Brazilian Journal of Geophysics (2022) 40, 1, 97–106
Brazilian Geophysical Society
ISSN 2764-8044
DOI: 10.22564/brjg.v40i1.2136

THE VOLCANIC OUTER HIGH OF THE CAMPOS RIFTED MARGIN IN SOUTHEAST BRAZIL: THE STRUCTURE AND FORMATION OF THE SEMA

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ABSTRACT. The SEMA (South East Magnetic Anomaly) is a high amplitude magnetic lineament in the most distal part of the Campos Rifted Margin in Southeast Brazil. It runs continuously from south to north along 85 km reaching 500 nT in deep waters. The aim of this paper is to investigate the structure, stratigraphy and nature of the SEMA, and to discuss its significance for the evolution of the margin. Based on seismic, magnetic and gravity analysis, we interpret the SEMA as a volcanic outer high. Its formation was prior to the salt migration oceanwards, probably earlier to the breakup, constraining a time-relative formation in the Late Aptian - Early Albian. It is bounded by a basinward dipping, large-scale fault that created a huge depocenter continentwards. The Volcanic Outer High of the SEMA marks the transition to a distinct tectonostratigraphic compartment and salt domain, characterized by intense halokinesis, significant thinning and modification of the pre-salt sequences, and increasing presence of volcanic and intrusive rocks. It forms a long volcanic ridge in the external boundary of the Campos Rifted Margin, which may have influenced the paleo-circulation. Moreover, its understanding could provide new insights into the breakup process.

Keywords: Southeast Magnetic Anomaly; magmatism; pre-salt; Brazilian margin; breakup; Campos Basin.

INTRODUCTION

The Campos Rifted Margin, located in the Southeast Brazilian margin (Figure 1), is widely viewed as a magma-poor margin, with little magmatic addition during the rifting. Based on this assumption, several models have been proposed to describe its tectono-stratigraphic evolution before and after the breakup, although none of these models can account for the complexities observed. The reason is that magmatic processes have a profound influence on the structural, depositional, thermal and subsidence history of a basin. In order to understand the crustal architecture and stratigraphic evolution, it is fundamental to identify and characterize the magmatic rock distribution and timing.

The tectono-stratigraphy of the basin registers a magmatic sequence in the Barremian (Cabiúnas Formation - Winter et al., 2007), with local younger volcanism after the breakup (Mizusaki et al., 1992), specially in the Cabo Frio High (Oreiro et al., 2008). However, this description is based on wells limited to the proximal and necking domains, with little or no information in the most distal part of the basin. In these domains, the Campos Rifted Margin was affected by the Early Rift magmatism in varying amounts from south to north (Stanton et al., 2019) with important consequences for the development of the extensional process, rifting style and depositional evolution. According to Mohriak et al. (2021), volcanic events in the Cabo Frio region in southern Campos are a major factor in basin development with igneous rocks intruding into pre-salt source rocks and reservoirs. Nevertheless, the distal domain remains poorly studied and understood. Recently, Norton et al. (2016) and Karner et al. (2021) proposed the presence of SDRs in the distal margin, suggesting a magmatic breakup in Campos Basin. Faw et al. (2017) interpreted it as a deep half-graben filled with sediments and possible volcanics and a drastic change in the tectonostratigraphy seawards. This large half-graben lies adjacent to the South East Magnetic

Anomaly, an important magnetic anomaly high located in the most distal part of the basin near the COB (Continent-Ocean Boundary - Stanton et al., 2019). The SEMA indicates an important lateral change in the margin structure and composition. The extent and the nature of the crust of the SEMA and how it affected the pre-salt sequences in the Campos margin are key questions that guided this study.

Our aim is to characterize the morphology, structure and crust of the SEMA, discussing its nature and influence on the pre-salt sequence. We show that it corresponds to a basement high that extends from south to north along more than 80 km. The basement of the SEMA is characterized by extrusive and intrusive igneous rocks in varying amounts and its formation strongly affected the pre-salt and post-salt deposition in the most distal part of the margin. These results may have important implications for the understanding of marginal outer highs, breakup related processes and for future hydrocarbon prospects in the Campos Rifted Margin.

METHODS

The present work was based on gravity and magnetic potential field analysis, and seismic interpretation with focus on the Distal Domain of the Campos Rifted Margin. The reflection seismic analysis was carried out along 3D sections selected (available for universities in the BDEP-ANP Exploration and Production Data Bank) in two-way time (TWT). The 2D regional seismic lines (Figure 4) correspond to the WESTERNGECO R0258_2D_SPEC survey acquired with a 4 km cable and processed by the Kirchhof Prestack Time Migration (PSTM) algorithm. The 3D detailed seismic examples (Figure 5) correspond to the PGS 3D streamer R0014-Campos Basin -PH2 survey acquired with a 4 km cable and processed in depth (Pre-Stack Depth Migration - PSDM) with a wide beam and Kirchhoff migration algorithms. Both seismic volumes are of public domain (ANP courtesy). The depth seismic display of Figure 5 was constructed blending an RMS, the wide beam, and the PSDM Kirchhoff volumes. The main stratigraphic horizons mapped were bathymetry, top salt, base salt, top basement, faults and intracrustal reflections. The interpretation of seismic data was carried out using the *DUG Insight* software.

