Morphometry of Neogene mass transport deposits of the continental slopes of Cabo Frio High, frontier region of Santos and Campos basins

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Abstract

This study examines the pattern and dimensions of Mass Transport Deposits (MTDs). Multichannel seismic samples data was used for describing the morphology of MTDs as well as the morphometric architecture and genesis of deposits. The study area is dominated by the strong halokinesis and flow of the Brazil Current and in between the Campos and Santos Basins (SW Atlantic upper slope). Results show that this area presents mass transport deposits over single and multiple events (i.e., Mass Transport Complex) deposited since the Neogene and extended throughout an area of nearly 68 km^2. The majority of the MTDs are characterized by chaotic and/or transparent internal seismic facies, which it is interpreted as signs of slumps and debris flow deposits. Also, the combination of morphometric parameters and local geological controls allowed us to recognize the possible triggers. Although it cannot determine the exact triggering mechanisms, these deposits are related to local gravitational instabilities such as seismicity and diapir reactivation.

Introduction

Mass transport deposits (MTDs) are gravity-induced units that can happen over a single event or multiple events, classified as characterized by mass transport complex deposits (MTCs) deposits (Moscardelli et al. 2006; Moscardelli and Wood 2008). They represent an important component of ancient and modern deep-water settings (Mulder 2011). Studies regarding MTDs are important for a better understanding of actual processes and geohazards and economic prospects in sedimentary basins (Locat and Lee 2000; Clare et al. 2018).

MTDs originated at the upper-mid continental slope as well as the flanks steep in deep-water (Posamentier 2004). Several mechanisms can generate MTDs having similar geomorphological characteristics (Moscardelli and Wood 2008). Gravitational instabilities in the upper slope can be triggered by tectonic activity, high sedimentation rates, sea-level fluctuations, and gas hydrate dissolution (Hampton et al. 1996; Posamentier 2004; Posamentier et al. 2011; Mulder 2011). Also, triggering mechanisms can be highly dependent on local gravitational instabilities that can occur over salt diapir flanks, channel-levee complexes, and mid-oceanic ridges (Moscardelli and Wood 2008; Mulder 2011).

In sedimentary basins, the potential triggering mechanisms for mass transport deposits are usually associated with the morphometric parameters associated with their architecture (Moscardelli and Wood 2015). The registered deposits consist of distinct geometric features. The magnitude and distribution of these units evidence an important role, that the mass transport deposits played in the stratigraphic configuration of the brazilian continental margin.

This paper presents a study about the mass transport deposits developed during the neogenic period on the continental slope at the Cabo Frio High, focusing on the description of geomorphological features and morphometric analysis, as well as on the analysis of the features of the associated deposits, to better understand the possible triggers of mass transport on the borders of the Campos and Santos basins.

Study Area

Cabo Frio province is the border between the two most important sedimentary petroleum-producing basins on the southeastern coast of Brazil, the Campos and Santos basins (Fig. 1) (Mohriak et al. 1995). Together, two basins represent nearly 89% of the oil and natural gas production in Brazil (Souza and Sgarbi 2019). Both sedimentary basins formed due to the breakup of the Gondwana supercontinent into the African and South American tectonic plates (Asmus and Ponte 1975; Castro and Picolini 2015). They reflect the tectonic evolution which is divided into three supersequences: rift, post-rift, and drift, corresponding to three different phases of sedimentation (Ojeda 1982; Moreira et al. 2007). Moreover, their geographic distributions of stratigraphic sequences, structural evolution, magnetism, and salt tectonics are distinct in age and style (Mohriak et al. 1995).

The Cabo Frio High is a structural evidenced through gravimetric data (Mohriak et al. 1987), that represents a crustal thinning resulted from the uplift of the mantle, composed of denser material, under the less dense sediments (Mohriak and Barros 1990). It is inserted in the continental margin region where there is an abrupt change in the coastline from E-W (Santos Basin) to NE-SW (Campos Basin), which is also observed in the bathymetry and the slope ranging from 1.5 to 7.5 degrees (Figueiredo Jr et al. 2004; Schreiner et al. 2007, 2008; Borges et al. 2014).

