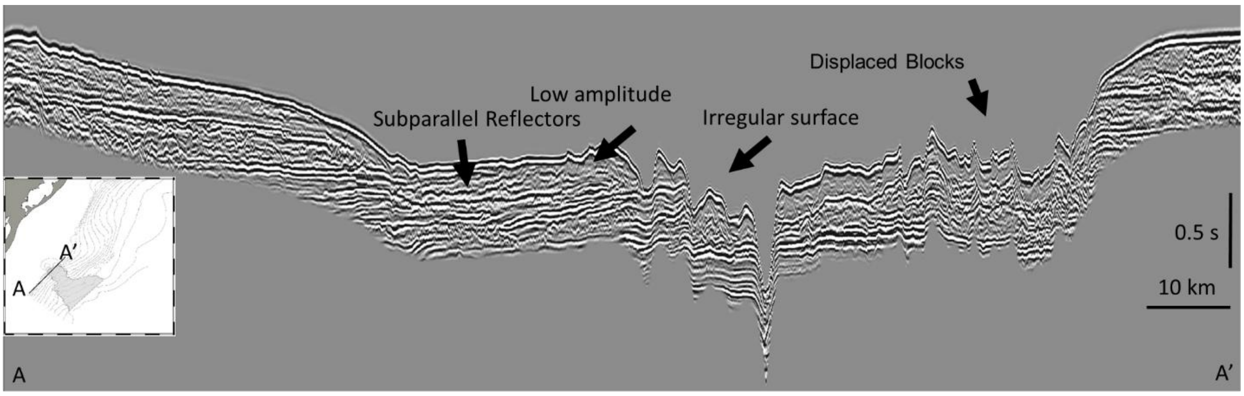


Figure 8. Strike oriented of slope-break indicating displaced blocks and the low amplitude layer above the seabed.

A central channel is connected to the canyon on the upper slope (Fig. 9) and meanders downslope for more than 150 km, developing constructional levees (Fig. 10). The canyon reaches 420 m of vertical relief and is 4 to 6 km wide, while the channel reliefs decrease downslope to a minimum of 60 m and the widths diminishes to 2.5 to 3 km. Slide blocks are observed inside the canyon. The levees are mostly transparent with heights nearly 200 m near the channel and widths of circa 6 km on both sides of the channel. A secondary canyon occurs along the southern lateral scarp, running downslope for 110 km, from water depths of 1,500 to 2,300 m, and disappearing in the middle of slope.

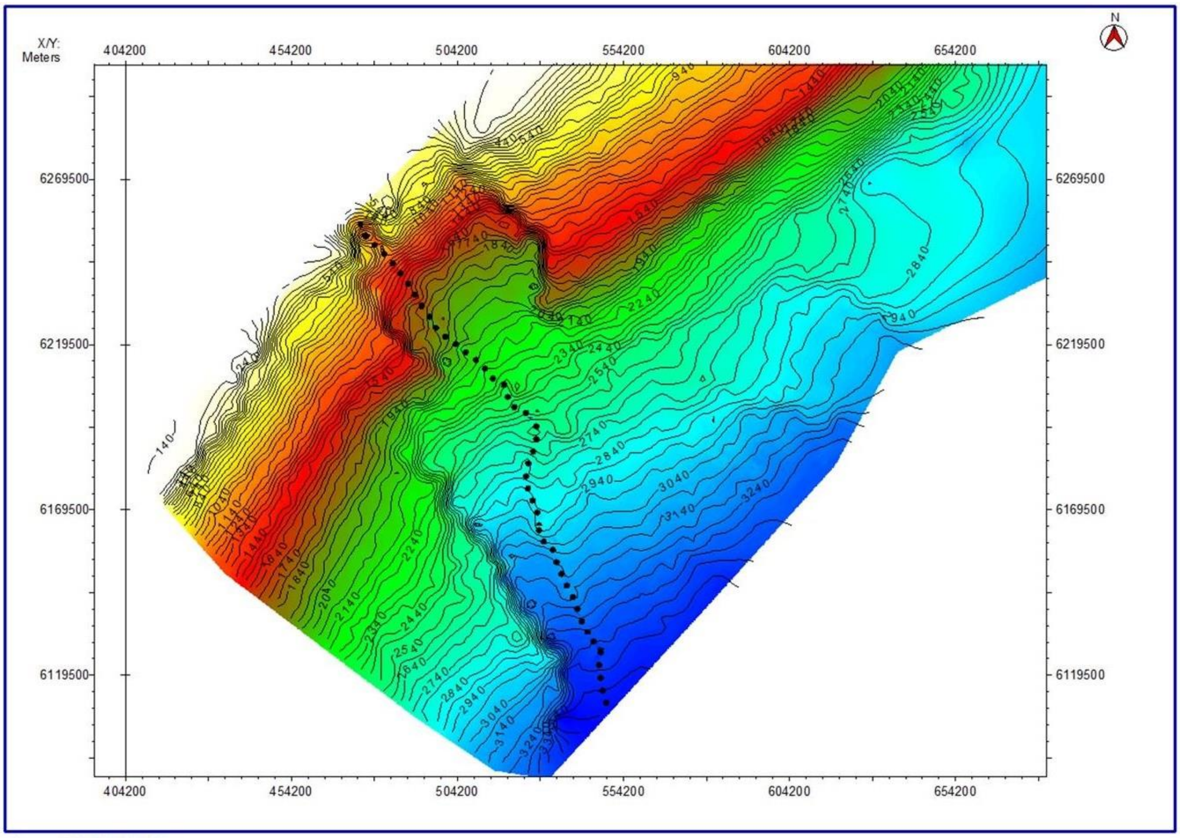


Figure 9. The main area of the Chui Megaslide with the inner canyon axis (dotted line) meandering the bottom of the failed area.

