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DISSERTAÇÃO DE MESTRADO

O BANCO DE SANTO ANTÔNIO: UM ESTUDO DE SÍSMICA DE ALTA RESOLUÇÃO EM UM DELTA DE MARÉ VAZANTE LOCALIZADO NA ENTRADA DE UMA GRANDE BAÍA TROPICAL, COSTA LESTE DO BRASIL

ANA CLARA CONI E MELLO

SALVADOR
2016

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Ana Clara Coni e Mello

Orientador : Prof. Dr. José Maria Landim Dominguez

Co-orientador: Dr. Luiz Antonio Pereira de Souza

Tese de Mestrado apresentada ao Programa de Pós-Graduação em Geologia do Instituto de Geociências da Universidade Federal da Bahia como requisito parcial à obtenção do Título de Mestre em Geologia, Área de Concentração: Geologia Marinha Costeira e Sedimentar.

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DEDICATÓRIA

Às minhas avós Maria Conceição M. Mello (in memoriam) e Lúcia Borges Coni, por serem grandes exemplos de fibra e humanidade na minha vida.

“Restará sempre muito o que fazer ...”

(Hino da Hidrografia)

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RESUMO

O Banco de Santo Antônio (BSA) é uma feição positiva localizada na plataforma continental de Salvador, adjacente à entrada da Baía de Todos os Santos (BTS), costa leste do Brasil. Esta feição tem sido reportada por cronistas e navegadores desde o século XVI como um perigo à navegação. Estudos anteriores tentaram determinar a origem e o volume de sedimentos arenosos estocados nesta feição. No entanto, até o presente momento, nenhum destes estudos obteve sucesso. No presente trabalho objetivou-se o uso da técnica de sísmica de alta resolução para a investigação da arquitetura e origem do BSA. Ao todo, 170 km de linhas sísmicas de alta resolução foram adquiridos durante dezembro de 2014 e fevereiro de 2015, utilizando um eletrodo sparker do sistema Meridata operando em frequências entre 0,3 kHz e 1,5 kHz, com potência máxima de 200J de energia. Três principais unidades estratigráficas foram identificadas: o embasamento, uma unidade transgressiva e uma unidade de nível de mar alto. O embasamento consiste de rochas sedimentares da bacia sedimentar de Camamu e rochas Pré-Cambrianas de alto grau metamórfico. A unidade transgressiva foi interpretada como um resultado de deposição em ambiente estuarino. A unidade de nível de mar alto foi interpretada como o próprio BSA, que apresenta uma forma crescente. Durante sua evolução, uma migração agradacional para leste ocorreu seguindo o sentido das correntes de maré vazante. Variações nas taxas de subida do nível do mar desde o último máximo glacial exerceram um importante papel no desenvolvimento do BSA. A paisagem do embasamento foi esculpida pela erosão subárea ocorrida durante o último máximo glacial, que apresenta um forte controle estrutural sobre o embasamento. A unidade transgressiva foi depositada durante períodos de desaceleração da subida do nível do mar ou períodos de estabilização, seguidos pelos pulsos de degelo MWP1A e MWP1B. A unidade de nível de mar alto foi desenvolvida predominantemente ao longo dos últimos 8 ka. Duas superfícies de ravinamento foram identificadas nos perfis sísmicos: RD1 no lado leste e RD2 no lado oeste da entrada da BTS. O desenvolvimento destas superfícies está associado a períodos de desaceleração do nível do mar após os pulsos de degelo MWP1B e MWP1C, respectivamente. O BSA está localizado essencialmente sobre a superfície de ravinamento RD1, que foi interpretado no presente estudo como um delta de maré vazante construído durante os últimos 8 ka. Sua posição lateral relativa à BTS resultou de uma deflexão das correntes de maré vazante em função do alto do embasamento presente, sobre o qual a superfície de ravinamento RD2 foi esculpida. O volume de sedimentos siliciclásticos estocados no BSA foi calculado na ordem de um bilhão de metros cúbicos. Este volume é compatível com as taxas atuais de transporte litorâneo estabelecidas ao longo dos últimos 7-8 ka. O BSA é, portanto, uma potencial fonte de areia para recuperação de praias para a cidade de Salvador e região metropolitana. Contribuindo, portanto, no aumento da resiliência da cidade a cenários futuros de elevação do nível do mar. O sparker operando em frequências entre 0,3 kHz e 1,5 kHz foi eficiente para a ensonificação de sedimentos arenosos em profundidades superiores a 100 m abaixo do pacote sedimentar.

Palavras chave: banco de areia, baía de todos os santos, variações do nível do mar.

ABSTRACT

The Santo Antônio Bank (SAB) is a large sand accumulation on the inner continental shelf of the city of Salvador, adjacent to the entrance of the Todos os Santos Bay (TSB), eastern Brazilian coast. This feature has been reported by chroniclers since the 16th century as a navigational hazard. Previous studies have tried to determine the origin and volume of sands stored within this feature without success. In the present study, high-resolution reflection seismic surveys were used to investigate the architecture, origin and evolution of the SAB. A total of 170 km of high resolution shallow seismic lines was acquired during December 2014 and February 2015 using a Meridata® sparker system operating on frequencies between 0.3 kHz and 1.5 kHz, with a maximum 200 J of energy. Three major stratigraphic units were identified: the bedrock, a transgressive unit and a highstand unit. The bedrock consists of sedimentary rocks of the Camamu Sedimentary Basin and high-grade metamorphic rocks of the Precambrian basement. The transgressive unit was interpreted as the result of deposition in an estuarine environment. The highstand unit represents the SAB itself, which exhibits a crescent shape. During its development, aggradation and eastwards migration took place following the dominant ebb-tidal current direction. Varying rates in sea-level rise since the last glacial maximum (LGM) played an important role in the development of the SAB. The bedrock landscape was sculpted by sub-aerial erosion during the LGM, and exhibits a strong control of the structural framework of the underlying sedimentary basins. The transgressive unit was deposited either during periods of decelerated rates of sea-level rise or stabilization following MWP1A (Melt Water Pulse) and MWP1B. The highstand unit developed mostly over the last 8 kyr. Two ravinement surfaces were identified through the seismic profiles, RD1 to the east and RD2 to the west of the TSB entrance. Their development was associated with periods of decelerating rates in sea-level rise after MWP1B and MWP1C, respectively. The SAB rests upon the RD1 surface, which was interpreted as an ebb tidal delta constructed during the last 8 kyr. Its lateral position in relation to the entrance of the TSB results from eastward deflection of ebb-tidal currents by a bedrock high, over which the RD2 surface was sculpted. The volume of siliciclastic sands stored in the Holocene unit of the SAB was determined as one billion cubic meters. This volume is compatible with present rates of gross longshore transport acting during the last 7-8 kyr. The SAB is potentially a major source of sands for beach nourishment for the urban beaches of the city of Salvador and metropolitan area, thus increasing the resilience of the city to future sea-level rises. The sparker operating on frequencies between 0.3 kHz and 1.5 kHz was very effective for ensonifying sandy sediments at depths greater than 100 m below the sediment-water interface.

Keywords: sand bank, todos os santos bay, sea-level changes.

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INTRODUÇÃO

1- INTRODUÇÃO

O conhecimento detalhado das zonas costeiras e de áreas submersas é essencial para a gestão do ambiente marinho e para a elaboração de cenários de resposta desta região às mudanças climáticas. O uso de métodos geofísicos tem se mostrado bastante eficiente na investigação dessas áreas submersas, principalmente na investigação de estruturas geológicas, estruturas do Quaternário, investigação de processos sedimentares, jazidas de sedimentos, e estudos geotécnicos para obras costeiras (Souza, 2006; Ayres Neto, 2001).

O estudo de bancos arenosos utilizando fontes sísmica de alta resolução tem sido realizado em todo o mundo desde a década de 1970. Destacam-se os trabalhos desenvolvidos por Houbolt (1968), Berné et al. (1994), Berné et al. (1996), Dyer e Huntley (1999), Marsset et al. (1999), Trentesaux et al. (1999) e Berné et al. (2002). Estes estudos tiveram como objetivo compreender a evolução geológica, origem da areia e as variações do nível do mar no desenvolvimento destes bancos. No Brasil, estudos neste sentido são escassos por motivos como a ausência de grandes campos de bancos arenosos (*sand banks fields*).

Apesar da ausência de grandes campos de bancos arenosos, como os observados no Canal Inglês e no Mar Amarelo, na plataforma continental brasileira ainda existem diversas feições geológicas submersas, e de origem não estabelecida até o momento. Muitas destas feições carecem de estudos geofísicos - geológicos detalhados. Neste sentido, o uso da sísmica de alta resolução torna-se uma excelente ferramenta na aquisição de dados de sub-superfície, promovendo um melhor entendimento dos processos que geraram estas feições.

A plataforma continental de Salvador se caracteriza por ser a mais estreita do território nacional, com apenas 8 km de largura (Dominguez et al., 2011). Nesta, se destaca uma feição positiva relatada pelos primeiros cronistas e navegadores que visitaram a região no século XVI. Esta feição, batizada de Banco de Santo Antônio (BSA), localiza-se adjacente à entrada da baía de Todos os Santos (BTS), e é delimitado pela isóbata de 20m. O BSA apresenta comprimento de cerca de 12 km e largura média entre 3 e 3,5 km, com orientação aproximada N-S. O seu topo é bastante raso (profundidades mínimas de 5 m) e é recoberto por grandes dunas hidráulicas (Rebouças, 2010; Dominguez et al., 2011). Possui uma altura de aproximadamente 15m. Sua área total é de aproximadamente 35,8km².

Muitos estudos já foram realizados na Plataforma Continental de Salvador. Os mesmos porém focaram principalmente na hidrodinâmica, na contaminação dos sedimentos, nos ambientes bentônicos e distribuição de sedimentos superficiais. Dentre estes estudos destacam-se: Lessa et al.,2000; Cirano &

Lessa, 2007; Dominguez & Bittencourt, 2009; Rebouças, 2010; Dominguez, *et al*., 2011. Apesar dos estudos realizados, até hoje não se conhece o volume de sedimentos arenosos estocados no BSA e entrada da baía de Todos os Santos (ou seja o seu espaço de acomodação) desde a sua inundação durante o Holoceno, nem a geometria do substrato rochoso da mesma, principalmente na sua entrada, onde predominam sedimentos siliciclásticos.

Estudos anteriores (Rebouças, 2010; Dominguez et al., 2011) apontam esta feição como uma potencial jazida de areia para a cidade de Salvador. Rebouças (2010) apresentou ainda uma estimativa preliminar da espessura mínima de sedimento no BSA, calculando um volume na ordem de 400 milhões de metros cúbicos de areia, com valor de D50 (diâmetro mediano), pelo menos nos sedimentos superficiais, equivalente ao encontrado nas praias de Salvador. No entanto, o volume total exato de sedimentos e a sua origem ainda eram desconhecidos, pois os sistemas geofísicos até então utilizados (CHIRP) não foram capazes de penetrar a cobertura sedimentar. Neste contexto, este trabalho objetivou determinar a geometria, origem e evolução do Banco de Santo Antônio, desde o último máximo glacial, a partir da aplicação da Sísmica de Alta Resolução.

OBJETIVOS

Objetivo geral

O presente estudo teve como objetivo principal determinar a geometria, origem e evolução do Banco de Santo Antônio, desde o Último Máximo Glacial até o presente, utilizando métodos sísmicos de alta resolução, empregando fonte acústica do tipo *sparker*, atuando com frequências abaixo de 2 kHz.

Objetivos específicos

- Determinar a geometria do embasamento rochoso na entrada da baía de Todos os Santos com ênfase na área onde está localizado o Banco de Santo Antônio;

- Reconstruir os padrões de sedimentação dominantes durante o Quaternário-Holoceno na entrada da baía de Todos os Santos e plataforma continental de Salvador, com ênfase no Banco de Santo Antônio.

Organização da Dissertação

Esta dissertação está organizada ao longo de três capítulos:

No Capítulo 1, é apresentada a contextualização do trabalho e os motivos que levaram ao desenvolvimento da presente dissertação.

No Capítulo 2, apresenta os resultados sob a forma de um artigo intitulado "*The Santo Antônio Bank: a high-resolution reflection seismic study of a deflected ebb-tidal delta located at the entrance of a large* *tropical bay, eastern Brazil*" submetido à revista Marine Geology (Qualis A2 para Geociências e fator de impacto de 2,710). Neste artigo foram abordados os principais aspectos e a evolução geológica após o último máximo glacial do Banco de Santo Antônio.