The maps were made with the *Oasis Montaj* software using BDEP dataset from magnetometry and gravimetry. The Bouguer Anomaly Map (Figure 1) from gravity data was provided by BDEP. An upward continuation of 10 km was calculated and then subtracted from the original Bouguer Anomaly grid resulting in the Residual Bouguer Anomaly Map of Figure 1B. The magnetic grid is from Stanton et al. (2019) and comprises eight different aerosurveys. According to Stanton et al. (2019), the individual survey acquisition parameters are: App040 (1969, 300 m flight height, variable line spacing and direction); CPRMRJ (1978, 150 m flight height, N-S direction, 1000 m line spacing); App270 (1999, 500 m flight height, 3000 m line spacing, N30°W direction); Mag1 (2002) and Mag2; EMAG01-BS-500 and EMAG01-BS-400 (1999, 150 m flight height, 1000 m line spacing, N30°W direction); EMAG01-BM-S-4 (1999, 300 m flight height, other parameters equal to the ones of the previous survey). All grids were knitted together using the suture method, trending to each other.

Afterwards, the Reduction to the Pole (RTP) was performed in order to transform the total field magnetic anomaly measured into the vertical component of the field caused by a source distribution magnetized in the vertical direction (Blakely, 1996). The RTP was calculated using inclination and declination values of paleomagnetic data (Raposo et al.,1998) from the Florianópolis dykes (Figure 3A). Those values were chosen since the age range of the dykes overlaps with the SEMA formation (~125 Ma), being an important parameter to constrain the RTP transformation. We proposed that the SEMA magmatism occurred between the end of the rift phase until the end of the sag.

We calculated the tilt derivative of RTP (Figure 3C), which is a phase transformation that can be used to detect edges of source bodies, enhancing the signal of both shallow and deep sources alike. To separate shallow and deep sources, an upward continuation map of the RTP at 10 km and a residual field of 5 km were calculated (Figures 3B and D, respectively).

RESULTS AND DISCUSSION

The distal Campos Rifted Margin magnetic and seismic signatures

The Campos Rifted Margin Magnetic Anomalies display a pattern of very high frequency and linearity in the Proximal Domain known as the Campos Magnetic High - CMH (Stanton et al., 2010). The anomalies increase in wavelength eastwards, with a general NE-SW orientation (Figure 2). A slight inflection of that trend to N-S northwards and NW-SE in some places can be observed, as well as circular, smooth and less defined anomalies throughout the basin (Figure 2). In this work we will focus on the magnetic pattern of the Distal Margin of Campos (for definition of marginal domains, see Stanton et al., 2019).

In the central and northern parts of the basin, a high amplitude negative magnetic anomaly (with values reaching 280 nT) trending NE-SW to NW-SE was interpreted by Alvarez et al. (2021) as the Campos Inflected Anomaly (CIA), associated to a regional transfer zone. Oceanwards, a high amplitude positive magnetic lineament with values reaching more than 480 nT (Figure 3) is observed near the Continent-Ocean Boundary, named SEMA by Stanton et al. (2019).

The SEMA constitutes a conspicuous feature that outstands in the distal margin, characterized by strong and positive magnetic anomalies over a region of shallower basement. It lies adjacent to a low tectonic compartment of very thin, deep and intensely tectonized crust (Figure 4). In the next sections we describe the SEMA in detail and discuss its nature.