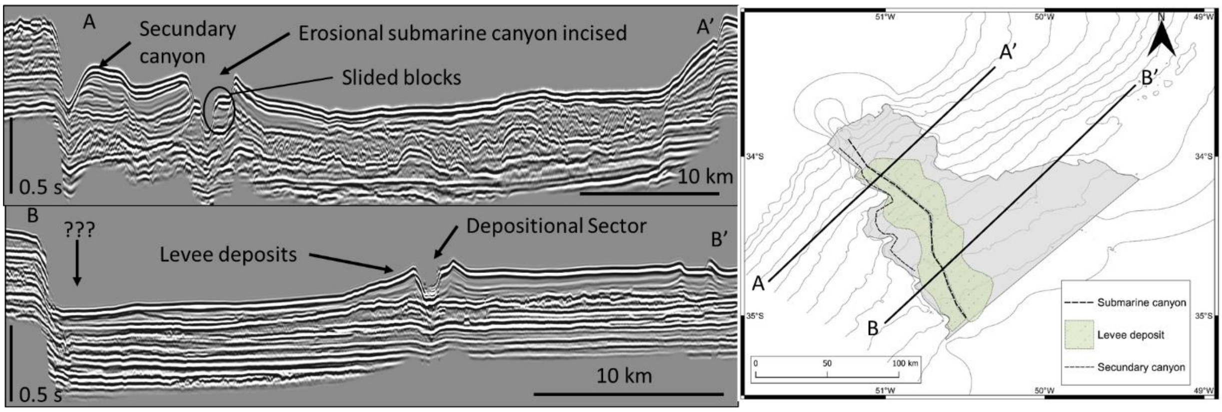


Figure 10. Strike profiles displaying the cross section of the canyons. The unconformity levee deposits produced by the rearrangement of the canyon forming process over the chaotic fill horizons. Profile A- A' presents erosive characteristics indicating a canyon inside the steeper zone. Profile B-B' shows deposicional characteristics indicating a channel on the gentler zone.

The body region comprehends the middle slope, between the isobaths of 2,140 and 2,700 meters (Fig. 2), being 70 to 130 km wide and 60 km long. It becomes wider downslope due to wider erosion related to a detachment of material coming from the south marginal escarpment. Highly chaotic seismofacies predominates inside the body region, with evidences of two distinct overlapping mass wasting deposits (Fig. 11). These deposits, named MTD 1 and MTD 2, have chaotic seismofacies and limited by an interval of hemipelagic deposits having an average thickness of 25 ms (~25 m). MTD 2 is younger overlapping MTD 1, and develops at its downslope end a deformation front with imbricated strata and blocks, deforming the present seafloor (Fig. 11). Retrogressive upslope faults on sidewalls and the disposition of respective headwall scarps suggest that these two events started from opposite sides (Fig. 12). MTD 1 and MTD 2 are the most recent events and occurred after the main slide failure, suggesting recurrent and very recent events during the evolution of the Chui Megaslide Complex.

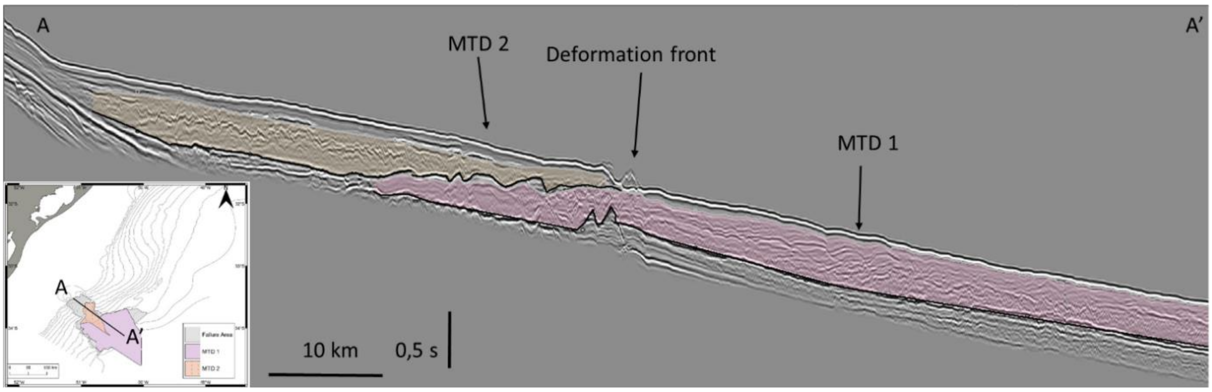


Figure 11. Dip oriented seismic profile showing the overlapping MTD 2 over the MTD 1. The glide surface (black line) between the deposits indicates a rough contact of the MTD 2 over the MTD 1, in the seabed the deformation front indicates the contact of one deposit over another (overlapping).