Por fim, o Capítulo 3 expõe as principais conclusões do trabalho

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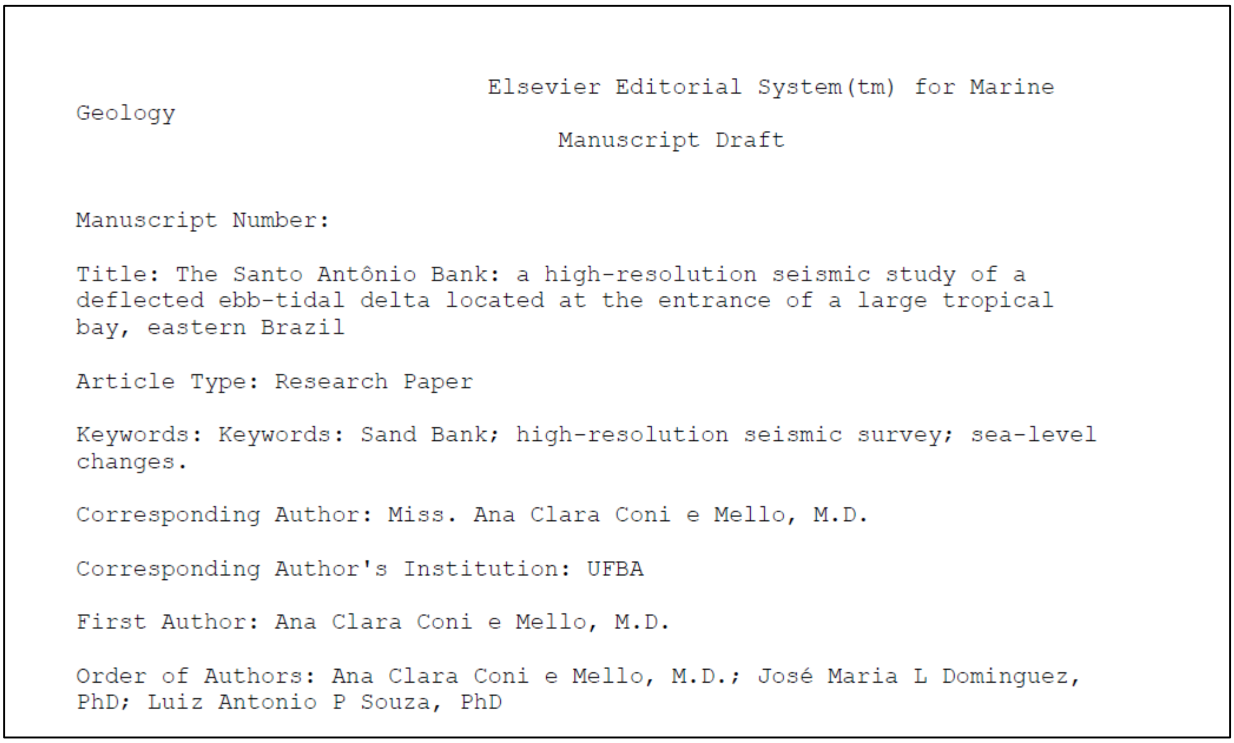
CAPÍTULO 2
ARTIGO

1- CONFIRMAÇÃO DE SUBMISSÃO DO ARTIGO

ARTIGO SUBMETIDO



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Manuscript Draft

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Title: The Santo Antônio Bank: a high-resolution seismic study of a deflected ebb-tidal delta located at the entrance of a large tropical bay, eastern Brazil

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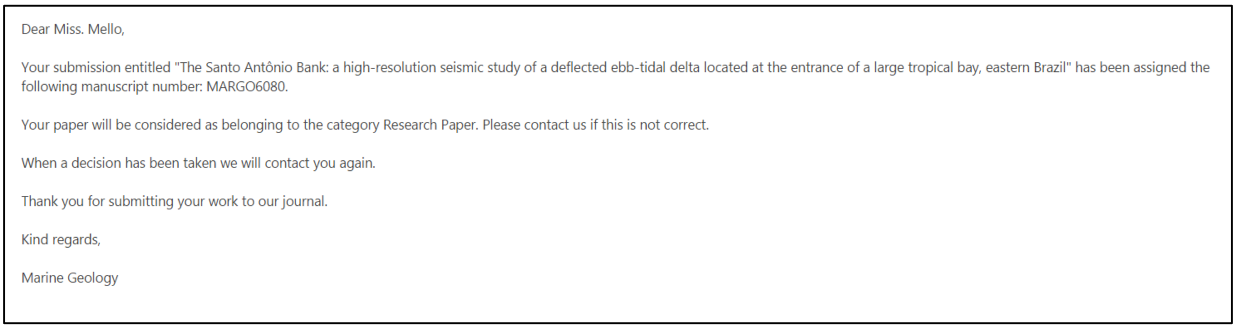

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Your submission entitled "The Santo Antônio Bank: a high-resolution seismic study of a deflected ebb-tidal delta located at the entrance of a large tropical bay, eastern Brazil" has been assigned the following manuscript number: MARGO6080.

Your paper will be considered as belonging to the category Research Paper. Please contact us if this is not correct.

When a decision has been taken we will contact you again.

Thank you for submitting your work to our journal.

Kind regards,

Marine Geology

O ARTIGO:

THE SANTO ANTÔNIO BANK: A HIGH-RESOLUTION SEISMIC STUDY OF A DEFLECTED EBB-TIDAL DELTA LOCATED AT THE ENTRANCE OF A LARGE TROPICAL BAY, EASTERN BRAZIL

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Abstract

The Santo Antônio Bank (SAB) is a large sand accumulation on the inner continental shelf of the city of Salvador, adjacent to the entrance of the Todos os Santos Bay (TSB), eastern Brazilian coast. This feature has been reported by chroniclers since the 16th century as a navigational hazard. Previous studies have tried to determine the origin and volume of sands stored within this feature without success. In the present study, high-resolution reflection seismic surveys were used to investigate the architecture, origin and evolution of the SAB. A total of 170 km of high resolution shallow seismic lines was acquired during December 2014 and February 2015 using a Meridata® sparker system operating on frequencies between 0.3 kHz and 1.5 kHz, with a maximum 200 J of energy. Three major stratigraphic units were identified: the bedrock, a transgressive unit and a highstand unit. The bedrock consists of sedimentary rocks of the Camamu Sedimentary Basin and high-grade metamorphic rocks of the Precambrian basement. The transgressive unit was interpreted as the result of deposition in an estuarine environment. The highstand unit represents the SAB itself, which exhibits a crescent shape. During its development, aggradation and eastwards migration took place following the dominant ebb-tidal current direction. Varying rates in sea-level rise since the last glacial maximum (LGM) played an important role in the development of the SAB. The bedrock landscape was sculpted by sub-aerial erosion during the LGM, and exhibits a strong control of the structural framework of the underlying sedimentary basins. The transgressive unit was deposited either during periods of decelerated rates of sea-level rise or stabilization following MWP1A and MWP1B (Melt Water Pulse 1A and 1B). The highstand unit developed mostly over the last 8 kyr. Two ravinement surfaces were identified through the seismic profiles, RD1 to the east and RD2 to the west of the TSB entrance. Their development was associated with periods of decelerating rates in sea-level rise after MWP1B and MWP1C, respectively. The SAB rests upon the RD1 surface, which was interpreted as an ebb tidal delta constructed during the last 8 kyr. Its lateral position in relation to the entrance of the TSB results from eastward deflection of ebb-tidal currents by a bedrock high, over which the RD2 surface was sculpted. The volume of siliciclastic sands stored in the Holocene unit of the SAB was determined as one billion cubic meters. This volume is compatible with present rates of gross longshore transport acting during the last 7-8 kyr. The SAB is potentially a major source of sands for beach nourishment for the urban beaches of the city of Salvador and metropolitan area, thus increasing the resilience of the city to future sea-level rises. The sparker operating on frequencies between 0.3 kHz and 1.5 kHz was very effective for ensonifying sandy sediments at depths greater than 100 m below the sediment-water interface.

Keywords: Sand Bank, high-resolution reflection seismic survey, sea-level changes.

1. Introduction

Sand banks are a common feature in many regions of the world and have been the focus of several studies, such as those carried out in the North Sea, English Channel, Celtic Sea, East China Sea and Yellow Sea (Berné et al., 1994; Berné et al., 1996; Dyer and Huntley, 1999; Marsset et al., 1999; Trentesaux et al., 1999; Berné et al., 2002). These features occur in a wide range of water depths, near estuaries, headlands, and on continental shelves, among other locations (Berné et al., 1994; Trentesaux et al., 1999).

Current definitions of sand banks can be inadequate at times, because they fit several different types of sand bodies into one single category. Berné et al. (1996) define these features as elongated sand bodies, with length varying between hundreds of meters to many kilometers, width from hundreds of meters to a few kilometers, and thickness of up to a few tenths of meters, that are related to either transgressive or lowstand deposits. Dyer and Huntley (1999) state that sand banks and elongated sand ridges can be found in several coastal and shelf seas in which sand is abundant and currents are able to move sediment, exhibiting a wide variety of forms.

Still according to Dyer and Huntley (1999), sand sources for these types of features can be either the local seabed or coastal erosion. These authors affirm that the majority of these features appear to have been created during the last post-glacial rise in sea level, with subsequent modifications due to currents and waves, obliterating their original characteristics. Two major categories for sand banks are usually recognized: active and moribund banks. Active banks occur in shallow water (<30 m), implying that they are still affected by modern processes such as tidal currents and waves, while moribund banks are commonly located in deeper waters and are not significantly affected by modern physical agents (Berné et al., 1994; Trentesaux et al., 1999).

According to Marsset et al. (1999) siliciclastic shelf sand bodies result from complex interactions between relative sea level changes and hydrodynamic processes. Sea level history controls the large-scale, long-term evolution and preservation of these sand bodies, while hydrodynamic processes act at smaller spatial and temporal scales. As noted by Trentesaux et al. (1999), many questions are still open concerning the origin, evolution and geometry of these features, such as the roles played by the intensity of tidal currents, the nature of available sediment, antecedent topography, and rates of sea level change.

The Santo Antônio Bank (SAB) (Fig. 1) is a sandy feature located on the inner continental shelf facing the peninsula of the city of Salvador, which is adjacent to the entrance of the Todos os Santos Bay (TSB). Since the 16th century this feature has intrigued sailors and, more recently, also many geoscientists, especially due to its size and relevance as a navigational hazard.

Some authors, such as Lessa et al. (2001) and Lessa and Cirano (2007), have suggested that this feature is part of a larger transgressive sand marine deposit present at the entrance of the TSB. As such, it would be related to an ebb-tidal delta. However, Rebouças (2010) by studying nautical charts concluded that the SAB does not behave as a classical ebb-tidal delta, because no significant movement of larger bedforms has been observed.

The SAB differs from most sand banks described in the literature in many aspects: (i) it is a "solitary" feature, contrasting to the sand bar fields present on many continental shelves, such as the English Channel and the Yellow Sea; (ii) it is located at the junction of two major sedimentary basins formed during the South America-Africa separation (namely, the Recôncavo and Camamu basins), suggesting the existence of structural-topographic control of the underlying bedrock over the development of the bank; (iii) it is hard to fit the SAB in current classification categories available in the literature; and finally, (iv) the SAB is located in a region with negligible input of siliciclastic sediments.

The general objective of the present study was to determine the geometry, origin and evolution of the SAB since the Last Glacial Maximum (LGM), using high–resolution seismic data.

2. Geological and Oceanographic Setting

The SAB is located at the junction of two sedimentary basins, Recôncavo and Camamu (Fig. 1). These basins formed during the separation of South America from Africa, at the beginning of the Late Jurassic (Magnavita et al., 1994; Magnavita et al., 2005). They are associated with a triple junction formed at the time, of which the Recôncavo is a failed arm (aulacogen). The E-W trending Barra Fault separates the Recôncavo Basin from the Camamu Basin. The SAB is positioned very close to the Barra Fault, which has led some authors to suggest structural control over the bank's development (Domiguez et al., 2011).

The Salvador Peninsula is a structural high (horst) of the Precambrian basement, comprised of high-grade metamorphic rocks (Barbosa et al., 2005) which outcrop along the shoreline.