The study area comprises the continental slope (~ 500m) and extends below 2500 m deep into the São Paulo Plateau. The seafloor features are associated with depositional and erosion processes, faults, ocean circulation, and salt tectonics. The continental slope has numerous geomorphological features, including submarine canyons, contour channels, salt diapirs, pockmarks, and submarine mass transport (Mohriak 1995; Duarte and Viana 2007; Ashabranner et al. 2012; Almeida and Kowsmann 2014; Mahiques et al. 2017). The passage from the middle slope to the lower slope in the northern region, approximately 1500 m isobaths, is recorded by the presence of a parallel channel fitted to the Cabo Frio fault zone and marking the internal limit of the region where the salt movement reaches the current seafloor (Duarte and Viana 2007). The contouritic channel or Santos Channel is nearly 100 m deep and 2 km wide, extending over 200 km (Duarte and Viana 2007).

Below 1500 m depth the slope decrease and exhibits a rough topography due to halokinetic processes, with mini basins and elevations, and with an outcrop of diapirs towards the São Paulo Plateau province (Mohriak et al. 1995, 2017).

Data And Methods

The 2D post-stack seismic data used in this study includes 51 seismic profiles that add up to 2370 km of lines with a spacing of 4 km, ceded by the Brazilian National Agency of Petroleum Natural Gas and

Biofuels (ANP) (Fig. 1). The seismic lines cover the Cabo Frio High, part of the Campos and Santos basins continental shelf and slope, and extend downslope to water depths of up to nearly 2700 m into the São Paulo Plateau.

The seismic attribute cosine phase was applied to the seismic data using OpendTect® software aiming to enhance reflectors' terminations and continuity (Chopra and Marfurt 2007). This allowed for mapping stratigraphic horizons and determining their thickness using a constant velocity of 1600 $m.s^{-1}$. Additionally, the seismic stratigraphic was used to recognize the seismic facies and geometry of the deposits.

The results of seismic interpretation were incorporated into ArcGis® software, and provided the basis for the morphometric analysis of the mass transport deposits. This study only includes measurements that could be confidently extracted such as area, length, thickness, length, and volume. These are used to describe the geometry and dimension of the MTDs (Moscardelli and Wood 2015; Clare et al. 2018). Calculations were based on studies by Clare et al. 2018.

The thickness of the deposit is calculated by the vertical difference in time between the baseline and the top line of each MTDs. The thickness was later converted to meters using a constant velocity of 1600 $m.s^{-1}$. For the total length of the deposit, an apparent length value was measured, that is, a length value in a straight line from the beginning to the end of the deposit (Clare et al. 2018). The latter was done, by measuring the 2D seismic.

For the area only the cross-sectional area of the seismic section is considered, as the seismic data is 2D. Thus, the deposit areas are the result of maximum thickness by deposit length (area = maximum thickness x maximum length). Lastly the volume was calculated based on measurements of the mass deposit itself, i.e., a function of the maximum thickness and area (volume = area x 2/3 maximum deposit thickness) (Alves and Cartwright 2009). This approach is often used when the scar is not preserved (Clare et al. 2018).

Results

In the Cabo Frio High region, two buried Mass Transport Deposits (MTD 1 and MTD 2) and one mass transport complex (MTC) with distinct seismofacies and structural architecture were mapped (Figs.1 and 2). They are indicative of major changes in the descent of the continental slope and interruption of the original stratigraphy. All the deposits are within the Upper-Quaternary Miocene sedimentary record (Duarte and Viana 2007).

Seismic Architecture

The deposits were characterized by internal transparent to chaotic seismic facies (Fig.3a') with visible low to high-frequency amplitude variations in all directions and non-homogenous patterns. The lower boundary of the deposits was marked by strong amplitude reflectors (Fig.3c'). This was here described as the erosive unconformities H1 and H2 (Fig.2). H1 is the lower boundary for MTD 1 and MTD 2, while H2 is the lower boundary for the MTC. Also, internal preserved slide blocks are seen locally as parallel reflectors within the chaotic facies (Fig.3b').

MTDs Distribution and Morphometric Parameters

These MTDs are buried beneath 30 m to 50 m of hemiplegic drape. They are found between 1000m depth, with the presence of landslide scars on the continental slope, and 2600 m, where they developed towards the São Paulo Plateau (Fig.1).