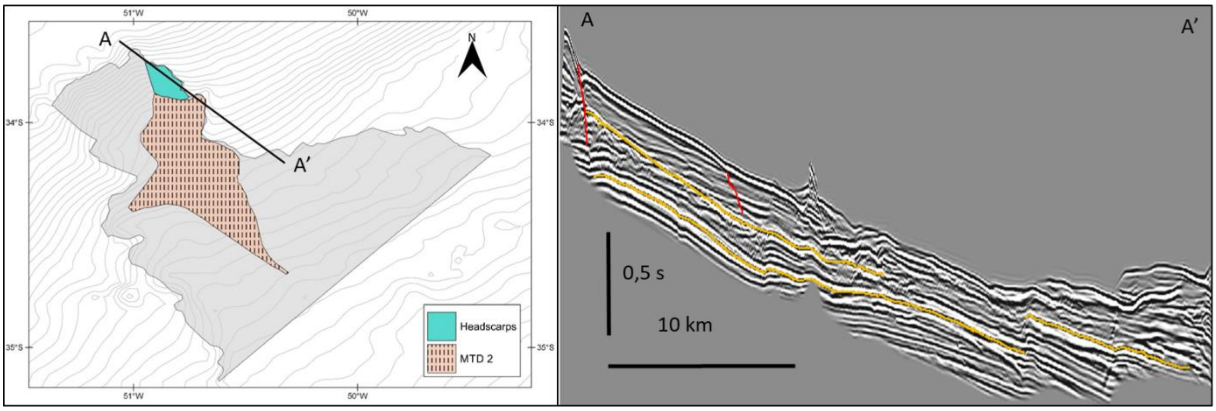


Figure 12. Headscarp from the north margin, red line. Successive glide surfaces, yellow lines, where the mass MTD 2 events passed.

In the region within our seismic coverage, MTD 1 has an area of nearly 12,000 km², developing a fan shape in a downslope direction. However, its total extension is unknown due to the absence of seismic data in the deeper basin area. Observing the thickness of the MTD 1 is possible to estimate a runout distance of approximately 180 km. Its average thickness is 0.2 sec (~200 m), reaching a maximum of 0.4 sec (~400 m). Internally, a series of wavy reflectors are representing rotated blocks, in a domino configuration, affecting continuously younger strata in a downslope direction (Fig. 13). These rotated blocks in its distal end are climbing over thicker chaotic facies and are affecting the present seabed, generating an undulated morphology. The area affected by these features is approximately 65 km long and 40 km wide, and the deposits are nearly 0.1 s thick.

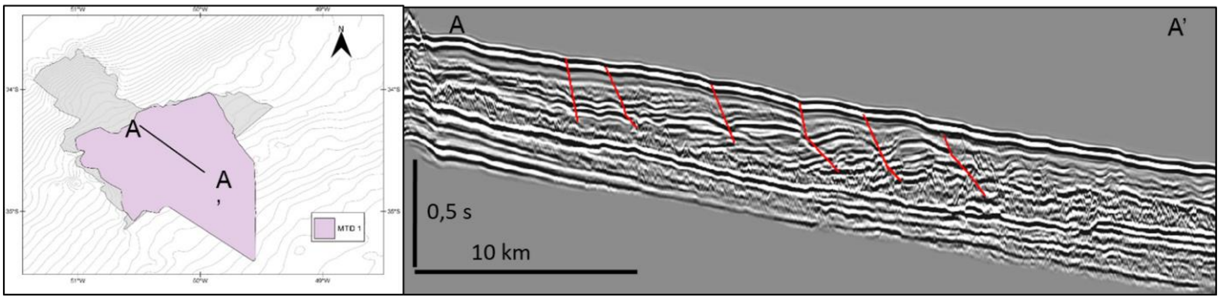


Figure 13. Dip oriented profile presenting series of rotated blocks (red line) transported along the MTD 1.

The MTD 2 occupies an area of circa 1,800 km² along approximately 100 km downslope, within the area covered by our seismic data. This event was originated on the northern lateral scarp removing approximately 58 km² of sediments (Figure 12). Large failed blocks failed still attached to the sidewalls, indicates where the failure process may have started (Fig. 12, 14 and 15). Blocks remained partially non-eroded, confining the passages of sedimentary mass to the center of the landslide area. Internally, chaotic subparallel reflectors have low continuity, contorted and disrupted reflectors indicating displaced masses characterizing the deposit (Fig. 13). High amplitude reflector occur on the base of MTD 2, suggesting hemipelagic deposition or bottom current reworking between MTD1 and MTD2 episodes. MTD1 forms an obstacle to the runout of MTD 2, resulting in deformation and consequently onlap termination on the MTD 1 (Figures 11 and 14). The maximum thickness occurs on the middle of the MTD 2 deposit, reaching 0.4 s (~400 m), gradually getting thinner downslope to circa 0.1s (~100 m) at the toe region.