The SAB has a crescent shape (Fig. 2) and in nautical charts it is limited by the 20 m isobaths, and can be as shallow as 5m (15m high). The feature is 12.7 km long, with N-S orientation, mean width of 3 to 3.5 km, and occupies an area of 35.8 km². In cross section it is asymmetric with its eastern flank (lee side) dipping as high as 5° and exhibiting clinoform geometry, while the western flank (stoss side) dips much more gently (0.35°) (Rebouças, 2010). The SAB is separated from the mainland by the Santo Antônio Channel, oriented SE-NW, reaching depths of up to 50 m (Figs. 1 and 2).

Siliciclastic sands border the shoreline up to a depth of 10-15 m and dominate at the entrance of the TSB and at the SAB itself (Rebouças, 2010; Dominguez et al. 2011) (Fig. 3). Sediment texture at the SAB varies from coarse sand at its western flank to medium sand at the top and fine sands at its eastern flank (Fig. 3). Quartz is the dominant mineral that composes these sands, which also include heavy minerals

(0.1-8.0%) and rock fragments (2-11%) (Rebouças, 2010; Dominguez et al., 2011). While bioclasts are rare at the bank, surface sediments eastward from the SAB are essentially bioclastic and made up of fragments of coralline algae (Rebouças, 2010, Dominguez et al. 2011).

The TSB is the second largest bay in Brazil (1,223 km²). The three rivers that discharge into this area, the Paraguaçu, Jaguaripe and Subaé (Fig. 1), contribute a mean annual freshwater outfall of 200 m³/s, which is negligible compared to the volume exchanged during each tidal cycle (<1% of the spring tidal discharge at the entrance of the TSB) (Lessa et al., 2000). The contribution of sediment input by these rivers is very low, at least nowadays. Even the Paraguaçu River, the largest of the three, has not been able up to today to entirely infill the Iguape sub-bay where it discharges. At the northern half of the bay, mud is the dominant bottom sediment, whereas sands cover the sea bottom at the entrance of the bay and at the Salvador Channel. These sands are suggested to be of marine origin (Macedo, 1977; Lessa et al., 2000; Dominguez and Bittencourt; 2009).

Tides are the main physical driving force controlling circulation in the TSB and the SAB. The tide in the area is semi-diurnal, with mean high-tide range of 1.7 m. Spring tides can reach up to 2.2 m (Cirano and Lessa, 2007; Lessa et al., 2009). At the entrance of the TSB and at the SAB, tidal currents reach their highest speeds, up to almost 1.1 m/s (Lessa et al., 2001; Cirano and Lessa, 2007), during both flood and ebb tides , however ebb tides are strongest at the SAB area (Fig. 4). Open ocean waves present heights of 1 to 2 m and periods of 5 to 6.5 seconds. According to Bittencourt et al. (2008), during the summer, E-NE waves are dominant, while during the winter, S-SE waves are more common. Still according to these authors, during the winter, storm waves are able to break on the SAB. The typical climate for the study area is tropical-humid, with mean annual temperature of 25°C and precipitation of 2,000 mm (Inmet, 1992).

The surface of the SAB is covered by a wide variety of bedforms. Sand dunes are very common in the Salvador Channel and in the northern portion of the SAB, exhibiting wave lengths between 100 m and 500 m and maximum height of 5 m (Dominguez and Bittencourt, 2009; Rebouças, 2010; Dominguez et al., 2011). These dunes are clearly seen in seismic records climbing both flanks of the bank, especially across its northern section.

Tidal sand ridges measuring 2 km in length and displaying wave-lengths of 500 m are present at the top of the bank and are easily seen in aerial photographs and satellite images (Fig. 2).

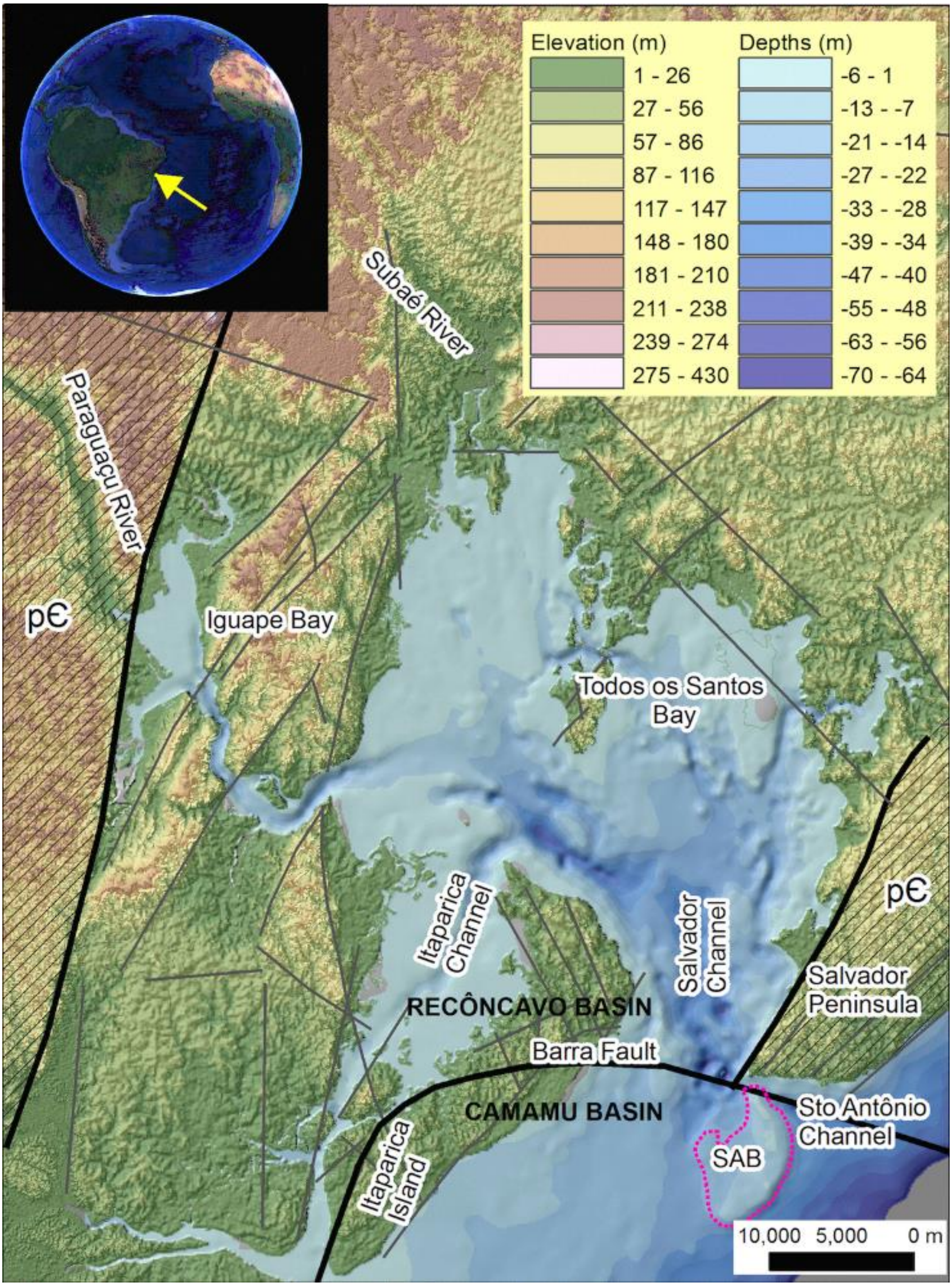


Figure -1- Shaded relief of the Todos os Santos bay and vicinities. Also shown its location of the Santo Antônio Bank (SAB). Please note that SAB limits are those portrayed in nautical charts (2012). Hatched pattern indicates Precambrian rocks (pЄ). In all other areas Cretaceous sedimentary rocks dominate. Thick black lines are major faults. Gray lines are other structural lineaments

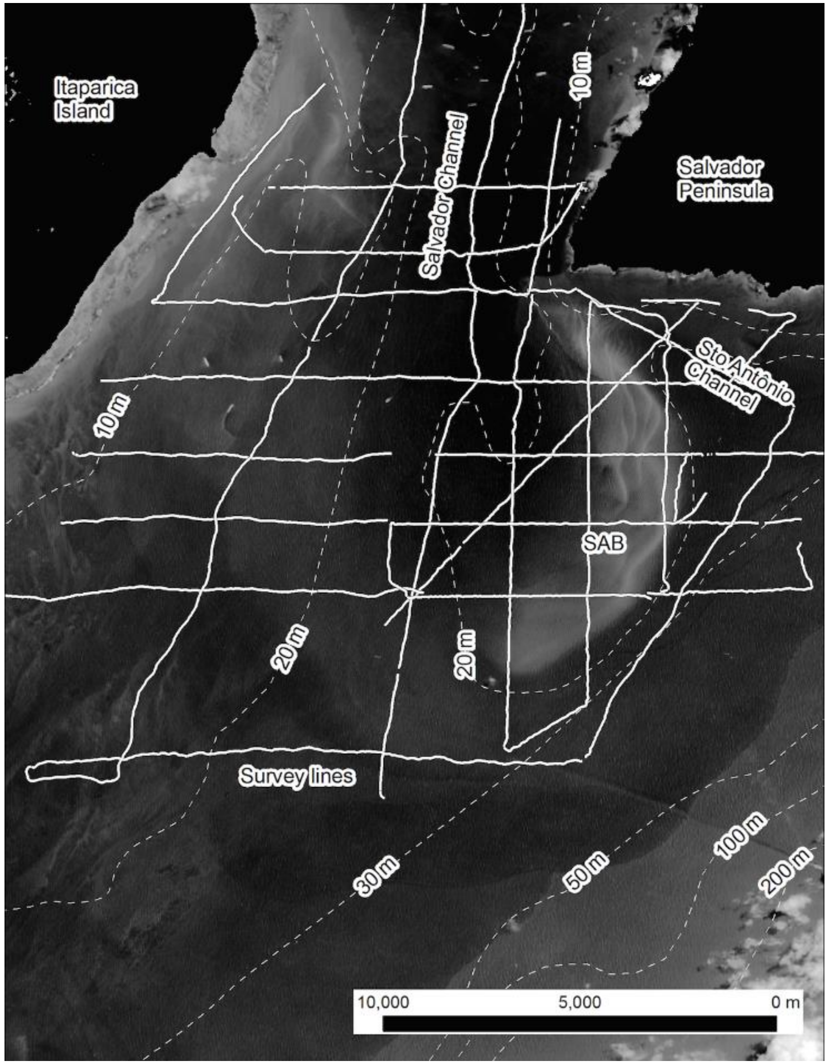


Figure -2 – Satellite image, showing: (i) entrance of the Todos os Santos bay, (ii) Santo Antônio bank, (iii) location of survey lines and (iv) simplified bathymetry in meters.

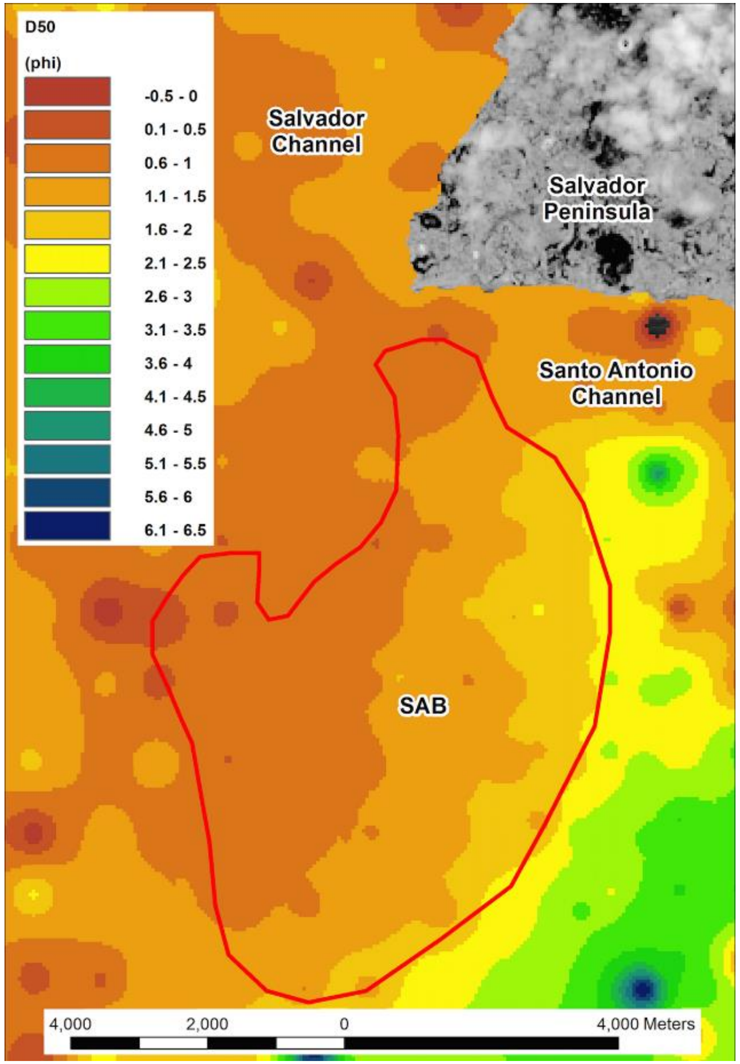


Figure -3 – Spatial distribution of median (D50) values of surface sediments at the SAB and neighboring areas. Red line indicates limits of the SAB as portrayed in nautical charts (2012). From Rebouças ,2010.