The buried deposits range from 50 m to 370 m depth from the seafloor surface (Tab.1). The average thickness for each deposit is 600 m, 540 m, and 870 m. While the length is 99 km, 36 km, and 57 km, for MTD 1, MTD 2 and MTC, respectively. Other morphometric parameters of the deposits are presented in Table 1.

Tab. 1 Table of morphometric parameters and internal pattern of mass transport deposits.

MTD	Depth below seafloor (m)	Maximum Thickness (m)	Maximum Length (km)	Area (km^2)	Volume (km^3)	Seismic Facies
MTD 1	370	600	99	59	24	Chaotic – Transparent
MTD 2	50	540	36	19	7	Transparent
MTC	280	870	57	50	29	Chaotic – Transparent

MTD 1

Mass Transport Deposit 1 (MTD1) corresponds to an individual deposit with internal transparent to chaotic seismic facies, superimposed on erosive unconformity H1 (Fig.2). The deposit has a maximum thickness of approximately 600 m, an area of 59 km^2, a maximum length of 99 km, and estimate volume of 24 km^3 (Tab.1 and Fig.3). In the seismic profile, near 2250 ms (Figs.2 and 3a), it is possible to find the deposit partially filling in the U-shaped contourite channel (Santos Channel). Below the slope, higher depositional features (montforms) are characterized by onlap and downlap terminations separating the

MTDs. While, towards the deeper region, the diapirs become evident and it is possible to notice (Figs.2b and 3ab), that the rise of diapirs uplifted and failed the deposit.

MTD 2

MTD 2 is characterized by internal transparent facies and presents a maximum length of 57 km, an area of 19 km^2, a maximum thickness of 540 m, and estimate volume of 7 km^3 (see Tab.1) concentrated in the most distal region of the MTD scars (Fig.3). Underneath MTD 2 there is an intense presence of salt diapirs and faults that can be associated with halokinesis in this region (São Paulo Plateau) (Fig.3bc). On the seafloor, scarps are also seen near MTD 2 deposits and can be also linked to halokinesis in the subsurface. Such pieces of evidence suggest that the diapiric mass lifted the overlying strata, promoting instability, faulting and forming minibasins in which the MTDs were later deposited Fig.3b.

MTC

The Mass Transport Complex consists of a vertical succession of multiple slide events stacked on top of the MTD 1 (see Figs.2 and 3c). The stacked MTDs are recognized by their transparent to a chaotic seismic character with variable dimensions that average 870 m thick, 50 km^2, and 29 km^3 (see Tab.1). The seismic sections showed the presence of erosive surfaces indicating landslide scars that coincides with the highest part (top) of the diapirs (Fig.3c). There is an intense presence of salt diapirs in all areas, which caused normal faults in the sedimentary layers above.

Regional Characterization

The study site presents longitudinal and lateral changes in the depositional patterns of the gravitational deposits and in the related structural controls (Fig.4). The shallowest landslide scars mapped are seen in the upper slope zone (~ 1500 ms TWTT) (Fig.3c). The mapped faults coincide with this region and directly affect the MTD 1 and MTC (Fig.4). Here the deposits are thinner and with a predominance of chaotic internal facies. The transitional zone of the slope does not present faults, being dominated by salt diapirs. Also, there is a change in the internal pattern of the deposits, despite being thicker, they show a predominance of chaotic to transparent facies and the presence of cohesive blocks.

In general, the seismic lines show cased the presence of diapiric structures throughout the study area. However, there is a higher occurrence in the distal zone of the slip scar (~ 2250 m). Moreover, MTD 2 is delimited by scarps associated with diapirs (see Figs.2 and 3).

Within the southeast of the study area, a contourite channel has been excavated along the 1500 m isobath, exhibiting a depression in the bottom morphology and extensive contourite drift at the base of the channel depression, which forms a barrier to mass transport deposit.

Discussion

Seismic Architecture and Deposit Characteristics

The two MTDs and staked deposits (MTC) cover a total sediment volume of ~ 60 km^3 and an area of ~ 145 km^2. Near the scar region they are mainly seen as chaotic with, low-to-high reflectors and internal blocks, that have been associated with slumps. On the other hand, towards the São Paulo Plato, distant from the scar region, the deposit is characterized by low-amplitude to transparent reflectors that can be associated with debris-flow (Hampton et al. 1996; Posamentier 2004, 2011; Mulder 2011). The internal distribution of the deposits suggests a transition from slumps to debris flows that is particular in these types of deposits, and can occur in the same event or depositional unit (Dott 1963; Stow et al. 1996; Bull et al. 2009).