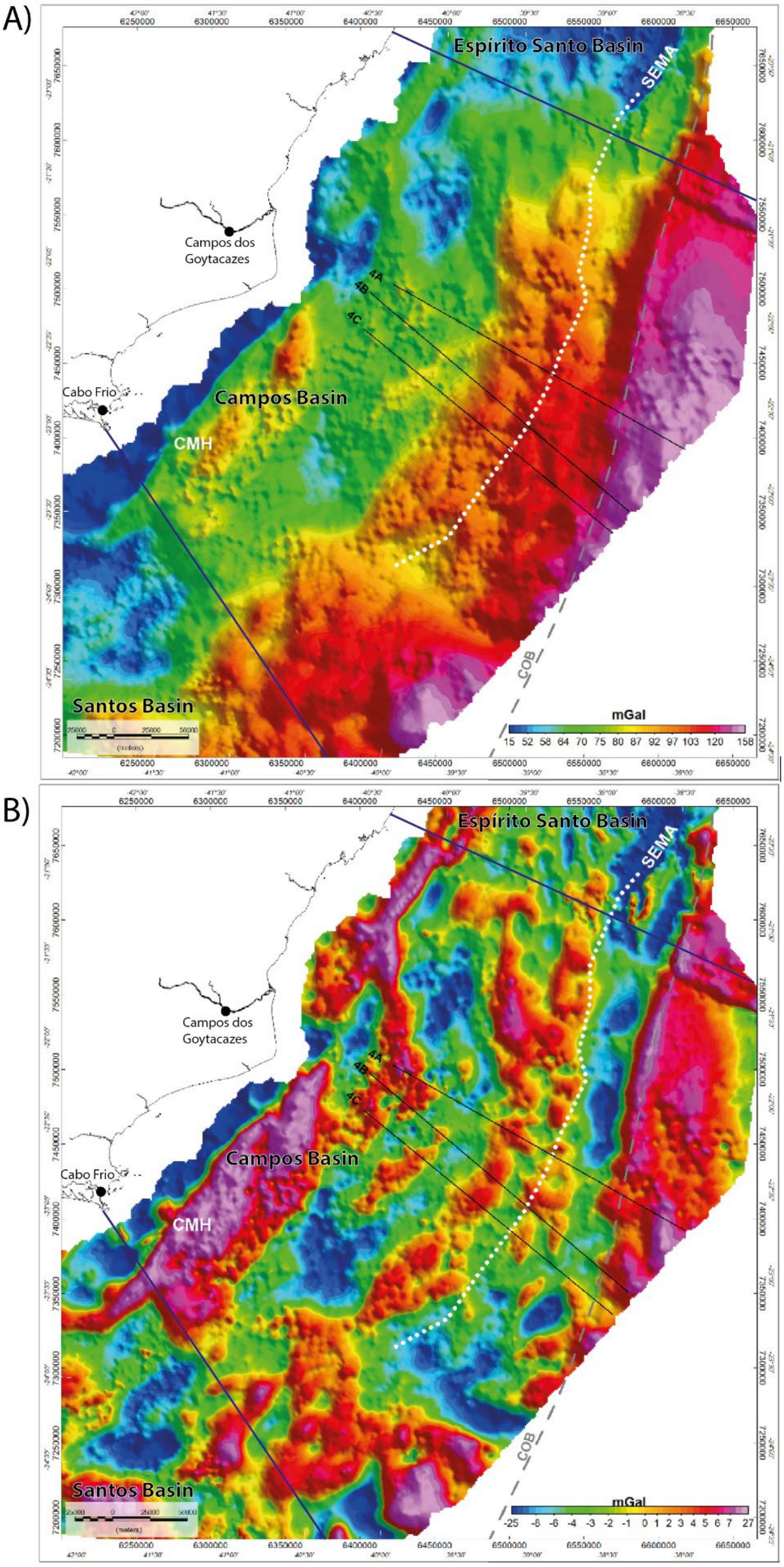

Figure 1: (A) Bouguer Anomaly Map; (B) Residual Bouguer Anomaly Map (10 km) showing the SEMA (white dotted line) and the location of seismic profiles of Figure 4 (black lines). The SEMA is located in Campos and southern Espírito Santo Basins in the Southeast Brazilian Margin. CMH: Campos Magnetic High; COB: Continent-Ocean Boundary. All dataset was provided by BDEP - ANP.

Potential Field analysis of the SEMA

The SEMA is a linear magnetic high located in the Distal Domain of the Campos Rifted Margin (Stanton et al., 2019 - Figure 2). It is one of the most prominent high amplitude magnetic anomalies of this basin. It reaches ca. 400-500 nT and occupies a broad area. From south to north, the SEMA forms a continuous lineament of high amplitude anomalies along ca. 85 km, exhibiting a general N30E trend which smoothly shifts to N-S at 22^{0}S (Figure 3).

The SEMA can be observed in all magnetic maps of Figure 3, representing anomalies of long- and short-wavelengths and of varying frequency spectra, indicating that its magnetic sources include deep and shallow geological bodies. In its southern part, the SEMA displays the highest intensities, ranging from 350-450 nT with a width (wavelength) of 30 km. The upward continued RTP map (Figure 3b) also shows the highest amplitudes to the south, suggesting that the SEMA deeper sources are located in this area.

The SEMA displays a wide magnetic high extending to the east in its central and northern areas, with variable width and amplitudes. To the south, the higher amplitudes are observed westward from the main trend while, to the north, the SEMA peak is located slightly to the east of the main trend (represented by a white dotted line in Figure 3). In its central part, the SEMA is characterized by lower magnetic amplitudes of ca 250-330 nT and larger wavelength when compared to the southern and northern areas. It displays two peaks across an area with a width of 45-60 km (see profile b-b' of Figure 4). At 22^{0}S the SEMA displays a second peak to the east of the main trend (represented by the white dotted line in Figure 3), with amplitudes reaching 500 nT. This magnetic peak to the east exhibits strong signature in the upward RTP and the tilt derivative RTP maps (Figures 3B and 3C, respectively), indicating the presence of deep and shallow sources generating the SEMA.

In its northern part, the trend of the SEMA shifts to N-S and back to N30E. It exhibits magnetic amplitudes between 200-250 nT and a width of ca. 30-35 km. To the east of the main trend of the SEMA it is possible to observe a curved-shape magnetic high (white arrow in Figure 3A), not clearly associated with it. It displays amplitudes higher than those observed to the west of the main trend and is characterized by long and short wavelength anomalies (Figures 3B and 3C, respectively).