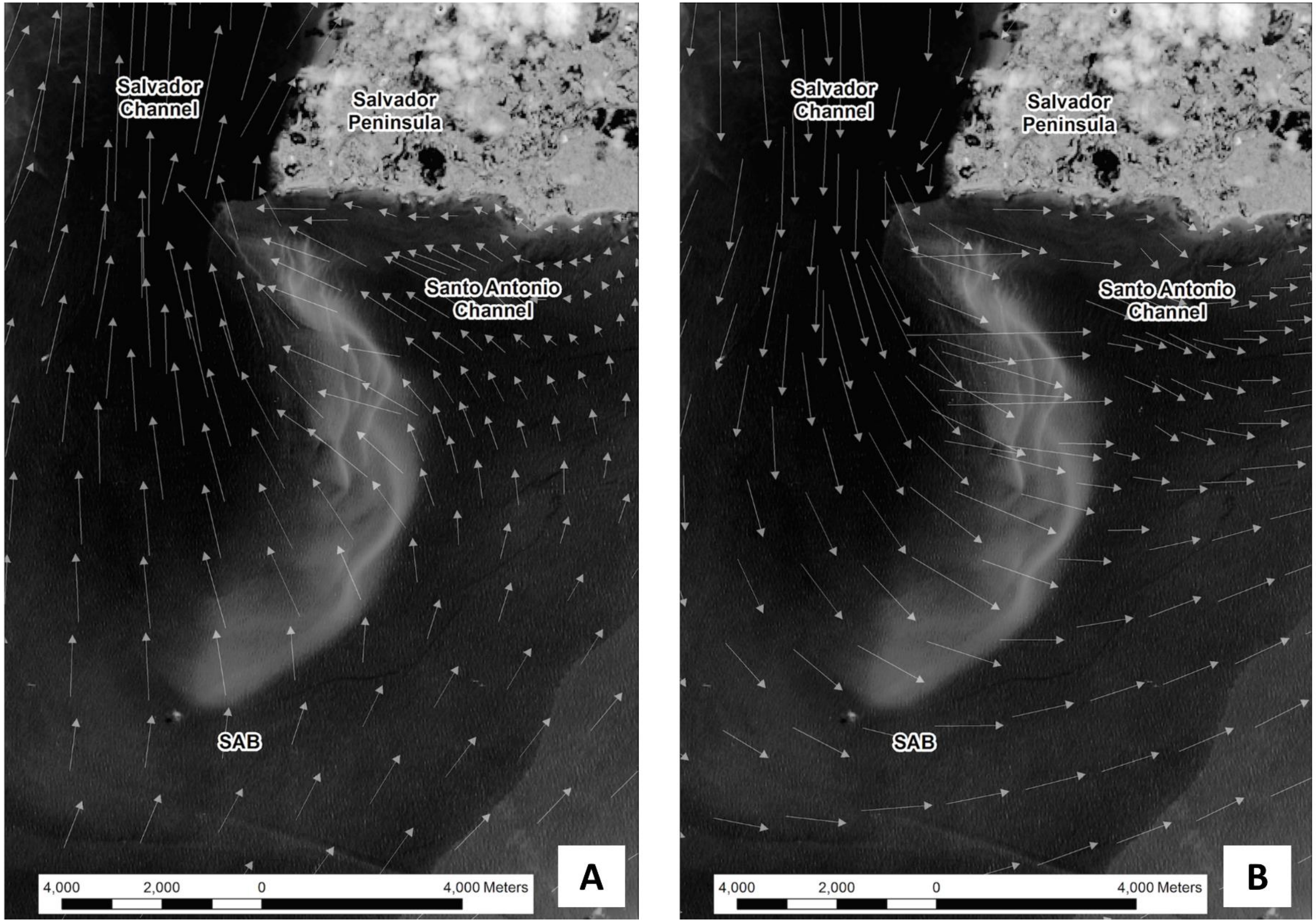


Figure 4- Modelled tidal currents at the entrance of the TSB and over the SAB, plotted on satellite image. A: flood tides, B: ebb tides. Largest arrow: 1.2 m/s. Smaller arrow: 0.1 m/s. Tidal currents from HYDROS CH2M HIL

3. Methods

A total of 170 km of high-resolution reflection seismic lines was acquired (Fig. 2) using a Meridata System with a sparker ELC 1200L seismic source operating within a frequency spectrum of 0.3 kHz to 1.5 kHz, and a maximum of 200J of energy.

Surveys were performed in December 2014 and February 2015. MDCS 5.2 software from Meridata® was used during field survey acquisition. Data processing and interpretation were done using the MDPS 5.2 software, also from Meridata®.

Seismic interpretation followed the classical principles of seismic stratigraphy (Vail, 1987) Thus, sedimentary packages were identified based on the following criteria: major discontinuity surfaces, lateral termination, geometry and amplitude of reflectors.

Sound velocity of 1,500 m/s was applied for the time-depth transformation. The limited water depth at the SAB and the dominance of sandy sediments in the study area lead to a large number of multiples, degrading the overall quality of profiles.

Maps of the depth at the top of the acoustic basement and of the major stratal discontinuities were produced using the inverse distance weighted interpolation method in Surfer10®. The same procedure was used to produce isopach maps of the major stratigraphic units. Data integration and map preparation were performed in ArcView10.1®.

4. Seismic Facies and Stratigraphic Units

4.1 Seismic Stratigraphic Analysis and Interpretation

Three major stratigraphic units were identified through the seismic profiles (Fig. 5): (i) Bedrock, (ii) Transgressive Unit, and (iii) Highstand Unit. The latter unit corresponds to the SAB itself

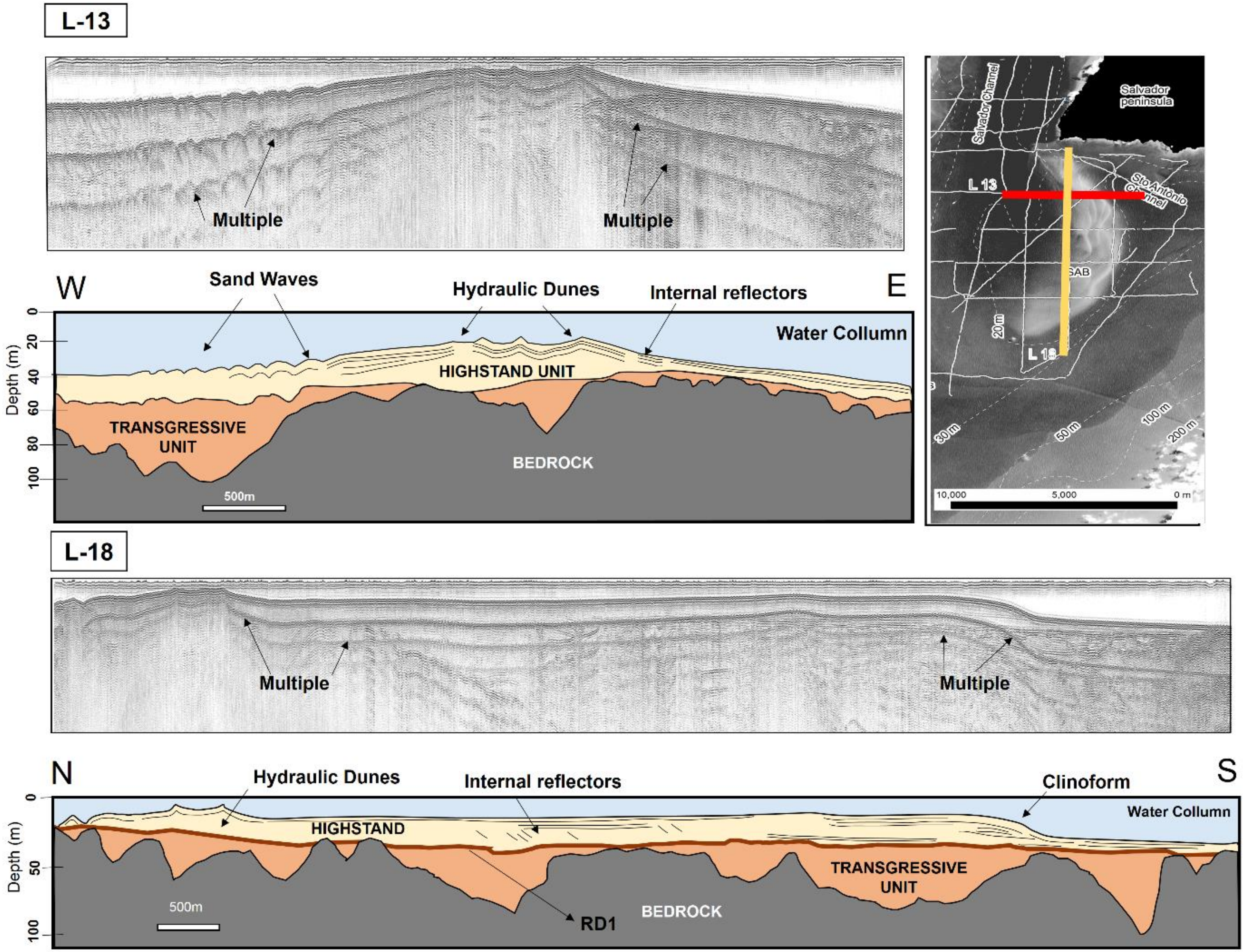


Figure 5- General geometry of the SAB and its major stratigraphic units. See inset at the right upper corner for location

4.1.1- Unit 1- Bedrock

This unit corresponds to the acoustic basement. Its top exhibits a very irregular geometry that is cut by numerous incisions, thus representing an erosion unconformity. The geometry of this unit reflects the heterogeneity of the sedimentary rocks of the Camamu Basin and its structural complexity. The top of the acoustic basement at the TSB entrance is located at a mean depth of 45 m below mean sea level (MSL), whereas at the SAB region, mean depth of the top of the acoustic basement is around 60 m below MSL. Maximum depths of as much as 120 m can be observed along the axis of the Salvador Channel at some locations of the entrance of the TSB (Fig. 5).

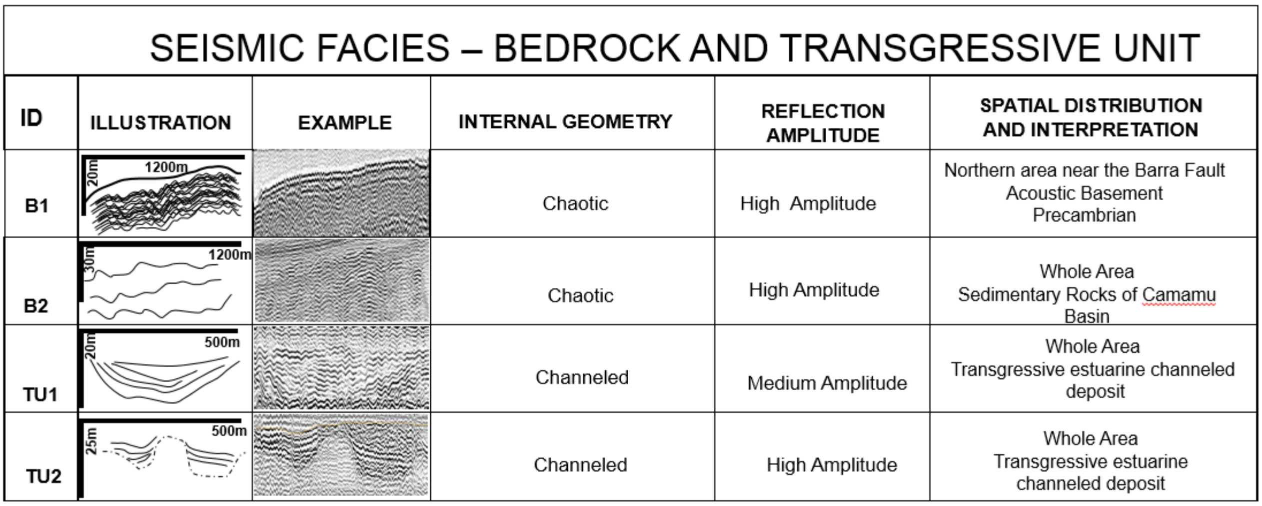
The acoustic basement was identified in all seismic profiles. To the east and west of the SAB, and near the coastline, this unit becomes shallower, reaching maximum depths of up to 30 m, and even outcropping along the shoreline.