Regarding the MTD mapped above the H1 horizon, this condition in combination with the colliding and shearing boundaries of the MTD 1 e MTD 2 suggests that each component failure occurred simultaneously. All the deposits mapped are above sequence 7 described by Duarte and Viana (2007), indicating that the MTDs originated during the last 4 ma during the Pliocene epoch in the Neogene period.

The measured morphometric parameters associated with the architecture of the deposits (area, volume, maximum thickness, length) in the studied area show similar dimensions to the mass transport deposits previously described in the Cabo Frio High region. Ashabranner et al. (2012) identified MTDs ranging from 100 m to 500 m thick, covering ~ 20 km, and buried within 50–65 m of hemipelagic sediment.

When compared to other deposits mapped on the Brazilian continental margin, the dimensions showed in our study are smaller. For example, the multiple stacked deposits mapped in the Amazon Fan, Pará-Maranhão, and Pelotas basins constitute large megaslide complexes, that can reach thousands of square kilometers in area (> 315000 km^2) and hundreds of meters in thickness with ~ 34000 km^3 for individual deposits (Silva et al. 2016; dos Reis et al. 2016).

Based on the results, the deposits mapped in the Cabo Frio High can be classified as detached, whose dimensions are smaller because in some regions they detached from their scar (Moscardelli and Wood 2008), occupy dozens of square kilometers of area (< 59 km^2) and only kilometers in length (36–99 km) (Moscardelli and Wood 2015).

The morphometric parameters associated with the architecture of MTDs allow us to link geological context, deposit geometry, and potential causal mechanisms, as well as to define where the sourcing areas of deposits are located, giving us important insight process and dynamics of different environments (Moscardelli and Wood 2008, 2015; McAdoo et al. 2000).

Possible triggers of the Mass Transport Deposit

Detached mass transport deposits are controlled by localized gravitational instabilities

(Moscardelli and Wood 2015), these systems are usually related with slope sedimentation, collapsing salt ridges, thrust core structures, upper slope instabilities, and unstable margins of deep-water mini basins (Moscardelli and Wood 2008).

From the geological controls interpreted in the morphology of the seabed in this area, the possible triggering mechanisms are associated with seismicity, reactivation of diapirs, and oversteeping slope.

The MTD 1 and MTC are positioned in the upper-slope, commonly characterized by slump scars. These depositional systems are usually sourced from those areas, which can indicate triggering by regional events (e.g., earthquakes) (Prior and Coleman 1984; Posamentier 2004). Seismic events have been mapped near Cabo Frio High by the Brazilian Seismographic Network in the last two decades (RSBR, 2022).

From the location of MTD 2 that overlays the most extensive salt deposits in the basin, it is reasonable to point salt reactivation as trigger as already evidenced in the Neogene (Mohriak et al. 1995; Cobbold et al. 2001). The deposit had its genesis from the flanks of salt masses, which were failed by the salt movement (Posamentier et al. 2004; Moscardelli and Wood 2008).

Conclusion

The Cabo Frio High shows a series of processes, most of them associated with slope failure, resulting in two single deposits (MTDs) and several stacked deposits (MTC). The data set contains information regarding the area, volume, length, and thickness of MTDs, which consolidate the idea that local geological controls play an important role in defining the architecture of MTDs.

The sliding surface of the MTDs coincides with the horizon of a 4 ma. From the Neogene to the present, mass transport deposits in the Cabo Frio High have been controlled by the interaction between the halokinesis, gravity tectonics, and slope physiography.

Declarations

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Conflicts of interest/Competing interests

Not applicable

Availability of data and material

The data are public and were provided by ANP (Brazilian National Agency of Petroleum Natural Gas and Biofuels).

Code availability

Not applicable

Authors' contributions

Antonio Henrique da Fontoura Klein led the research presented here and contributed to manuscript ideas and review.

Arthur Antonio Machado led the research presented here and contributed to manuscript ideas and review.