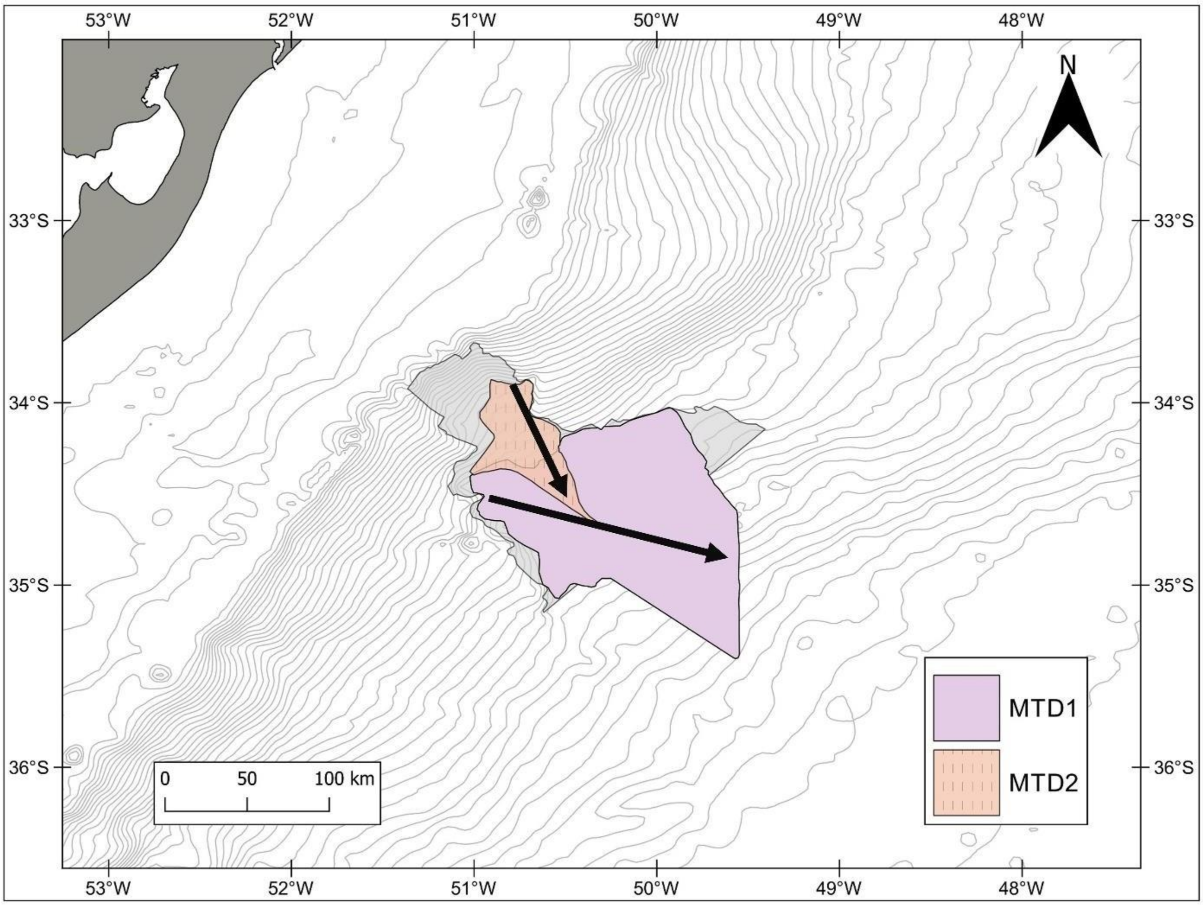


Figure 14. Map with the spatial distribution of MTD 2 partially overlapping the MTD 1 with the orientation axis of the slide processes.

Slide blocks, conditioned by normal faults, are detaching from the southern flank of the Rio Grande Cone. These normal faults are located on the upper cone and are part of the extensional zone pertaining to the Rio Grande Cone gravity tectonics regional deformation. Two large blocks were individualized: block A, with 900 km² and Block B, with 730 km². These displaced blocks provide further evidences that the latest instability events occurred in the middle of the slope (Fig. 15).