Two seismic facies were identified in this unit based on the character of its internal reflectors (Fig. 6):

(i) Seismic Facies B1 - Precambrian Bedrock – this seismic facies is present only over a narrow strip (1.2 km wide) bordering the shoreline of the Salvador Peninsula. It is almost devoid of internal reflectors, showing a chaotic pattern with occasional high-amplitude signals. This facies ends abruptly southward, coinciding with the trace of the Barra Fault, which separates the Camamu Basin from the Salvador High and the Recôncavo Basin. This facies was interpreted as the Precambrian bedrock that outcrops along the shoreline and surf zone of the Salvador Peninsula;

(ii) Seismic Facies B2 - Camamu Basin Bedrock – this seismic facies is present southward from the Barra Fault and is characterized by parallel, dipping, discontinuous, high-amplitude reflectors, which were interpreted as representing sedimentary rocks of the Camamu Sedimentary Basin. These rocks outcrop along the shoreline of Itaparica Island and its bordering shallow marine shelf.

Figure 7 shows a map of the top of the acoustic basement. The incisions on the top of this unit are part of a much larger drainage system, encompassing the entire TSB, which was sculpted during Pleistocene lowstands, as suggested by Dominguez and Bittencourt (2009), Dominguez et al. (2011) and Dominguez (2015). An interesting aspect about these incisions is that they are oriented NW-SE and also E-W, suggesting structural control which will be discussed further herein (Figs. 1 and 7).



SEISMIC FACIES – BEDROCK AND TRANSGRESSIVE UNIT

ID	ILLUSTRATION	EXAMPLE	INTERNAL GEOMETRY	REFLECTION AMPLITUDE	SPATIAL DISTRIBUTION AND INTERPRETATION
B1	20m 1200m		Chaotic	High Amplitude	Northern area near the Barra Fault Acoustic Basement Precambrian
B2	30m 1200m		Chaotic	High Amplitude	Whole Area Sedimentary Rocks of Camamu Basin
TU1	20m 500m		Channeled	Medium Amplitude	Whole Area Transgressive estuarine channeled deposit
TU2	25m 500m		Channeled	High Amplitude	Whole Area Transgressive estuarine channeled deposit

Figure 6- Seismic facies identified in the Bedrock (acoustic basement) (B1 and B2) and at the Transgressive unit (TU1 and TU2)

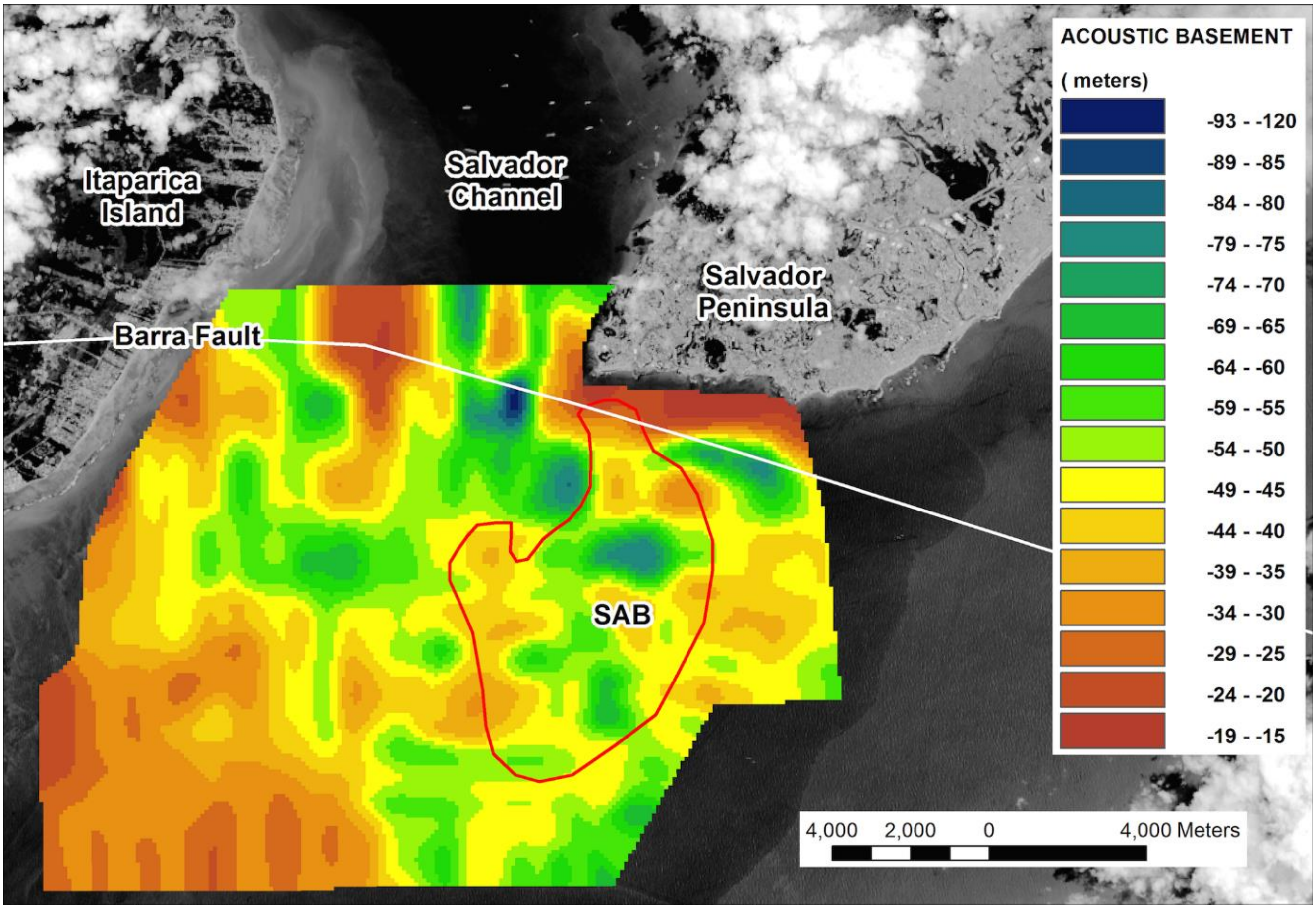


Figure 7- Geometry of the Acoustic Basement. *Red line indicates limits of the SAB as portrayed in nautical charts (2012).*

4.1.2- Unit 2 – Transgressive Unit

This unit infills the bedrock incisions. The maximum thickness observed for Unit 2 was 53.4 m, whereas mean thickness was only 11.7 m (Fig. 8). Eastward from the SAB, Unit 2 virtually disappears and Unit 1 (Bedrock) comes very close to the seafloor, occasionally even outcropping.

Two seismic facies were found in this unit (Fig. 6). Both of them are characterized by channeled reflectors. However, each seismic facies presents different seismic amplitudes:

(i) Seismic Facies - TU1 – this facies showed medium-amplitude, discontinuous internal reflectors. This signature can be indicative of finer sediments deposited under conditions of lower energy levels, thus preventing better stratal segregation.

(ii) Seismic Facies - TU2 – this facies, on the other hand, exhibited high-amplitude, laterally continuous reflectors, which are indicative of alternation of contrasting textural sediments (sand and muds), possibly deposited under conditions of higher energy when compared to Seismic Facies TU1.

Two major depocenters are present in this unit (Fig. 8). The westernmost depocenter has a triangular shape, increasing in width and thinning westward. The easternmost depocenter, overlaps with the SAB and is segmented into three smaller depocenters, oriented mostly perpendicular to the present day SAB.

Unit 2 was interpreted as a transgressive unit deposited in an estuarine setting during the sea level rise that took place after the LGM. This interpretation was based on the overall discontinuous geometry of this unit, infilling incisions in the bedrock, as well as the channeled reflectors of the seismic facies. Similar features and interpretations have been described for sandbanks studied in the Celtic Sea by Berné et al. (1996), Marsset et al. (1999) and Trentesaux (1999).

Unit 2 is bounded at the top by two relatively flat planar surfaces that are separated by a step (Fig. 9). The western planar surface is located at a mean depth of 20 m, whereas the eastern planar surface, on top of which the SAB developed, is at a mean depth of 40 m below MSL. Both planar surfaces were interpreted as ravinement surfaces, and named respectively as RD2 and RD1. The presence of these two ravinement surfaces is suggestive of the existence of either two stabilization periods or of significant decreases in sea level rise rates during the overall transgression.

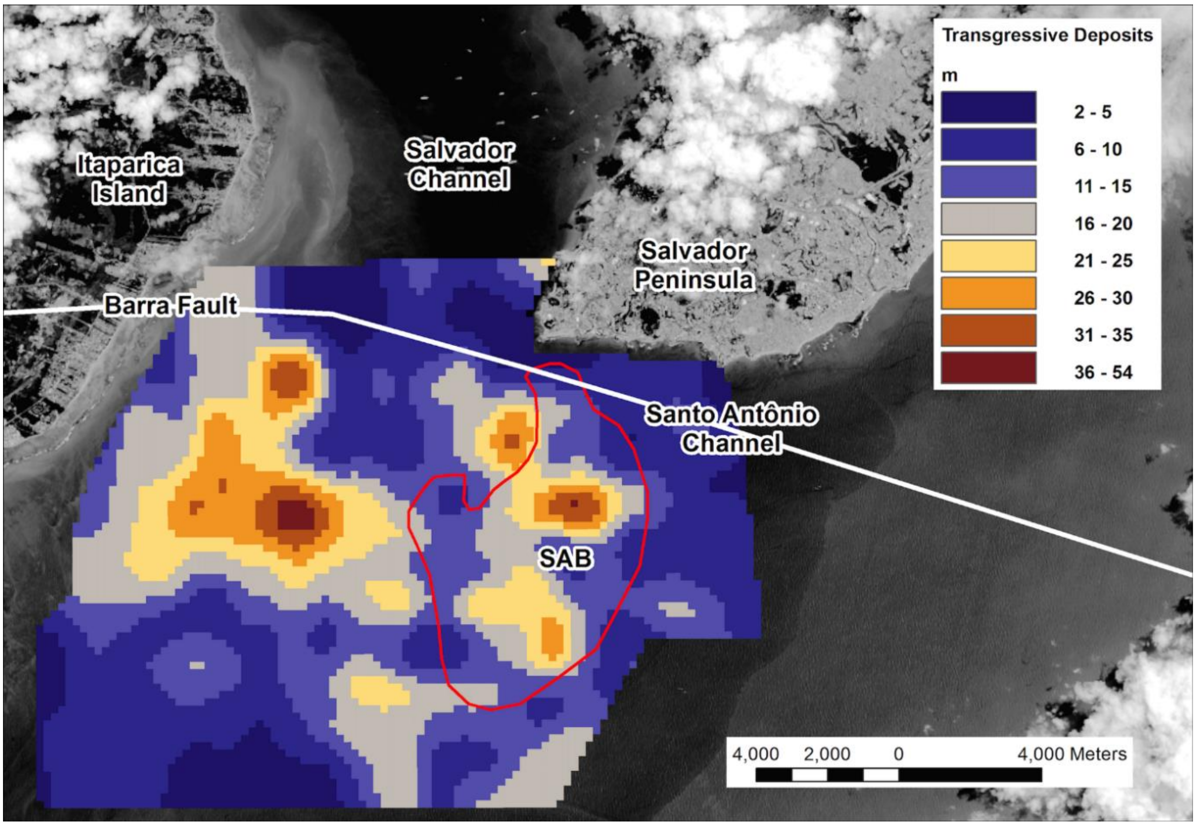


Figure 8- Thickness of the Transgressive Unit. *Red line indicates limits of the SAB as portrayed in nautical charts (2012).*