Bruna Pandolpho contributed to data interpretation, discussion of results, and manuscript review.

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Figures

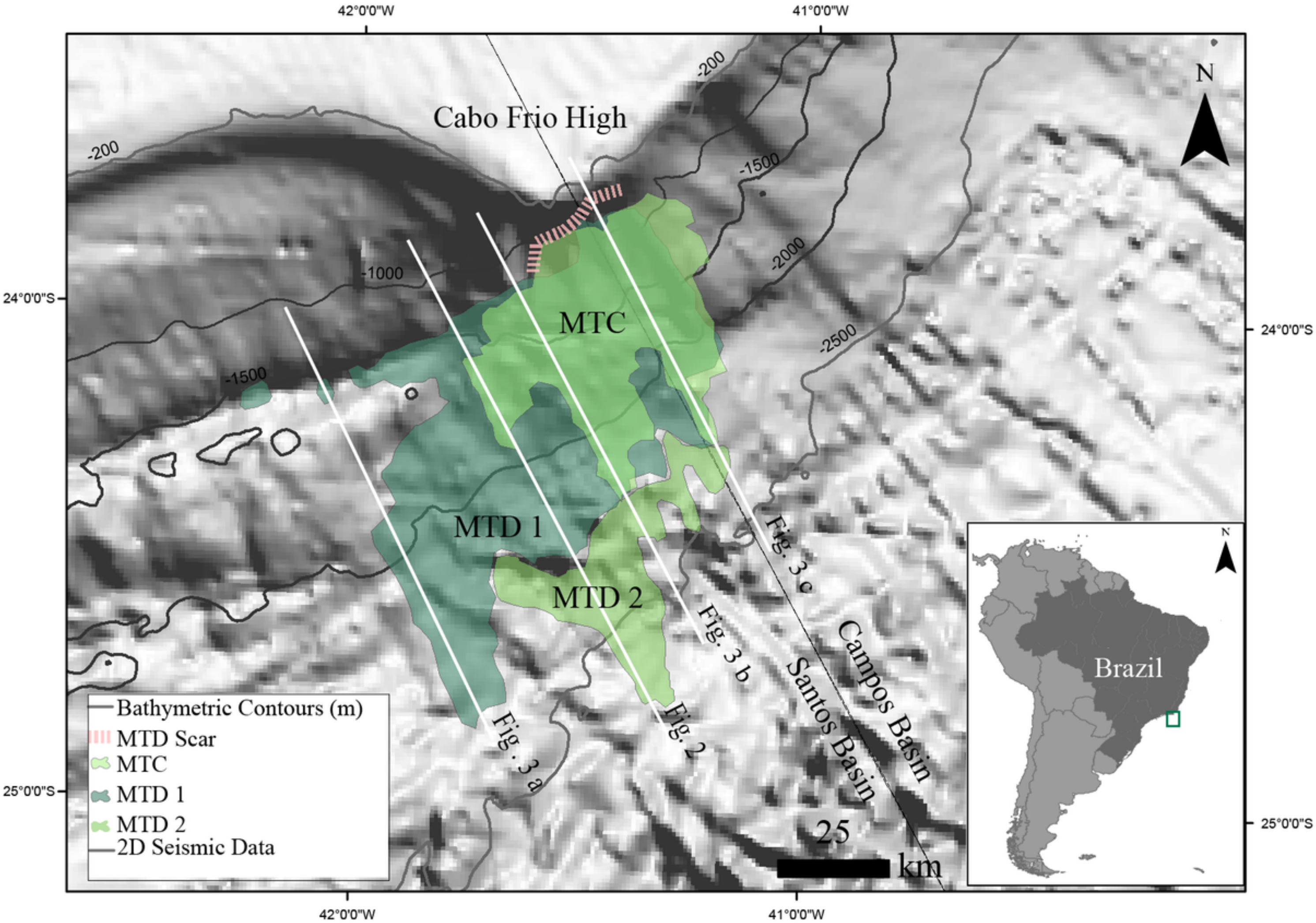

Figure 1

Regional map of Cabo Frio High with the limits of the MTDs, superimposed on the shaded relief map of the bathymetry (background map from the Leplac project, provided by Alberto Torres and Artur Aryes), showing the location of interpreted seismic lines. The study area is located approximately 200 km from the coast. The three MTDs studied here are positioned between the upper continental slope and the São Paulo Plateau.