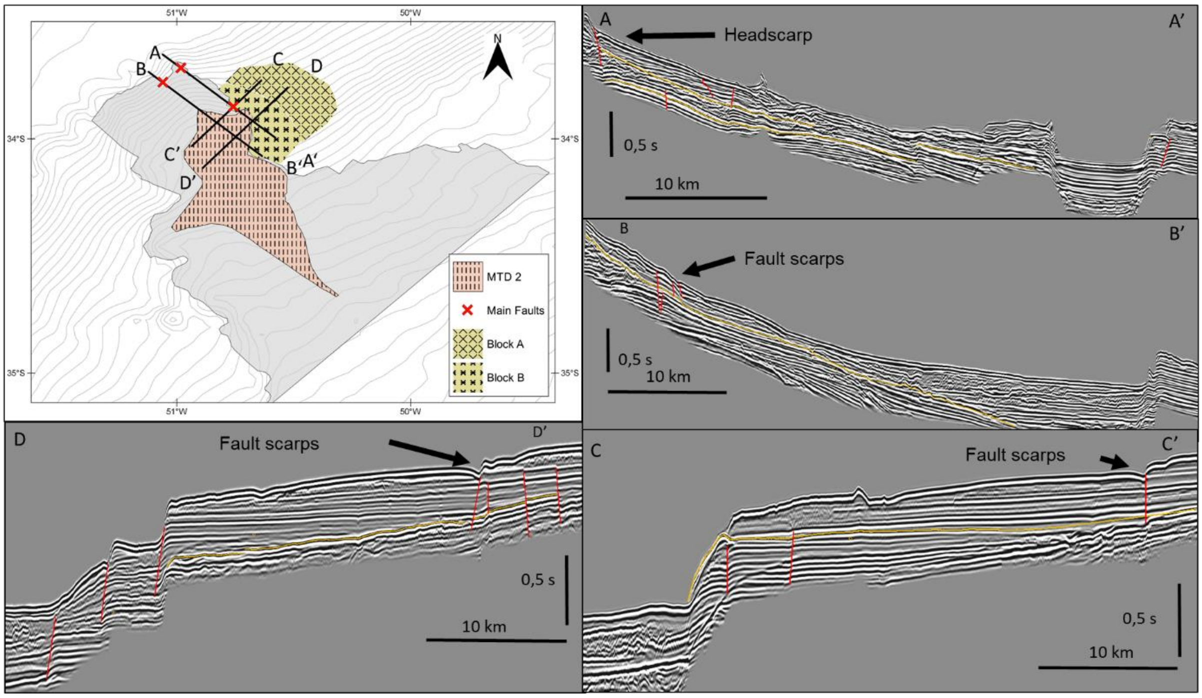


Figure 15. The seismic profiles (A-D) shows the series of faults (red line) indicating the extensional strength submitted to the depocenter and the blocks located in the south flank of the Rio Grande Cone. The glide surface (yellow line) is present in the lower part of the record separating the deformed masses from the underlying underformed or deformed layers (Chen et al., 2014).

In water depths deeper than 2,900 m, the toe region is the main depositional area (Fig. 2). The failure corridor becomes wider reaching 140 km, and the lateral escarpments are shorter (150 m), in part due to the increased depositional thicknesses. The chaotic seismic facies intervals present lower amplitudes and interlayered with thicker plan-parallel seismic units. The deposit gradually loses continuity as the horizon becomes deeper. This characteristic indicates a decrease in the momentum of the mass movement reaching the depocenter. The presence of series of interbedded chaotic deposits reveals again the complex recurrent nature of the Chui Landslide. Different thicknesses, internal arrangements, runout extensions and the presence of non-deformed internal blocks characterize events with distinct energy levels (Fig. 16). The rough seabed morphology indicates the presence of uncovered debris deposits with small blocks indicating recent mass wasting events and MTDs not yet buried by hemipelagic sedimentation (Fig. 16). Despite the number of deposits registering the episodes, only the last events have the deposit preserved. Even though, there are evidences that at least 7 episodes 260 km from the slope, indicating displaced deposits removed or transported by the recent events. Such deposits presents different stages of preservation. Towards the deep basin, the reflectors become more contorted, gradually decreasing their continuity and weakening the seismic amplitude signal, characterizing disintegrative debris Flow (Fig. 16).

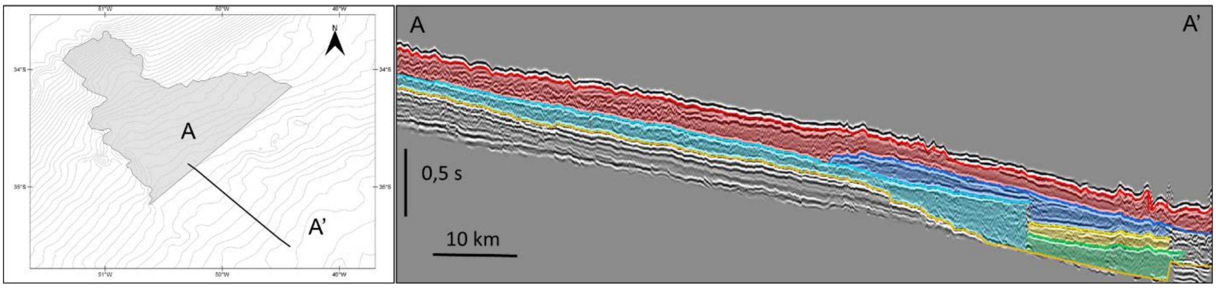


Figure 16. Middle portion of dip seismic profile showing gradual loss of amplitude of seismofacies. Series of chaotic seismofacies, represented by different colors, interbedded by a high amplitude reflector probably of early strata transported during late events. (Dip oriented)