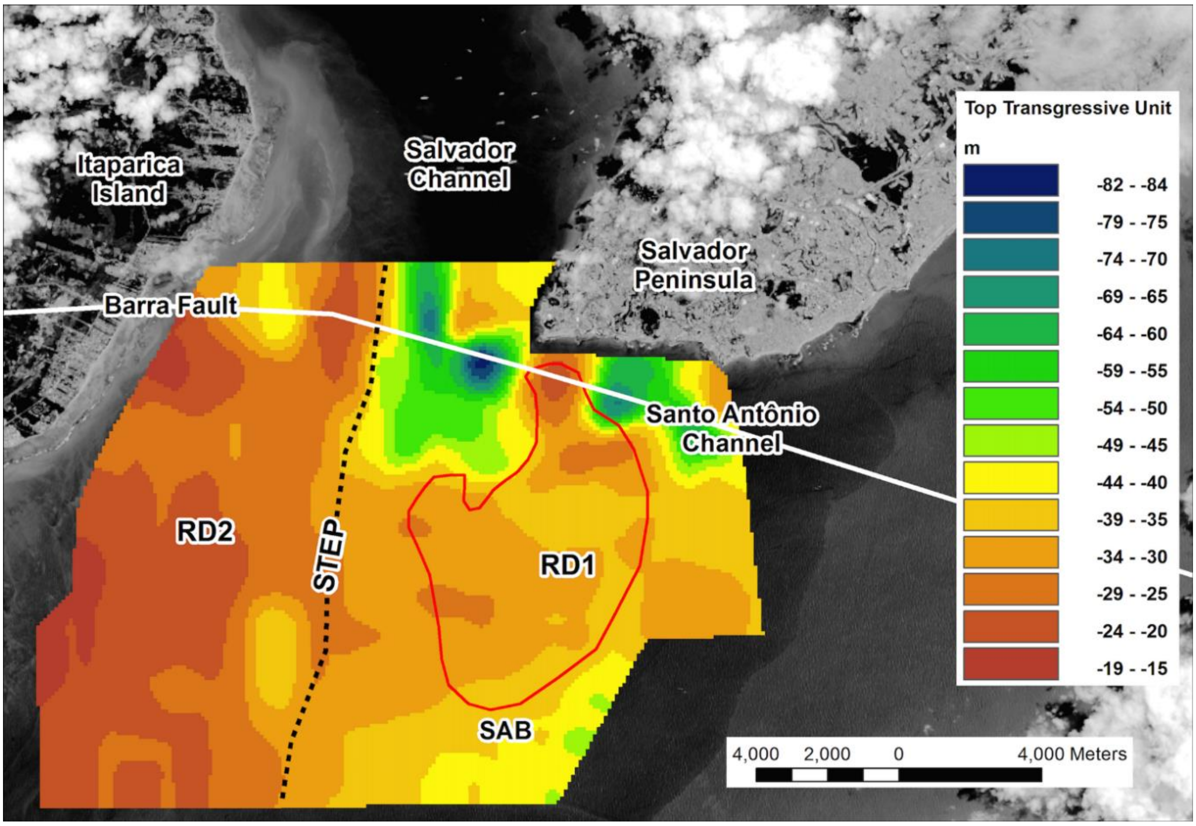


Figure 9- Top of the Transgressive unit, showing the Ravinement surfaces RD1 at -40 m and RD2 at -20 m, separated by a step (broken line). *Red line indicates limits of the SAB as portrayed in nautical charts(2012).*

4.1.3- Unit 3- Highstand Unit

The Highstand Unit is limited at its base mostly by the RD1 and RD2 flat surfaces and at its top by the present seafloor. The base of the SAB is generally the RD1 surface (40 m below MSL) (Fig. 9). Only at its northern extremity, closer do the shoreline, the bank rests over a broad ridge of the bedrock (Fig. 5). The top of the Highstand Unit can be positioned as shallow as 5 m below MSL. However, the unit is also found at water depths of up to 83 m in the deeper present day channels of the TSB (e.g. Salvador Channel).

Because the SAB is the most important feature of Unit 3 (Fig. 5), only the six seismic facies occurring within the SAB limits will be described (Fig. 10). Aggradational and progradational reflectors are typical in this unit. Figure 11 shows the approximate spatial distribution of these facies.

(i) Seismic Facies HU1 – Wavy parallel reflectors (Figs. 10 and 11) - this facies is present only at the top of the SAB in close association with the tidal sand ridges. Wavy parallel, high-amplitude reflectors are characteristic. Although these reflectors are dominantly symmetrical regarding the surface tidal sand ridges, they may locally show internal truncations suggesting that these tidal ridges may experience limited lateral migration. The spatial distribution of the HU1 facies seems to be correlated to the higher tidal speeds experienced at the top portion of the SAB (Figs. 4 and 11). Ebb and flood currents are approximately equivalent in this area, reaching high speeds of almost 1.2 m/s, with slightly higher currents during ebb tides.

(ii) Seismic Facies HU2 - Climbing sand dunes (Figs. 10 and 11) – although this facies is observed at both flanks of the bank, it is more common in the stoss (western) side of the SAB, where seafloor gradients are smaller than at the lee side. This facies is directly associated with active sand dunes present at the surface of the bank. Major internal reflectors display high amplitudes and dip gently, possibly representing climbing surfaces associated with dunes migrating up the bank flanks

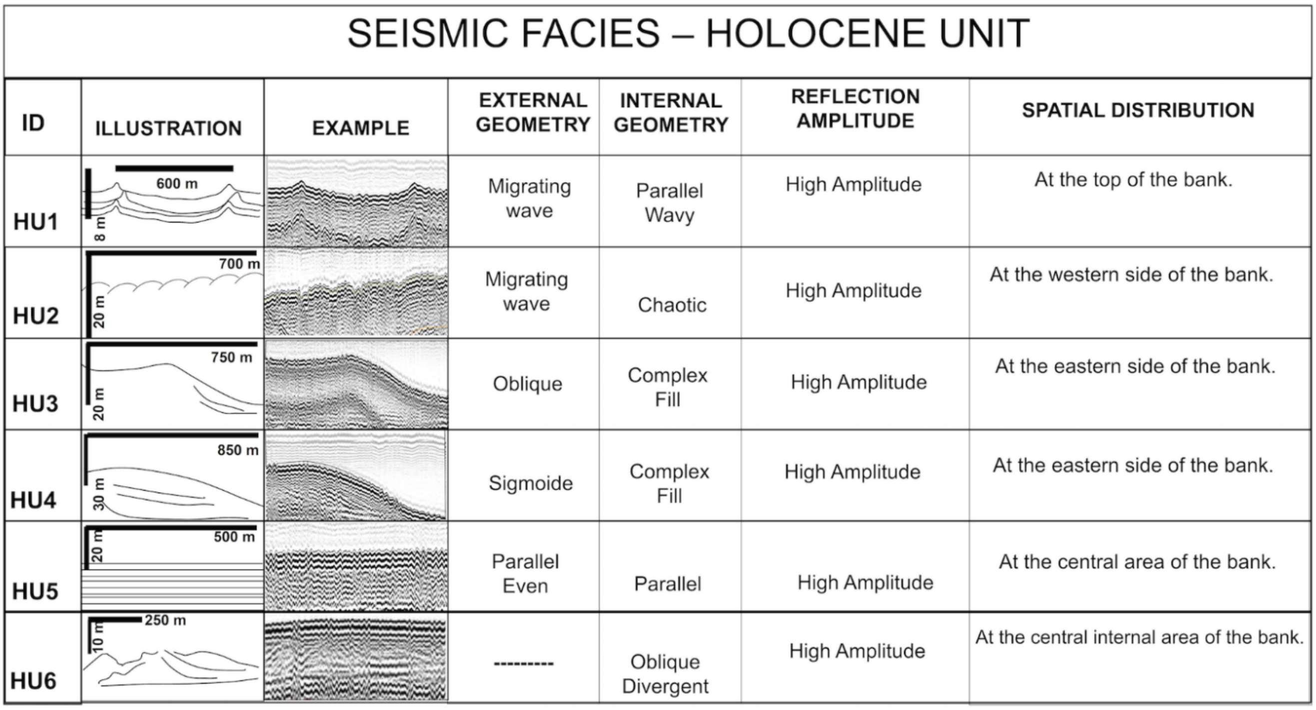
(iii) Seismic Facies HU3 – High-angle oblique clinoform (Figs. 10 and 11) - made up of oblique, high-amplitude, eastward dipping reflectors present at the central eastern flank of the SAB. This facies is up to 20 m thick and extends 850 m lengthwise. This geometry is indicative of lateral eastwards progradation of this portion of the SAB, under shallow water high-energy conditions (Mitchum Jr et al., 1983).

(iv) Seismic Facies HU4 – Sigmoidal clinoform reflectors (Figs. 10 and 11) - this facies occurs only at the southern portion of the SAB and is characterized by high-amplitude sigmoidal reflectors dipping at angles similar to those of the present day seafloor. The maximum thickness of this facies is 25 m. This sigmoidal geometry is indicative of a relatively low sediment supply and progradation in a deeper, low-energy sedimentary regime (Mitchum Jr et al., 1983). This facies indicates that the bank is also prograding southward. At this portion of the bank, sands are finer in association with a drop in tidal current intensity (Rebouças, 2010).

(v) Seismic Facies HU5 - Plane parallel reflectors (Figs. 10 and 11) – it is widely distributed across the SAB, particularly in its central portion, near the top and at its central core. Internal reflectors exhibit high amplitude and continuity, as well as plane parallel geometry. The presence of this facies at the top of the SAB suggests the influence of high-energy processes, with no significant sediment deposition. Its occurrence in the central core of the bank also suggests the dominance of high-energy conditions since the early stages of bank development.

(vi) Seismic Facies HU6 - Low-angle oblique reflectors (Figs. 10 and 11) – found in the northern, central and southern areas of the SAB, and in the central inner core of the bank. Internal reflectors display a low-amplitude signal, probably related to the presence of fine sand sediments. Reflectors dip at gentle angles predominantly east and southward, although west and northward dips are also present. This facies is also possibly related to the beginning of bank development.

Figure 12 shows an isopach map of Unit 3. The greatest thicknesses of this unit occur at the eastern flank of the SAB and at the Santo Antônio Channel. The SAB is the main deposit of the Highstand Unit, with thickness varying from 8 m (western side) to 57 m (eastern side).



SEISMIC FACIES – HOLOCENE UNIT

ID	ILLUSTRATION	EXAMPLE	EXTERNAL GEOMETRY	INTERNAL GEOMETRY	REFLECTION AMPLITUDE	SPATIAL DISTRIBUTION
HU1	600 m 8 m		Migrating wave	Parallel Wavy	High Amplitude	At the top of the bank.
HU2	700 m 20 m		Migrating wave	Chaotic	High Amplitude	At the western side of the bank.
HU3	750 m 20 m		Oblique	Complex Fill	High Amplitude	At the eastern side of the bank.
HU4	850 m 30 m		Sigmoide	Complex Fill	High Amplitude	At the eastern side of the bank.
HU5	500 m 20 m		Parallel Even	Parallel	High Amplitude	At the central area of the bank.
HU6	250 m 10 m		---------	Oblique Divergent	High Amplitude	At the central internal area of the bank.

Figure 10- Seismic facies identified in the Santo Antonio Bank. *See figure 11 for spatial distribution*.

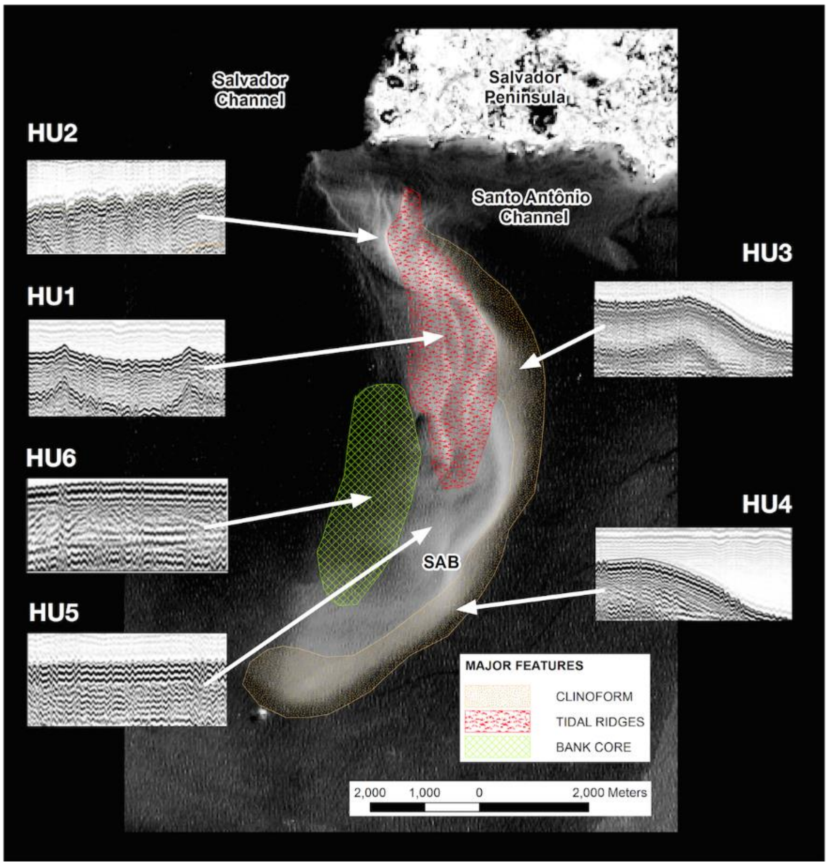


Figure 11- Schematic spatial distribution of seismic facies in the SAB. HU1 – wavy parallel, HU2 – climbing sand dunes, HU3 – high-angle oblique clinoform, HU4 – sigmoidal clinoform, HU5 – plane parallel, HU6 – Low-angle oblique.