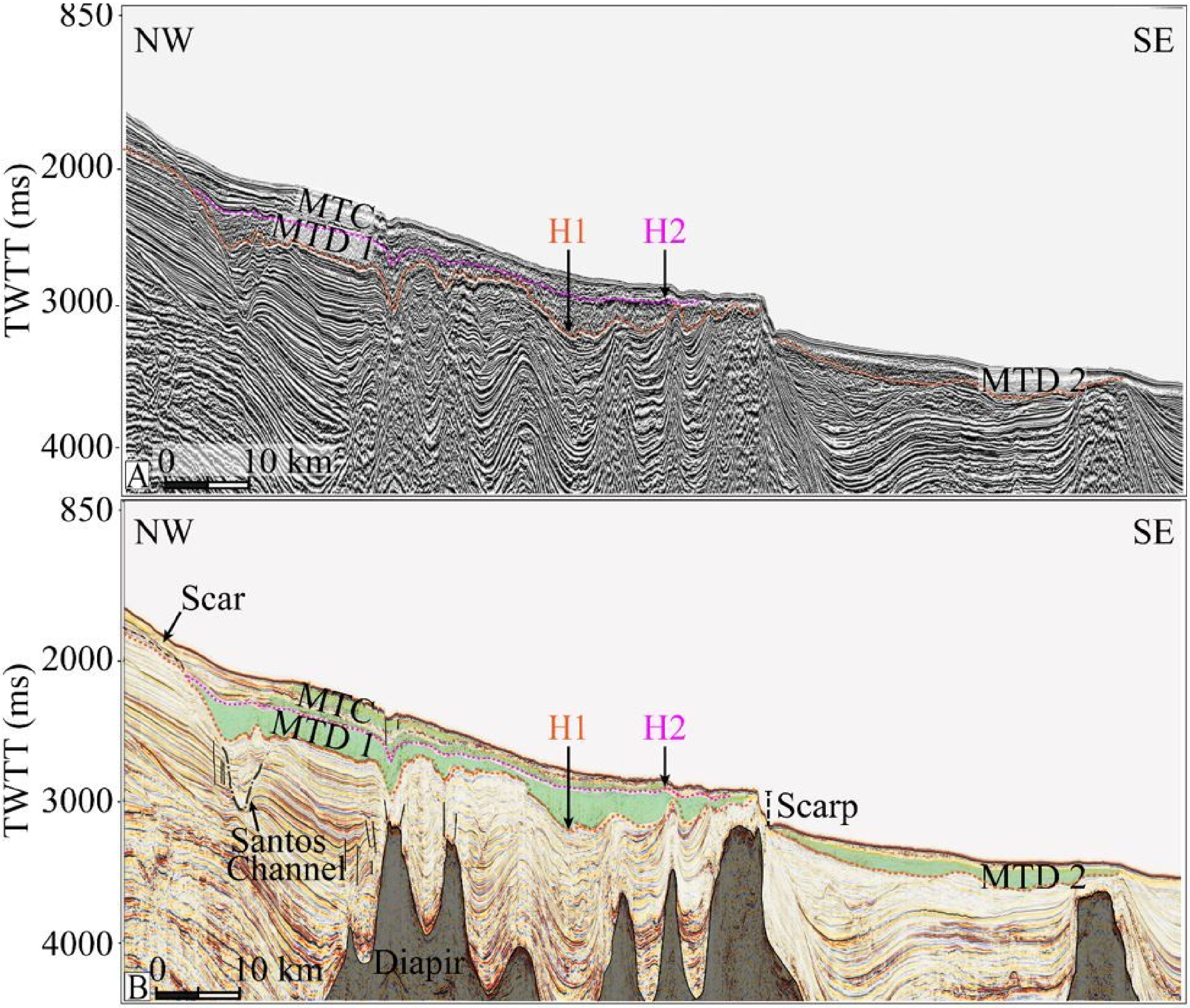

Figure 2

Seismic section (location in fig. 1) with Cosine of Phase attribute (A). The attribute highlights the terminations of the reflectors around the chaotic deposit, improving the interpretation of the horizons, as well as the lower and upper limits, (H1 and H2) (B).