5. Discussion

The Chui Megaslide complex resulted from several gravitational transport events affecting the continental slope on the southern Brazilian margin, adjacent to the Rio Grande Cone. The headscarps are located on the edge of continental shelf, and the lateral scarps are continuous from the upper slope to the lower slope, in water depths of up to 3,000 m. The erosional scar on the slope represents an area of circa 22,000 km^2 and the total volume of removed sediments is nearly 2,400 km^3. Considering the uppermost sedimentary section from the seabed to 0.5 sec (TWTT) (~425 m), the estimated volume of MTD 1 is circa 2,000 km^3 and MTD 2 is close to 300 km^3, assuming 1,700 m/s as interval velocity (Hamilton, 1979). The total volume of MTD 1 and MTD 2 altogether (2,300 km^3) is therefore similar to the total eroded value (2,400 km^3) from the main failure area. MTD 1 and MTD 2 were originated on the sidewall scarps, and from different opposed sides, and MTD 2 is shallower and juxtaposed over MTD 1, characterizing the receding nature of the failure events, which were responsible for widening the failure area in a downslope direction. MTD 1 is nearly 200 m thick and its base is 300 m below present seabed. Its headwall scarp occurs at older mass transported deposits stacked in deeper units (below 0.5 sec TWTT) on the Chui Megaslide complex, were derived from previous slope deposits, continuously sliding down during successive mass transport events, as was confirmed by Reis *et al.* (2016) who identified 8 stacked MTD units composing the Chui Megaslide complex.

Normal faults and erosional scarps are located on both sidewalls and some displaced blocks are still hanging and potentially instable during new clearing events. This is especially present on the southern flank of Rio Grande Cone, where numerous normal faults related to the extensional tectonics domain can start further gravitational events (fig. 15).

The deposits have disintegrative characteristics, i.e., tend to lose its internal structures as the material moves downslope (Parsons et al., 2007), relocating older deposits on the deep portion of the basin. The runout distance of MTD 1 is 160 km and MTD 2 is 60 km in a relatively gentle slope. Since the runout distance is a balance of buoyance and gravity, probably the transported material was mixed with water to allow flows for long distances (Parsons et al., 2007). The dominant terrigenous mud composition of the slope sediments (Martins, 1984; Miller et al., 2015) can further intensify the runout potential.

The second seismic facies presented are a well develop submarine canyon system located inside the failure area crossing the slope downwards. The seismic records presented a canyon probably formed after several gravity (turbidity) currents that shaped the valley downslope. This feature provides additional information of processes involved in the evolution of the landslide area. Canyons incised on continental slopes have their formation under speculation, however, the key processes associated to the maintenance and evolution are erosional and depositional hyperpycnal events (Baztan et al., 2005). The present canyon morphology displays evidences of variation during the shaping events, observed in the division between erosional and depositional sectors. The upper portion of the slope record the erosional dominant sector, on the other hand, the lower portion of the slope presents the depositional sector. The slope gradient and velocity of the flow relation can be the main characteristic related to the dominant process, as the slope become gentler the flow decrease the speed and the depositional character prevails forming the levee deposits. The division is clear, although, the discontinuities inside the canyon deposits shows a variation in the energy of dominant process or reactivation by new gravity flow events.

The canyon represents a modifying agent of remobilization and burring the earlier deposits and subsequently rearranging the seismic reflectors. Experimental studies observed levee formation after 5-10 events (Lüthi, 1980), the overspill depends from flow density and the speed (Parsons et al., 2007). The geomorphology of the canyon suggests a consistent current to develop such structures. The formation flow acts transporting the material downslope and depositing over the chaotic deposits. The chaotic pattern changes producing an unconformity horizon between the canyon base and the top of mass transport deposit. The occurrence of this feature leads to evidences that the area is evolving or alternating the material transported downslope. Likewise, the rearrangement difficult a proper estimation of such events, due to the extension of the canyon, affecting the MTD 1 and 2.

The other canyon recorded present characteristics differing from the main canyon. The feature is located close to the sidewalls but without connections that indicate as a tributary channel. The seismic expression is distinct from the other canyon, in upper slope region the feature is marked by erosional termination along the south margin of the landslide. There are no slumps inside the channel or in the moat periphery, a wedge shape deposit show deposition associated to material transportation. The deposit presents different characteristics from usual geometry of levee deposits. The seismic facies form a wedge shape deposit suggests a shaping process similar to contour currents.

A contourite field, northward, is apparently associated to landslide material suspended and resulted from mass transport events. This material is suspended after the mass wasting events and exposed to contour currents that carry the material (Mulder et al., 2008). The transport and deposition parallel to bathymetric morphology along the continental slope (Hernández-Molina et al., 2008), marking the pathway of the contour current. The deposit created after the landslide events has large wedge shape, constituted by a moat close to Rio Grande Cone foot. The contourite deposit is classified as giant separated elongated drift (Rebesco and Stow, 2001), characterizing an extensive depositional feature. This type of contourite is recognized as typical from steeper slopes, observed in the foot of the Rio Grande Cone, separated by an erosional or non-depositional moat (Fig.17) (Rebesco et al., 2014). This feature provides information about the current circulation acting on the slope foot, as (Hernández-Molina et al., 2016) observed in the circulation patterns of Uruguayan continental shelf. The most probable dominant current over the contourite deposit is Antarctic Bottom Water, analogous to Uruguay, where the bottom current flows close to the continental shelf at 3,000 m depth. In the present study, the due to the cone presence, the contourite field is bedded along the 3,600 m isobath. The currents interaction with the seabed morphology are record in several study cases (Viana et al., 2007), where the constriction of the current flow against topographic obstacles increase laterally the current intensity towards the converging axis (Niedoroda et al., 2003). This constriction erodes the Rio Grande Cone foot characterized by the moat nearby (Fig. 17A - B), presenting a great evidence to the landslide triggering.