The SEMA linearity is interrupted to the south at ca. 23^{0}S by an E-W negative zone (see the RTP and the upward continuation maps of Figures 3A and 3B). However, the tilt derivative map shows that the signature of the SEMA is continuous to the south of 23^{0}S, indicating that in this area the SEMA is characterized only by shallower sources. Such interruption of the SEMA coincides with the Araruama Transfer Zone (Magnavita et al., 2012) interpreted as a sinistral strike-slip fault zone.

The Bouguer Anomaly Map (Figure 1A) shows that the SEMA corresponds to a zone of positive gradient, indicating an increase in basement density. The Residual Bouguer Anomaly Map (Figure 1B) represents the short-wavelength features commonly related to basement topography and/or local density variations and shows that the SEMA is associated with a series of gravity highs, NE-SW orientated, that inflects northwards to N-S. Therefore, the gravity and magnetic maps reveal similar orientation pattern for the SEMA. Its trend accompanies the variation of direction of the basin rifting structures (Chang et al., 1992), suggesting a relationship between the SEMA and the rift propagation from south to north.

The seismic morphostructure of the SEMA

The SEMA is characterized by an abrupt rise of the acoustic basement in seismic data, displaying thinner rift and sag deposits and expressive halokinesis when compared to the adjacent low tectonic compartment of the distal margin to the west. It is regionally bounded by a continentward dipping fault with important heave that creates a very deep half-graben depocenter (~ 8 km thick) reaching 12 km depth. It is filled with a thick rift sequence, displaying strong reflectivity seismofacies indicative of sill and sediment intercalations. This volcanic seismofacies are located mainly in the half-graben in the west border, intruding the lower syn-rift section (Figure 5).

The top basement along the SEMA is also highly reflective attesting for volcanic rocks on the top of the SEMA structure at a 7.5 to 6.6 km depth (Figure 5). The basement displays internal seismofacies that are free of reflection and a remarkable subhorizontal and continuous high-amplitude crustal reflector separating a thin non-reflective upper crust (ca. 1.5 to 7 km thick) from a high-reflective lower crust at ca. 12 to 14 km (~7.0s at TWT; Figure 4), interpreted here as a detachment fault.

The SEMA structural high coincides with the highest amplitudes of the magnetic anomalies (Figure 4), as represented by the peak at the eastern end of the seismic profiles. The positive magnetic peak occurs right to the west of a region of intensely negative anomaly and a low tectonic compartment continentwards (Figures 2 and 4). The basement exhibits a rough and irregular topography formed by a series of half-graben shoulders and horsts with important differences in structural relief across and along the strike (Figure 4). The overall basement relief decreases from south to north, with top basement depths varying from ~5s (~8-9 km) in the southern region to ~6.3-6.5 s (~10-11 km) in the northern one (Figure 4).

To the north of 22^{0}S, the basement seismofacies do not show a clear and sharp contrast along the SEMA (Figure 4A), challenging its discrimination from the pre-salt carbonates, probably due to similar acoustic impedance. Since the magnetic amplitude of the SEMA remains high to the north (Figure 3), it is likely that the basement is also characterized by magmatism there. To the south of 22^{0}S, the basement along the SEMA displays, in addition to the subhorizontal high energy reflectors described above, sub-vertical intracrustal reflectors at ca. 12 km (Figure 5) and ca. 7 s (Figure 4B). The long and short wavelength magnetic anomalies indicate that the SEMA is associated