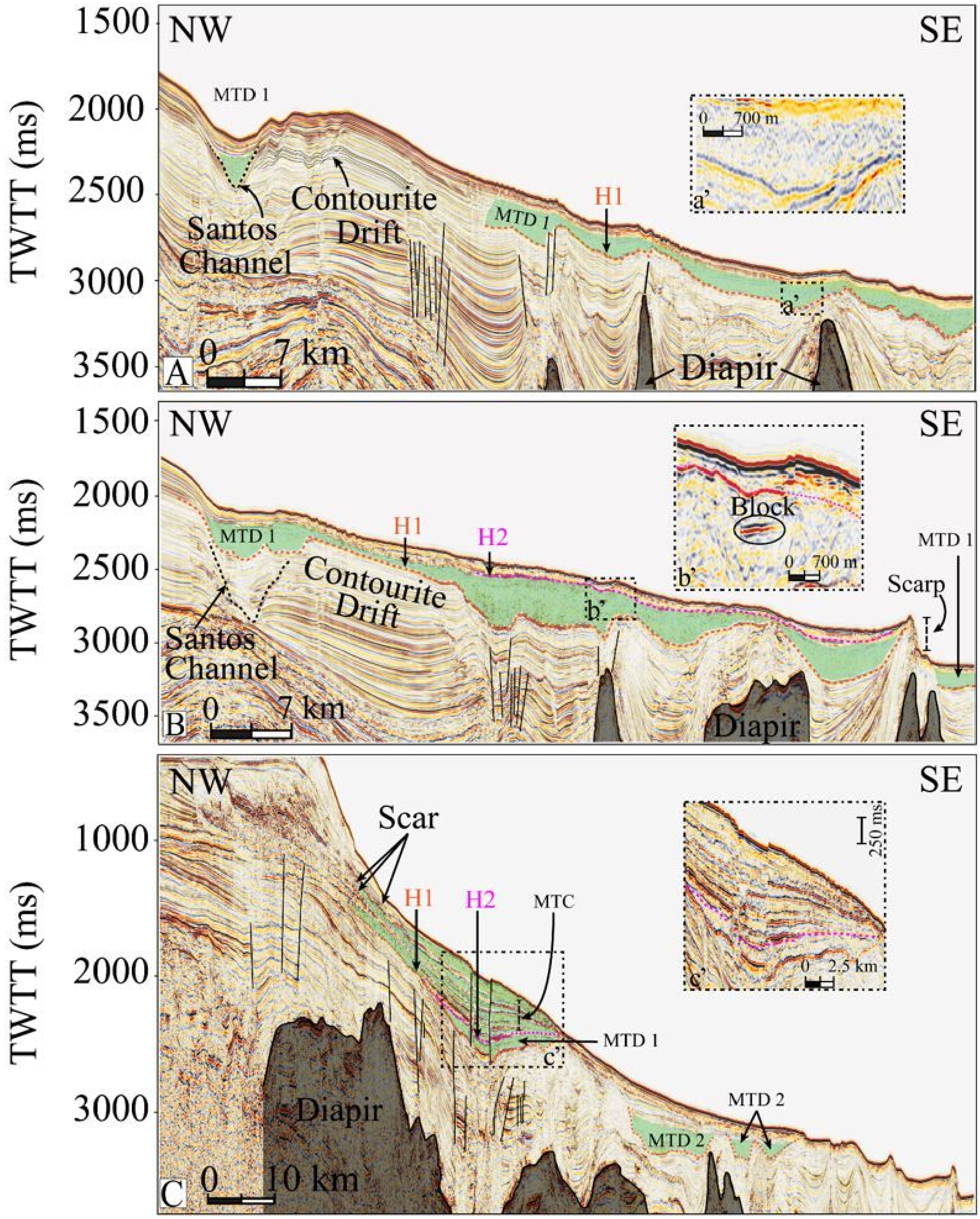

Figure 3

Three seismic sections are located in different sectors in the study region (location figure 2-2). Note the identification of a single deposit – section A which is separated by the contourite drift in the southwest region of the study area, as we proceed to the northeast region on the slope sections B and C, there are more deposits.