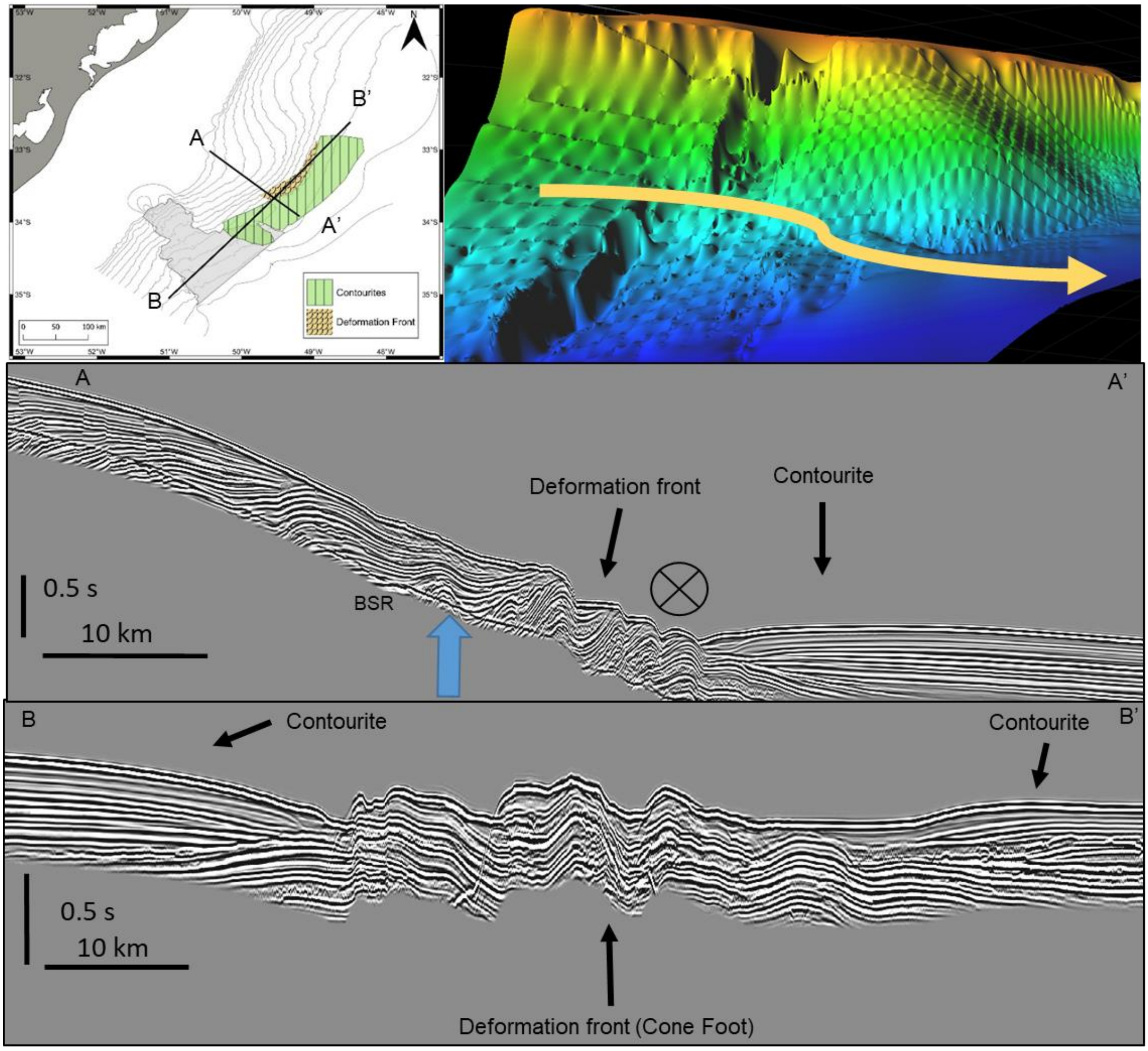


Figure 17. A. Dip profile crossing the Rio Grande Cone; show the deformation front and the contourite deposit, the presence of BSR. B. Strike profile of the Rio Grande Cone covering the two sides of the contourite deposit margin the Rio Grande Cone.

3D surface of the seabed of the Chui Megaslide area and the Rio Grande Cone with yellow arrow indicating the path of the contour current that acts over the deposit.

Evidences of gas hydrates (BSR) found in the seismic profiles can indicate a factor associated to landslide start in the slope. (Miller et al., 2015) recorded several gas hydrates layers interbedded with massive muddy sediments in the Rio Grande Cone at different depths (1.4 - 18 m) and pockmarks, from gas hydrates dissociation, covering extensive fields (2 x 19 km), indicate a density of 8 pockmarks per square kilometers and diameters between 200 and 600 m. In the Chui Landslide area, the gas hydrate stability zone (GHSZ), is recorded at 0.5 s deep or approx. 425 m (1700 m/s). Gas and gas hydrates are frequently associated to trigger submarine landslides, which the relationship link to shear strength destabilization (Lee et al., 2007). Sea- level changes are the main factor to this destabilization due to eustatic variation, which determine the pressure generated by hydrates in response of gas liberation during the Pleistocene falls in sea level (Liu and Flemings, 2009). Gas hydrates evidences associated to faults suggest a great possibility to be the main triggered mechanism due to gas liberation (Urgeles and Camerlenghi, 2013). Studies associated the occurrence of gas hydrates to several submarine landslides (Mienert et al., 2005; Riboulot et al., 2013). The connection of marine slumps and gas hydrates reservoirs has effects in the gas input to the ocean and atmosphere (Paull et al., 2002), leading to climate change (Maslin et al., 2004).