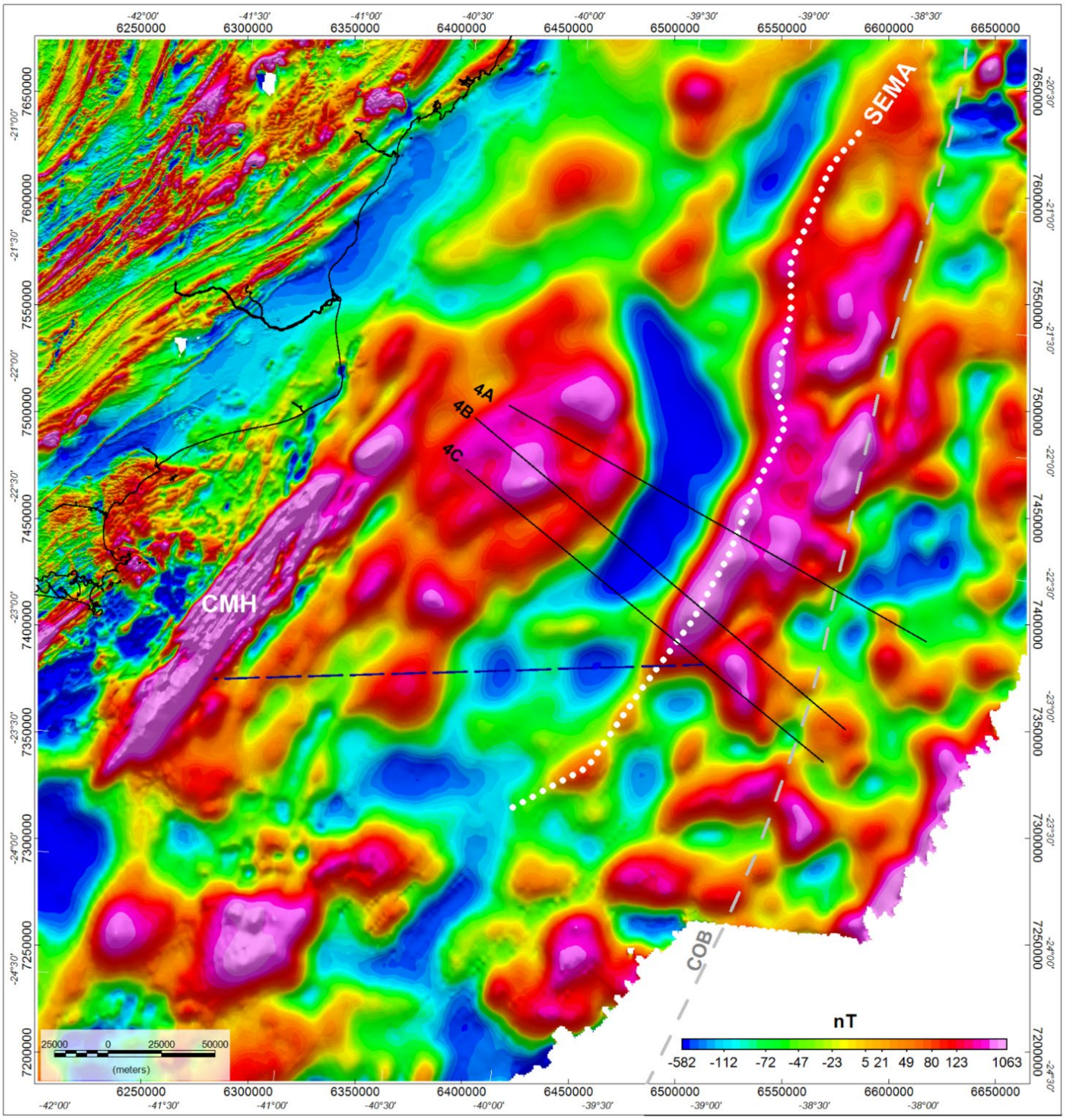

Figure 2: The magnetic anomaly Reduced to the Pole (RTP) of the Campos Rifted Margin. The black lines are the location of profiles in Figure 4; the blue dashed line is the Araruama Transfer Zone (after Magnavita et al., 2012); the grey line is the Continent-Ocean Boundary (Stanton et al., 2019); and the white dotted line is the SEMA.

with deep and shallow magnetic (and magmatic) sources. The presence of disrupted high-amplitude reflectors in the rift section and reflection-free bodies interrupting the rift stratification (Figure 4B) points out the existence of igneous rocks within it. These may be associated with deeper gabbroic bodies, as indicated by high energy intracrustal reflectors, interpreted as a magmatic plumbing system (Figures 4 and 5).

The rift and post-rift sedimentary section in the SEMA displays remarkable differences when compared to the tectonic compartment of the distal margin to the west. Along the SEMA and seawards, the margin is characterized by: 1) thinner pre-salt section; 2) sparse syn-rift wedges; 3) discontinuous reflectors in the sag sequence with local carbonate build-up constructions, probably favored by the SEMA basement high; and 4) a drastic change in the halokinesis style: the SEMA marks the transition to distinctive salt tectonic styles, from a salt dome domain to the west to salt walls and allochthonous salt domains oceanwards, where the salt displays evidence of compression and displacement, forming a detached salt-sheet riding over the oceanic crust (Figures 4 and 5).