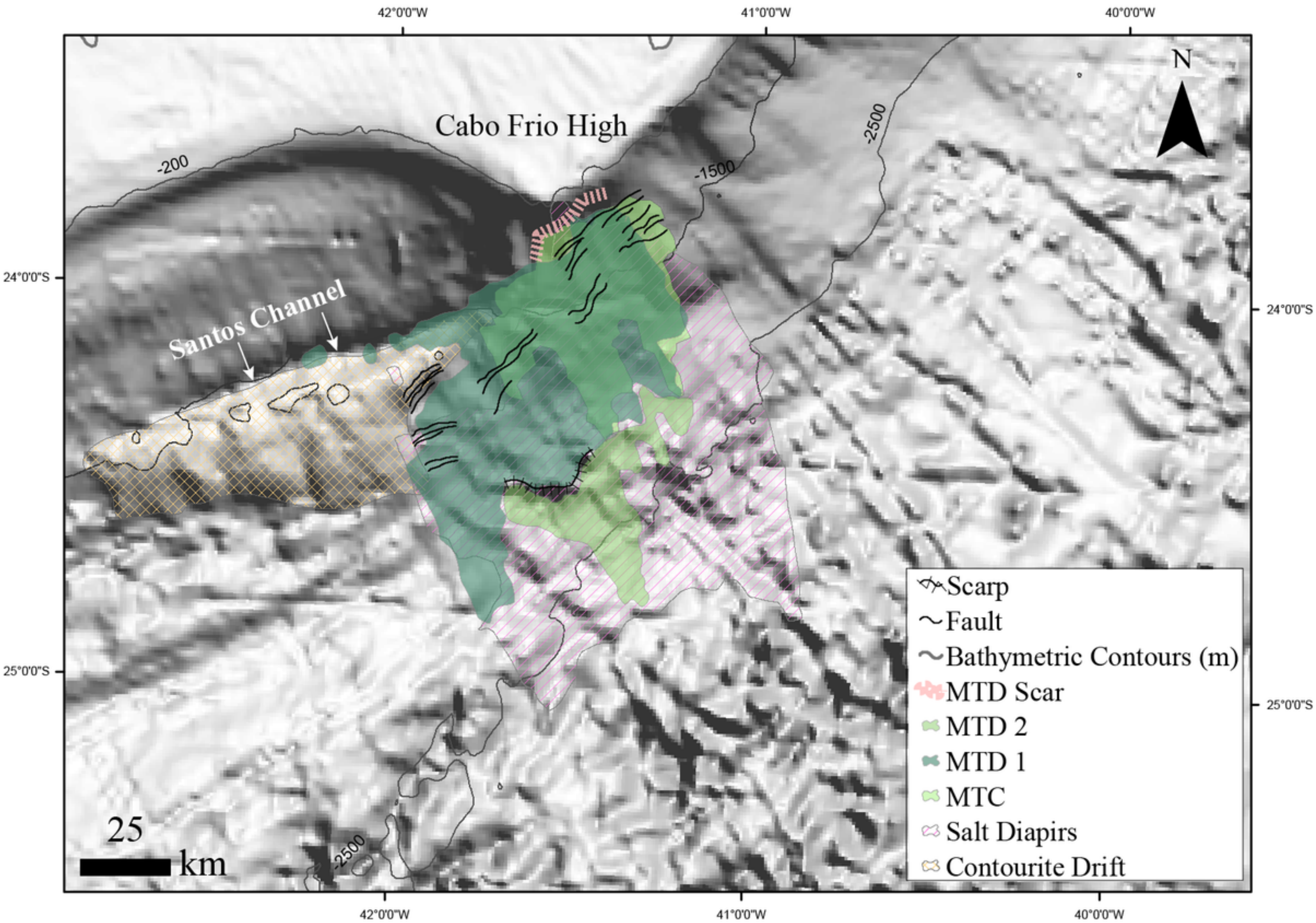

Figure 4

Regional characterization of the border area of the Santos Basin with the Campos Basin. The MTDs are arranged in the green shaded area that extends from the continental slope to the São Paulo Plateau. Emphasizing that the interpretation of salt diapirs and faults were considered only those associated with deposits, being by interruption or modification of the external architecture.