In the studied region, the most likely key process that generate the conditions to initiate a landslide event is the sediment accumulation coming from La Plata River, as a result of high input of sediments. The oceanographic conditions found in the continental slope benefit the sediment deposition in the outer shelf near the Chui Megaslide complex. The La Plata River could represent the main agent responsible to originate the gravity flows in the area by inputting the material to depocenters since deglaciation periods (Lantzsch et al., 2014). The rapid accumulation of sediment generated an excess of pore pressure, resulting in weak sediment layers and increasing slope destabilization (Lee et al., 2007). Such sedimentation of terrigenous mud from continental discharge also creates good conditions to gas hydrates formation (Paull et al., 1994) leading to gas dissociation by mud volcanoes or faults (Miller et al., 2015) and, consequently, slope failure. These conditions reach the southernmost portion of Pelotas basin, where others submarine landslides are recorded (Hernández-Molina et al., 2016).

The hemipelagic sedimentation provides evidences of intervals between the mass wasting episodes (Laberg et al., 2006). Periods of hemipelagic sedimentation takes place in the intervals of episodic high energy events. The superficial deposition represents one of these intervals during the present days. Previous studies on Pelotas basin determine sedimentation rates to the region. (Chiessi et al., 2014) established sedimentation rates of 10 $cm.kyr^{-1}$ to 60 $cm.kyr^{-1}$ near the submarine landslide at ~650 m isobath. The most likely period, base in sedimentation rates, for the last event comprehends the Pleistocene, at 33 kyr to 200 kyr BP. Despite the variation associated to sedimentation rates caused by oceanic current oscillation or river discharge, the hypothesis of the latest events happened during the Pleistocene is synchronized with other events. During this period, sea level change is related to trigger many other events (Mienert et al., 2005; Riboulot et al., 2013), caused by combination of high sedimentation rates and isostatic readjustment during glaciation and deglaciation periods (Lee, 2009).

6. Conclusions

Using seismic methods was possible to establish the sequence of the structures associated to the landslide. The region present the seabed filled of chaotic deposits formed during mass movements from the silting of the margins. The last events comprehend two mass movements that eroded the sidewalls transporting large amounts of material towards the abyssal plain. Such erosional process indicates how the mass wasting events can affect bringing instability to the continental slope and the geomorphologic features. The MTD 1, the larger event of the two, represent the erosion and deposits from south margin, chaotic seismic facies and large portions from previous episodes transported downslope characterized their internal configuration. Long period exposure to gravity flow currents before the following landslide event also provides evidences to this deposit formation. The action of contour currents on suspended material resulted in the formation of a field of contourites, such deposit registered the imprint of the contour current direction (S-N). The MTD 2 is located upper slope and present an eroded portion of south flank from Rio Grande Cone, north margin of the complex, formed internally by chaotic fill as well. The inexistence of the same gravity flow structures, indicate a different timing event after the MTD 2. Seismofacies associated to chaotic patterns constituted internally the deposits. At last, both deposits (MTD 1 and MTD 2) are covered by an inner canyon probably resulted by a long period gravity flow formation process. The apparent cause to triggered the landslides are the combination of several factors, erosion by currents, loss of pore pressure due to high sediment accumulation and gas hydrates.

This study represents an example for synergies derived from an interdisciplinary approach combining geological, geophysical and oceanographic interpretation for characterization of depositional and erosional features related to gravitational mass transport. Consequently, the findings described here may serve as a guideline for future studies to identify similar features, being useful to fulfill the lack of studies in the southernmost continental slope of Brazil.

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7. References

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CONSIDERAÇÕES FINAIS

A região apresenta diversas feições morfossedimentares ainda pouco estudadas na região da margem continental sul brasileira. Tais feições possuem grande importância para a dinâmica sedimentar de regiões profundas indicando um potencial para estudos morfoestratigráficos. Cânions submarinos indicam processos atuando por um período considerável sugerindo que existem fluxos menos densos, como correntes de turbidez, atuando com certa frequência na quebra do talude. Esse material que entra em suspenção por correntes de turbidez e, principalmente, movimentos de massa levam a formação de outros depósitos como contornitos ao norte do Deslizamento do Chuí. Além disso, falhamentos na região indicam a suscetibilidade para novos deslizamentos, principalmente no flanco sul do Cone do Rio Grande. As implicações dos consecutivos movimentos de massa no talude evidenciam grandes efeitos sobre a feição morfosedimentar. Futuros estudos na região podem apresentar grandes avanços nos estudos de deslizamentos e suas implicações.

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