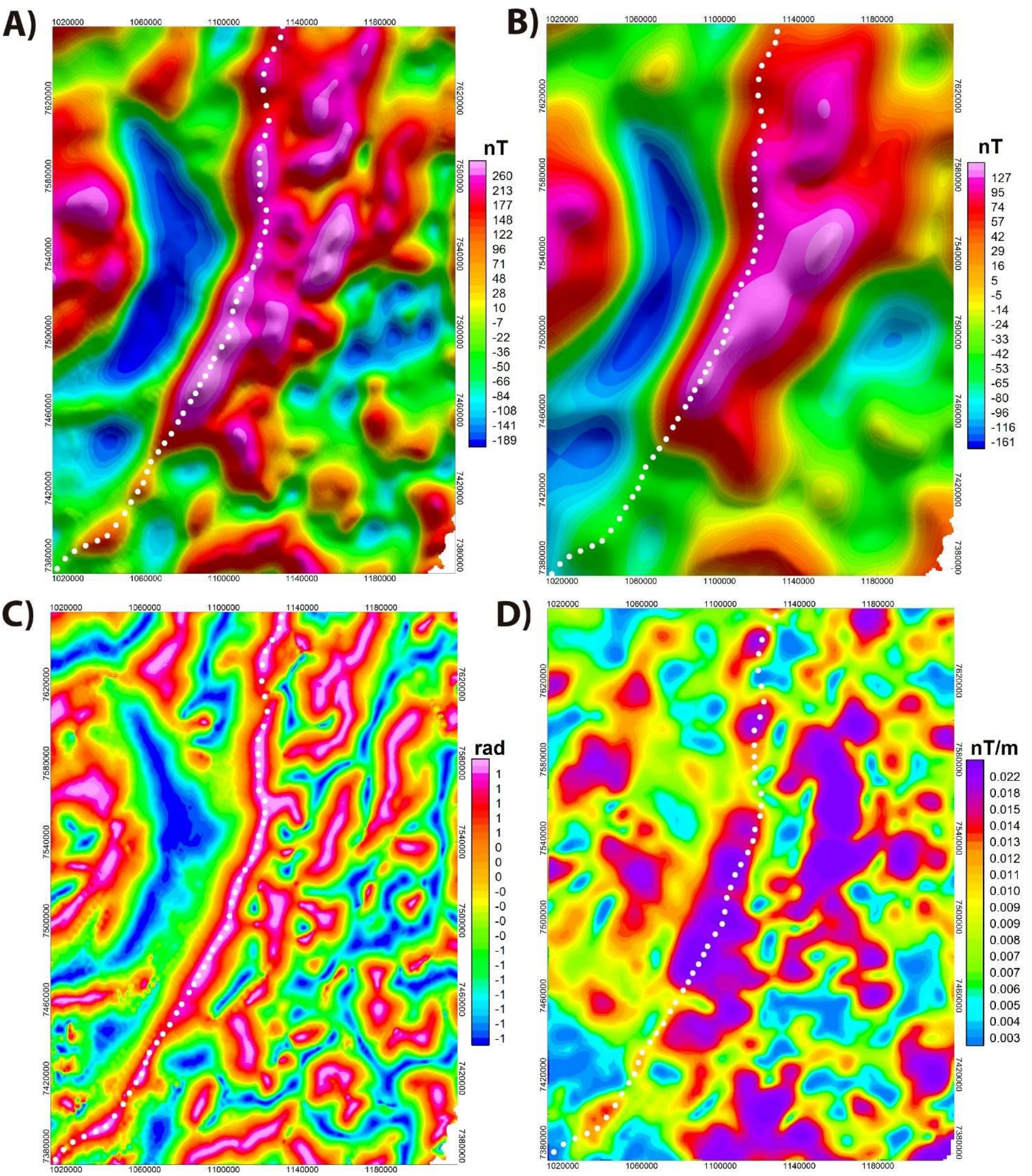

Figure 3: Magnetic anomaly maps of the SEMA. A) magnetic anomaly Reduced to the Pole (RTP) map. B) Upward continuation of 10 km of the RTP map. C) Tilt derivative of the RTP map. D) Analytical Signal Amplitude. The white dotted line represents the SEMA; the white arrow shows the location of the curved anomaly (see main text for details).

Tectono-magmatic significance of the SEMA

The morphostructure and geophysical signature observed along the SEMA, characterized by a top basement with high amplitude and discontinuous reflectors overlying a basement high with internal chaotic and reflection free seismofacies, and associated with very high amplitude positive magnetic anomalies, point out a volcanic outer high in the most distal part of the Campos rifted margin.

High energy and disrupted reflectors observed from the seismic data (Figure 5) and interpreted as volcanic sills intrude the lower syn-depositional sediments of the eastern half-graben (Figure 2). In the SEMA, the high reflectivity seismofacies indicate volcanic rocks that are disrupted and display a wedge configuration. They fill a late syn-rift depocenter and overlap the basement high (Figure 5). The volcanic sequences in the SEMA are likely to be