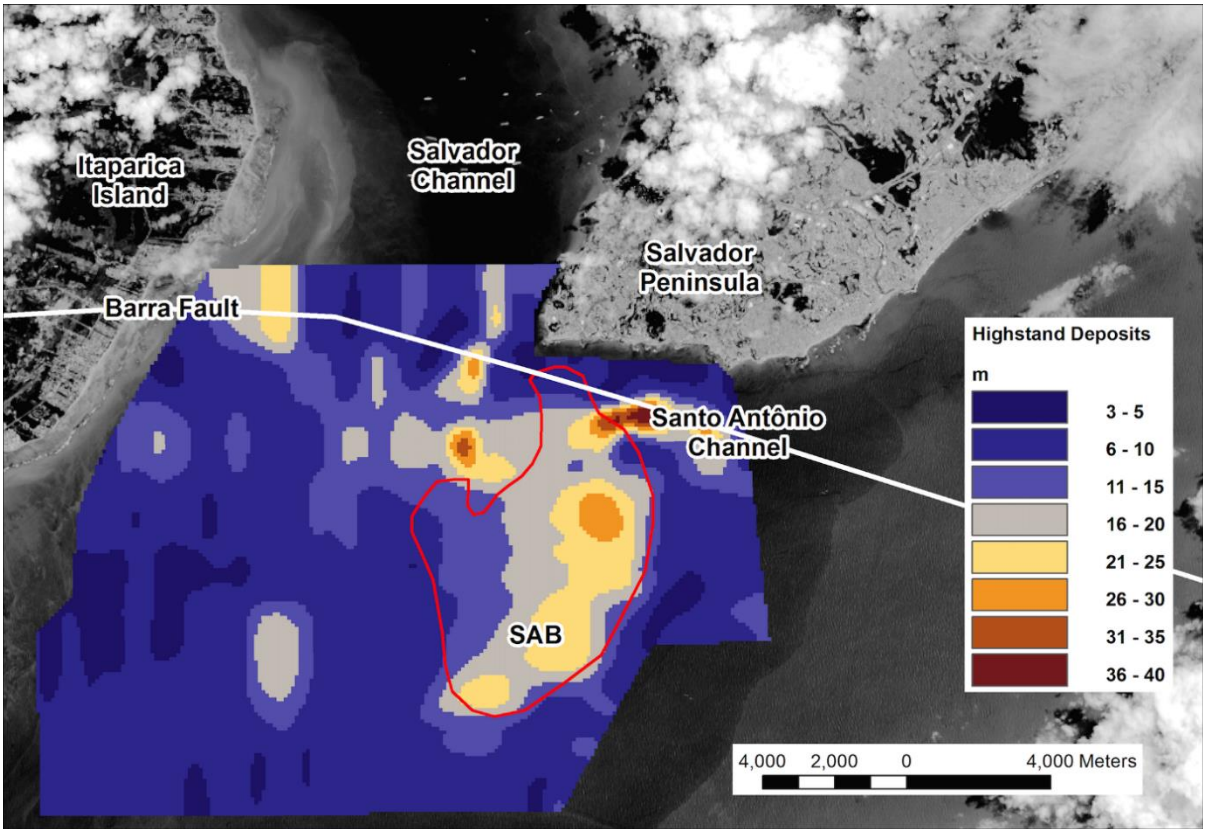


Figure 12- Sediment thickness of the Highstand Unit. *Red line, indicates limits of the SAB as portrayed in nautical charts(2012).*

5. Sea level changes and the evolution of the Santo Antônio Bank

Sea level changes have played an important role in the development of many sand banks worldwide. Most of the tidal ridges studied in the North Sea (Well Bank area), Gulf of Lions and Celtic Sea have been considered lowstand deposits, given that some of these banks lie today at depths of 50 to 150 m (Houbolt, 1968; Berné et al., 1994; Berné et al., 1996; Marsset et al., 1999). Tidal ridges in the Yellow Sea have had their origin related to the Holocene Transgression or to the subsequent highstand (Li et al., 2001).

Because of the lack of core and age data, the role of sea level changes in the evolution of the SAB was reconstructed using eustatic sea-level curves available in the literature as a template for placing chronological controls over the deposition of the units that were identified. Thus, the curve proposed by Liu et al. (2004), which was constructed from a compilation of data from the continental shelves of the East China Sea (Liu, 2001), Sunda Shelf (Hanebuth et al., 2000) and Bonaparte Sea (Yokoyama, et al., 2000), was applied in the present study.

5.1 Phase 1 – Last Glacial Maximum (Fig. 13A)

During the LGM (20 kyr BP) the sedimentary rocks of the Camamu Basin and the high-grade metamorphic rocks of the Precambrian basement were exposed to subaerial erosion. This process may have helped in the re-activation of ancient incised valleys formed during previous Quaternary sea level lowstands. The maximum depth of the top of the acoustic basement mapped through the seismic lines was 120 m below MSL, indicating that the study area was completely exposed during the LGM.

Many incised valleys have been identified in other areas of the continental shelf of the state of Bahia. These features still exhibit a clear expression on present day bathymetry, especially in areas that receive little sediment from the continent (Dominguez and Bittencourt, 2012; Dominguez et al., 2013).

At the present study area, these incisions showed a geometry that is suggestive of a remarkable control exerted by the tectonic infrastructure of the Recôncavo and Camamu basins, which will be discussed further herein.

During this phase, the TSB was part of the watershed of the Paraguaçu River (Dominguez and Bittencourt, 2009; Dominguez, 2015), which discharged directly onto the upper continental slope, considering the shallowness of the shelf break in the area (60 m).

5.2 Phase 2 – Holocene Transgression (Fig. 13B)

After the LGM, with the melting of large ice sheets in the Northern Hemisphere, sea level presented an initially slow rise up to approximately 14 kyr BP. This was followed by Meltwater Pulse 1A (MWP1A), which brought sea level to 70 m below current MSL over an extremely short span of only few centuries. After MWP1A, a relatively stable to slowly rising sea level period ensued lasting for about 2,000 years, culminating in the Younger Dryas at 12.7 kyr. This earlier stabilization in sea level probably favored the beginning of the infill of the bedrock incisions, which were rapidly flooded during this meltwater pulse (Fig. 13B). This earlier infill corresponds to the basal portion of Unit 2 (Transgressive Unit).

Meltwater Pulse 1B (MWP1B) followed the Younger Dryas, causing renewed flooding of the bedrock incisions, aborting the infilling process. MWP1B was followed by another period of either stabilization or decrease in sea level rise rates, lasting also approximately 2,000 years, according to the sea level curve proposed by Liu et al. (2004). This sea- level stabilization after MWP1B allowed the final infilling of incisions in the SAB area (Unit 2). At the end of MWP1B (~11 kyr), sea level stood around 40 m below current MSL. This depth coincides with the position of ravinement surface RD1, which required a prolonged time period for its development, due to the combined action of waves and currents. As mentioned previously, the RD1 surface caps Unit 2 in the SAB area.

The RD1 surface was the base upon which the initial core of the SAB began to develop in a region located southwestward from the present bank (Seismic Facies HU6). This corresponds approximately to an age of 10 kyr (Fig. 13C).

According to Liu et al. (2004), another Meltwater Pulse (MWP1C) took place between 9-9.5 kyr, which caused a rise in mean sea level of approximately 15 m. MWP1C may have drowned the incipient SAB, whose remnants are now preserved as the inner bank core.

The development of the RD2 ravinement surface must have begun after MWP1C because of the depth at which it is located (20 m below current MSL).

5.3 Phase 3 – Holocene Highstand (Fig. 13D)

The final push in sea level rise during and after MWP1C allowed the flooding of vast areas of the TSB, which today has an average depth of 9.8 m below MSL. The flooding of the TSB increased tidal prism in the bay, intensifying ebb and flood currents at its entrance. The bedrock caped by the RD2 surface has since acted as an obstacle for the exiting ebb tide, deflecting currents eastward and, thus, favoring the development of the SAB around its initial core formed during the final stage of the transgressive phase (Fig. 4).

During the present highstand, the SAB underwent progradation eastward, as indicated by the sigmoidal and oblique high-angle reflectors (facies HU3 and HU4) accompanied by aggradation and eastward displacement of the bank axis relative to the position that was occupied earlier by its inner core.

As the SAB aggraded vertically with time, concomitantly with its eastward migration, water depths became increasingly shallow at its top and further aggradation was precluded by an increase in tidal current velocity at the top of the bank.

The SAB can thus be appropriately considered as a deflected ebb tidal delta. The asymmetrical disposition of this feature in relation to the entrance of the bay is more apparent than real and derives from the role the bedrock caped by the RD2 surface plays in deflecting ebb tidal currents.

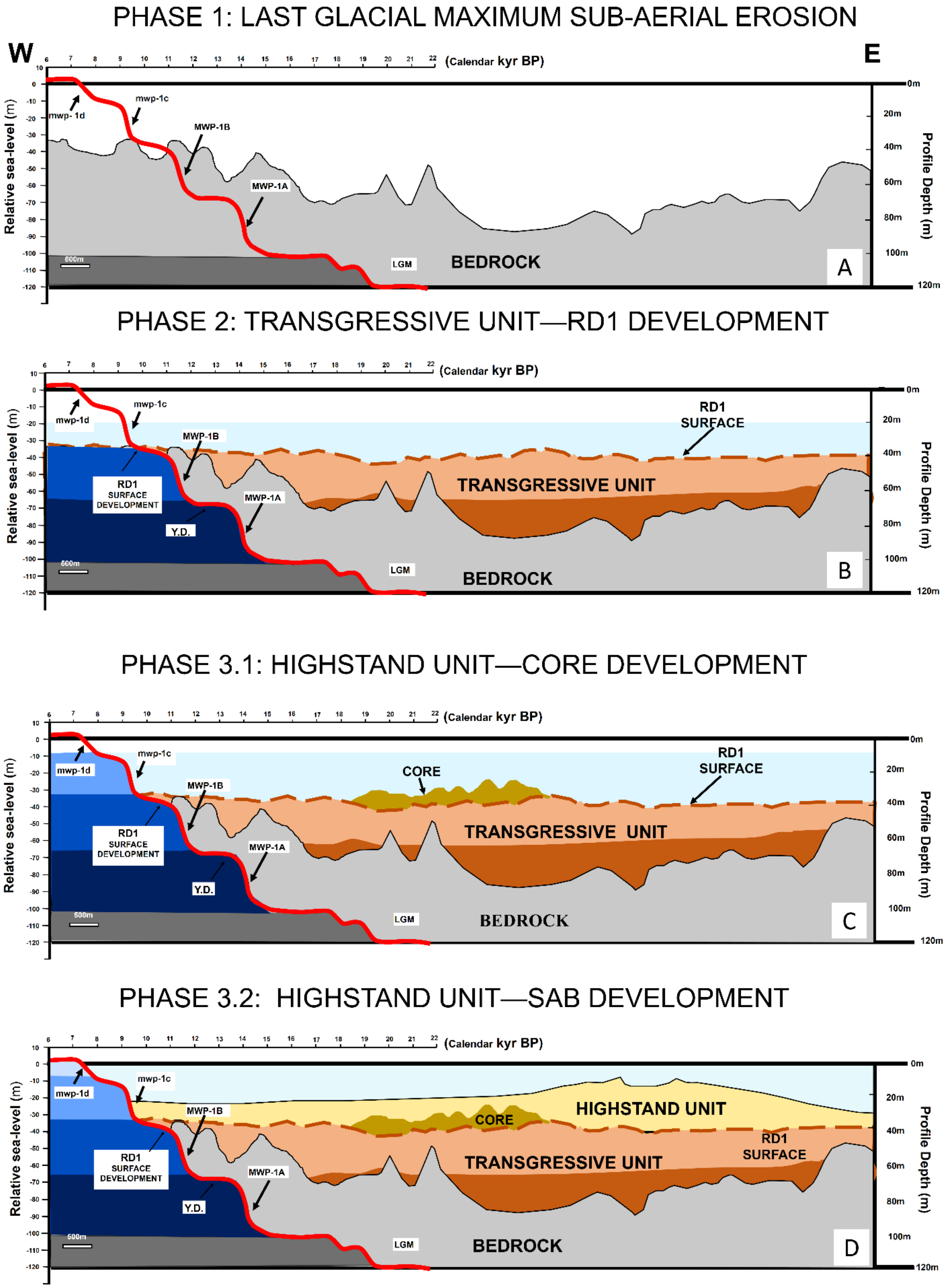


Figure 13- Development history of the SAB, during the Last Glacial cycle. Red line is a simplified version of Liu et al. (2004) sea-level curve used in this paper as reference, to set chronological limits to the SAB evolution