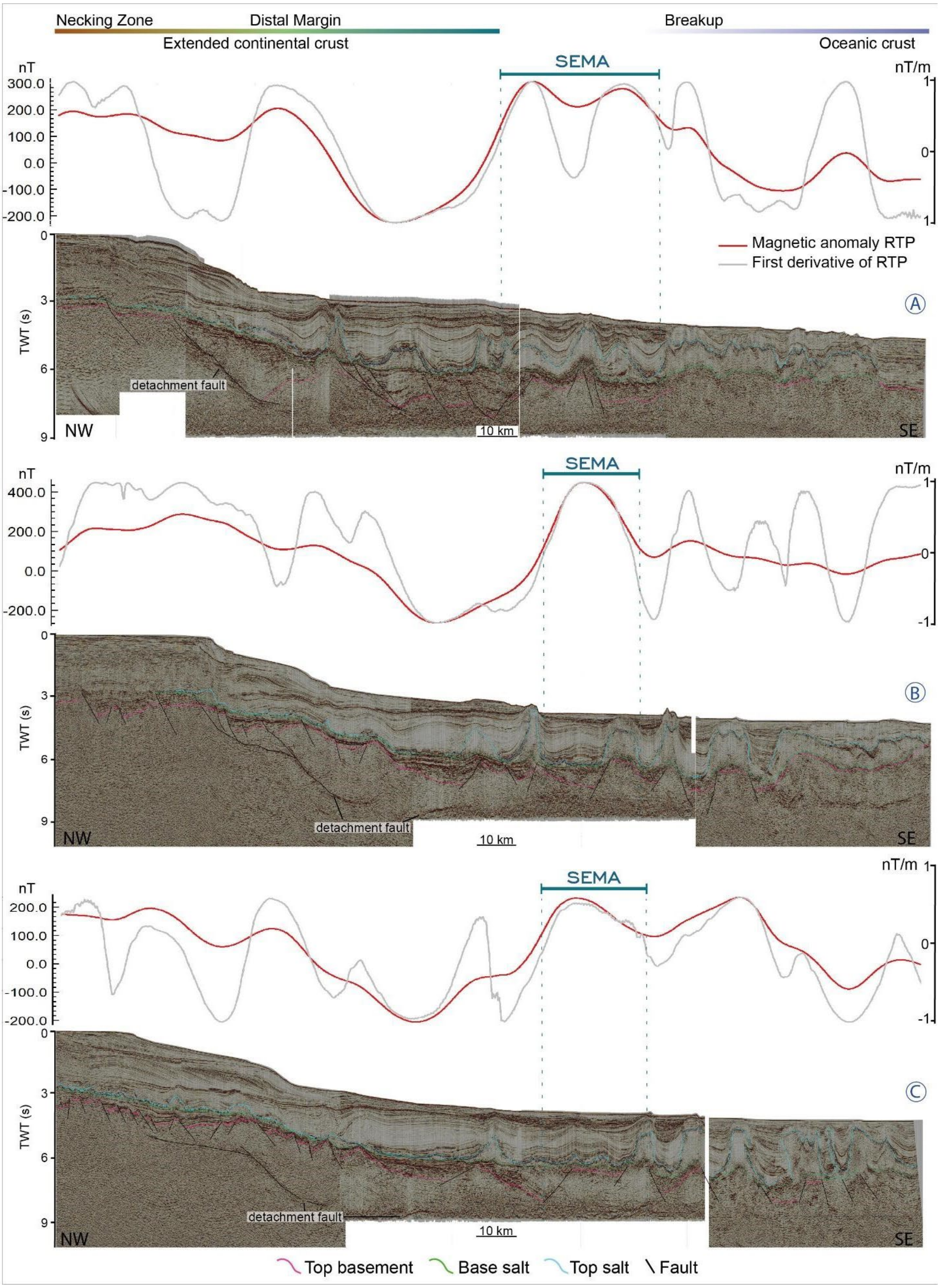

Figure 4: Seismic sections in the Campos Rifted margin with RTP magnetic profiles (RTP anomaly axis on the left and tilt derivative of RTP axis on the right top of each profile), showing the crustal architecture, domains and the basement associated with the SEMA from south to north (locations in Figure 2).