6. Ravinement surface

Transgressive ravinement surfaces are scours cut by tides and waves during the landward shift of the shoreline. There are two major types of transgressive ravinement surfaces: those generated by tides and those by waves, which are commonly superimposed by transgressive shoreface deposits (i.e. coastal onlap) (Catuneanu, 2006). The amount of sediments eroded during the development of these surfaces can lead to depths of up to 40 m in some cases (Hanebuth et al., 2011).

Several authors have reported the presence of flat surfaces in areas in which sand banks occur. Some of these surfaces have been interpreted as ravinement surfaces. The presence of such features were first discussed and identified by Houbolt (1968) in his study of the sand ridges of the North Sea. The author found that most of the studied sand ridges were isolated features resting on an essentially flat surface, which was at the same level as the surrounding sea bottom. Flat surfaces in the Celtic Sea area have been interpreted as originating during lower sea level stages in Pliocene-Quaternary times (Berné et al., 1996; Marsset et al., 1999). Wang et al. (2012) identified the presence of planar erosional surfaces at depths varying between 5 and 20 m in the sand ridge field of the Yellow Sea. Berné et al. (1994) in their study in the Middelkerke Bank (southern North Sea) also found planar surfaces at depths of 20-30 m separating estuarine-tidal flat deposits and the overlying bank itself. These examples show that many Holocene sand banks worldwide have been built on flat surfaces. As a result, Berné (1994) classified sand banks/ridges in two major types from a stratigraphic point of view:

(1) *"Sand banks resting on a flat surface, where bank build up is only related to a convergent pattern of sand transport. In this case the whole bank consists of Holocene deposits (early Holocene in the case of moribund sand banks at the outer shelf – late Holocene in the case of active sand banks at estuaries and inner shelf)."*

(2) *Sand banks whose cores consist of eroded fluvial or estuarine sediments of early Holocene age, in the case of inner shelf sand banks, and of Pleistocene age in the case of outer shelf "moribund" sand banks or erosive bedrock morphologies."*

The SAB is akin of these two categories. Most of the SAB rests on a flat surface located 40 m below MSL (RD1), approximately coinciding with the lower limit of the bank. However, at its northern extremity, much closer to the shoreline, the bank has developed over a broad ridge resting almost directly on top of erosional remnants of the bedrock (Figs. 5 and 9).

The RD2 surface located westward from the SAB forms a wide rocky terrace with mean depths of 20 m below MSL, facing southeastward (Fig. 9). RD2 has insignificant sediment cover, with reef constructions bordering the present day shoreline (Araújo et al., 1984). Based on the findings of the present study, the sculpturing of this surface is likely to have been promoted mostly by wave action, since it faces the direction from where the most frequent and energetic waves arrive. RD2 might also represent the cumulative effect of several incisions caused by wave action during previous similarly positioned highstands, which then underwent further reworking during the present highstand period.

The ease with which these two ravinement surfaces have been sculpted probably derives from the fact that they have been incised into fine-grained sedimentary rocks. In fact, in the interior of the TSB, islands are bordered by abrasion terraces sculpted by wave action, although energy levels in the interior of the bay are very low (Dominguez and Bittencourt, 2009; Dominguez, 2015).

7. Structural control

There has been some controversy about the origin of the TSB. Earlier authors have proposed a strong neotectonic control in the development of the bay (Tricart & Da Silva, 1968; Martin et al., 1981). More recently, this interpretation has been questioned and it has been suggested that the TSB had its origin associated with differential erosion between the high-grade metamorphic rocks of the Precambrian basement and the fine-grained sedimentary rocks of the Recôncavo Basin (Dominguez and Bittencourt, 2009; Dominguez, 2015).

Rifts are intrinsically complex sedimentary basins characterized by numerous faulted blocks, abrupt changes in depocenters, transfer faults, and accommodation zones occurring very close to each other (Withjack et al., 2002). This results in great heterogeneity in the spatial distribution of sedimentary lithologies, deposited under the strong influence of tectonic activity. Because the Recôncavo Basin is an aborted rift (aulacogen), where major activity and subsidence has ceased about 90 myr ago (Magnavita et al., 1994), it has been subjected to prolonged subaerial erosion since that time, particularly after the Miocene and culminating in the Quaternary glaciations (Dominguez and Bittencourt, 2009; Dominguez, 2015). The structural and lithological heterogeneity of rift basins exert a strong control on erosion, which manifests itself into the evolving landscape (Fig. 1). In addition, the studied area is located at the junction (Barra Fault) between the Recôncavo Aulacogen and the Camamu Basin (Fig. 1).

Major bedrock incisions at the study area are oriented NW-SE and NE-SW (Fig.7), mimicking the large rhombohedral geometry of the TSB, which is itself controlled by major lineaments (Fig. 1). These incisions also coincide and are extensions of lineaments on the continent. Thus, the framework of the Recôncavo and Camamu basins has exerted control on the location and orientation of fluvial incisions during Quaternary lowstands. This added great complexity to the landscape, which was later flooded during transgression periods, and to the sedimentary facies deposited therein. This complex, flooded landscape has also caused, as previously mentioned, the deflection of ebb tidal currents eastward, focusing sediment transport towards the area now occupied by the SAB.

In a sense, the structural framework of these Cretaceous sedimentary basins continues to control sediment dispersal and deposition in the study area.

8. Origin of the sand

The source of the sand present in a sand bank is one of the major questions related to the development of these features. Houbolt (1968) concluded that because tidal currents were very strong in the North Sea, much of the sand available was not transported towards the shore during the Holocene Transgression, but kept offshore and acted as a source for the construction of the sand ridge field in the study area. However, these banks are located at 50 m below MSL. Dyer and Huntley (1999) proposed that sand can come either from the seabed or from coastal erosion. Other studies attribute the supply of sands to estuaries and bay systems. Examples of this are the Hinder Banks and Flemish Bank, supplied by sediments from the Rhine river (Baak, 1936 apud Houboult, 1968), the Yellow Sea ridge systems, supplied by the Yangtze River, and also the Changjiang and Hunaghe deltas (Li et al., 2001; Wang Zhang et al., 2012). Several authors have also concluded that part of the sands have originated from the erosion of older nearby deposits (Houbolt 1968; Swift, 1975; Berné et al., 1994; Berné et al., 1996; Marsset et al., 1999; Li et al., 2001).

The total volume of sand at the SAB resting on the RD1 surface was calculated at around 1 billion m³. There is a lack of big rivers transporting significant volumes of sand to the Salvador Continental Shelf and adjacent area. Moreover, the three rivers that discharge into the bay (Paraguaçu, Subaé and Jaguaripe) are not able to supply a significant volume of sand to the TSB entrance (Macedo, 1977; Lessa et al., 2000; Dominguez and Bittencourt, 2009). Therefore, sand accumulations present at the SAB and Salvador Channel have either been reworked from pre-existing deposits or have been brought by longshore currents.

According to Fontolan et al. (2007), most of the sand available at the coastal zone is found near estuaries and bay channels as ebb and/or flood tidal delta features. This occurs because most of the sand transported by longshore currents is trapped at the entrance of bays and channels and are used to build the tidal deltas.

Assuming that most of the sand deposited at the SAB originated from coastal currents after sea level stabilized around 7-8 ka BP, gross longshore transport of sand would have to be around 125,000 m³ per year. Although no evaluation of longshore sediment transport is available for the study area, gross annual longshore transport of 200,000 m³/year has been calculated for the region of the municipality of Ilhéus, located 150 km southward from the present study area (DHI, 2013) Therefore, it is reasonable to assume that sands transported by longshore currents were the major source of sediment in the construction of the SAB.

To this major source we can also add the sands delivered by the Paraguaçu River during low sea-level stands, which were then reworked and transported landward during the post-LGM transgression.

9. Conclusions

The Santo Antônio Bank resulted from the complex interaction between a pre-existing topography, varying rates of sea-level rise, the action of waves and tides, and their morphodynamic mutual adjustments. Prolonged sub-aerial erosion of sedimentary rocks of the Recôncavo and Camamu basins gave origin to a complex topography similar to what occurs today at the TSB. Erosion was highly influenced by the structural framework of these basins, exerting a strong control in the orientation of incisions in the bedrock. Later, during the post-LGM transgression, these incisions controlled the distribution of depocenters and tidal circulation within the flooding TSB. The geometry of the bedrock acted in deflecting the ebb currents eastward, focusing sedimentation in the area where the SAB is located. The SAB is, thus, a type of deflected ebb tidal delta constructed under the influence of the above factors. During the last 7-8 kyr, aggradation and east-southward progradation took place.

The volume of sand stored within the SAB (1 billion m^3) is compatible with gross annual longshore transport rates acting over the past 7-8 kyr. These longshore sourced sands were trapped at the entrance of the bay by tidal inflows and outflows, helping in the construction of the SAB.

The SAB is possibly the most important sand deposit available to the metropolitan area of the city of Salvador. This bank can be used in future beach nourishment and civil engineering projects. Some of the urban beaches of the city have already disappeared and the remaining ones are threatened by projected sea level rises during coming decades. In this sense, the SAB contributes to increase the resilience of the city of Salvador and its adaptation to climate changes.

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CAPÍTULO 3
CONCLUSÕES

1. CONCLUSÕES

O Banco de Santo Antônio, resultou de uma complexa interação entre uma topografia pré-existente , variações nas taxas de subida do nível do mar, pela ação de ondas e maré, e pelo ajuste morfodinâmico mutuo. A prolongada erosão subaérea das rochas sedimentares das bacias do Recôncavo e Camamu, originou esta topografia complexa similar pelo que ocorre atualmente na BTS.

A erosão foi fortemente influenciada pelo arcabouço estrutural desta bacias, gerando um forte controle na orientação das incisões do embasamento. Em seguida, durante as a transgressão após o máximo glacial essas incisões controlaram a distribuição de depocentros e a circulação da maré , durante a inundação da BTS. A geometria do embasamento agiu como um alto topográfico defletindo as correntes de maré vazante em direção à leste da desembocadura, e direcionando a sedimentação para a região onde o BSA está localizado. O Banco de Santo Antônio é portanto, um delta de maré vazante, defletido, e construído através da influência dos fatores citados. Durante os 7-8.000 anos A.P. a agradação e progradação com sentido leste e sul ocorreu predominantemente

O volume de areia estocados no Banco de Santo Antônio (1 bilhão de metros cúbicos), é compatível com uma taxa anual de transporte litorâneo atuando nos últimos 7- ka. O sedimentos transportados pela deriva litorânea foram trapeados na entrada da baía pelas correntes de maré vazante e enchente, ajudando na construção do BSA.

O Banco de Santo Antônio é possivelmente o mais importante deposito de areias disponíveis para Salvador e área metropolitana, para serem usadas em futuras obras de recuperação de praias e projetos de engenharia civil. Algumas das praias urbanas de cidade já desapareceram a e outras continuam ameaçadas pelas projeções de subida do nível do mar. Neste sentido, o BSA contribui para aumentar a resiliência da cidade de Salvador e sua adaptação às mudanças climáticas.