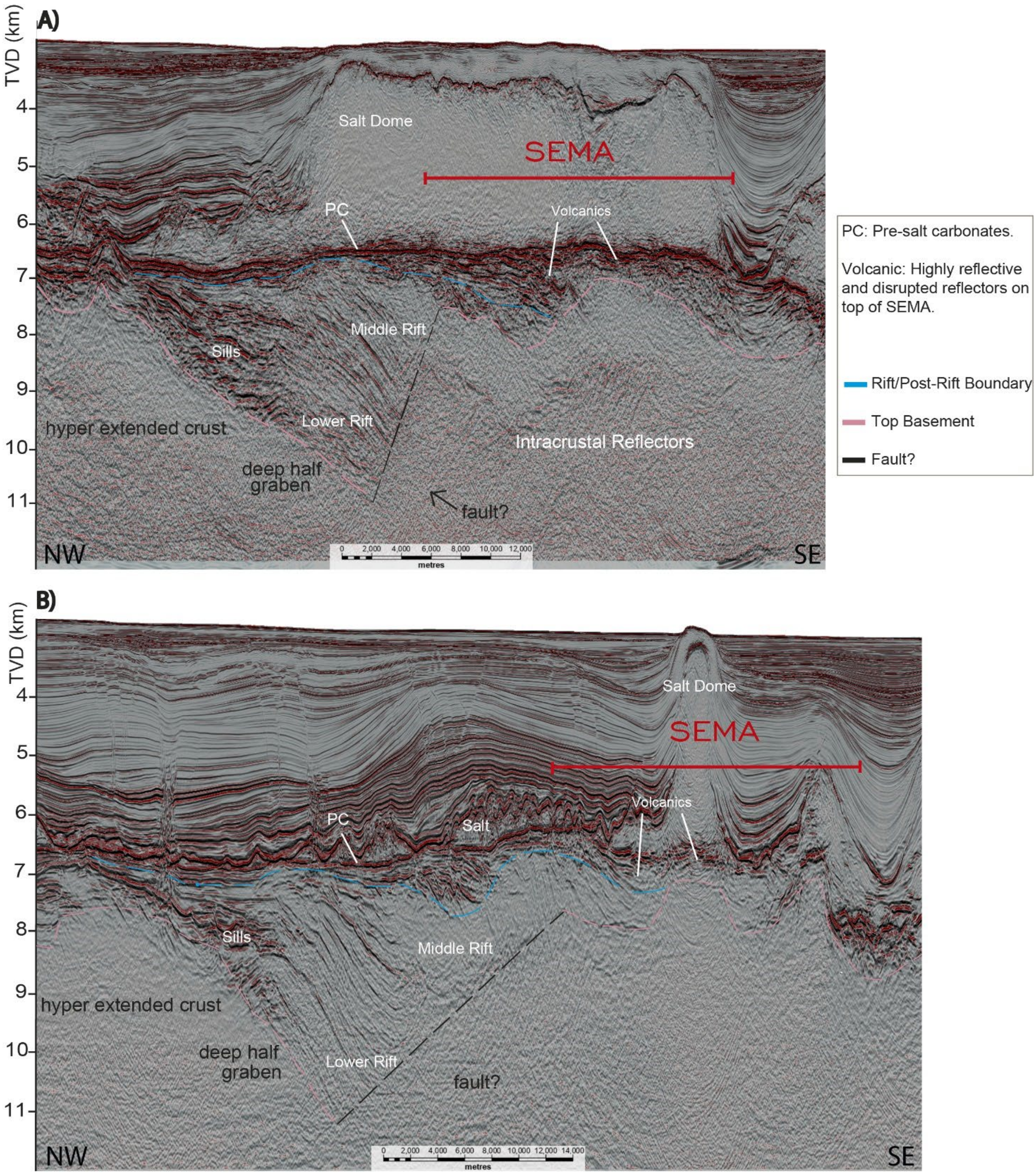

Figure 5: Dip seismic section examples showing the SEMA in the northern (upper figure) and southern regions (lower figure). Note the basement step, volcanics, thinning of pre-salt sequences, salt walls and diapirs along the SEMA.

extruded from late rift to early post-rift (Figure 5). This unit was later covered by Aptian pre-salt carbonate and salt deposits. Szatmari and Milani (2016) estimated the salt deposition in Late Aptian - Early Albian. Thus, the emplacement/formation of the SEMA is interpreted to be pre-salt, possibly breakup.

Previous works as in Araujo et al. (2022) proposed that there is a migration of the deformation from the proximal to the distal margin which corroborates that the pre-salt carbonates in the SEMA are younger than the pre-salt carbonates in the proximal margin. A recent hypothesis (Karner et al., 2021) interpreted the most distal part of Campos margin as “magmatic crust”. According to Karner et al. (2021), the entire basement of the distal domain and along the here proposed SEMA would be volcanic, including the deposits in the western depocenter, both formed after the breakup, proposed in late Valanginian–early Hauterivian (132–134 Ma). The deep half-graben described here would be filled by SDRs, as also suggested by Norton et al. (2016), that define a magmatic necking zone, east-ward of the region on which lies the oceanic crust formed by subaerial seafloor spreading (Karner et al., 2021). Norton et al. (2016) also suggests that the region above the SEMA would be the Continent-Ocean Boundary.

Only a few faults affecting the crust of the SEMA can be identified. This may be due to unresolved structures by seismic data or even may really reflect a change in the tectonic style of the margin. A decrease or absence of faults is coherent in the context of a volcanic high. A magmatic accommodated extension would result in fewer faults, as shown by numerical modeling (Lavier et al., 1999). A rifted and thinned continental crust is usually characterized by rough basement topography, with faulting and graben-half graben related morphology, which is not observed along the SEMA. The nature of the crust on and oceanward of the SEMA is unconstrained by well data. However, it constitutes a basement high, developed adjacent to a deep region of very thin crust (~3-4 km), where the continental upper crust is decoupled from the lower crust (or mantle) by a large-scale regional detachment (consistently observed in our seismic data) from south to north (Figure 4). Therefore, the geophysical observations evidence that the SEMA marks a boundary between two contrasting tectonostratigraphic and crustal domains.

Based on the evidences presented, we propose that the SEMA constitutes an outer high in the form of a linear volcanic ridge. The formation of this volcanic structure seems to be related to deep crustal structures (the regional sub-horizontal detachment and large-scale fault / graben that bounds along its western margin). The tectono-sedimentary relationship between the SEMA and the post-rift and salt deposition constrains a time-relative formation in Late Aptian - Early Albian for the SEMA (based on salt deposition age of Szatmari and Milani, 2016). Its formation is associated with a basinward dipping, large-scale fault that created a huge depocenter continentwards and a significant thinning and modification of the pre-salt sequences seawards, with increasing presence of volcanic and intrusive rocks, which probably resulted in important modifications in the pattern of the margin depositional evolution. A linear basement ridge, 85 km long, located in the outer Campos Rifted Margin would have an impact on the paleo-water circulation in Aptian-Albian times and later.

The understanding of the most distal parts of a rifted margin and magmatic structures like the SEMA could foster our knowledge of breakup related tectonic, magmatic and sedimentary processes. Still, there are remaining relevant questions such as what is the nature of the crust seaward of the SEMA; does the SEMA represent a failed magmatic breakup and thus an eastward rift jump; or does the SEMA represent a syn-breakup volcanic ridge, formed by an incipient yet not fully developed spreading center.

CONCLUSIONS

The SEMA is a high amplitude magnetic lineament, with a cross-section width between 30-50 km, ~85 km long and trends southwest to northeast. Based on seismic, gravity and magnetic observations we propose that the SEMA represents a volcanic outer high in the most distal part of the Campos Rifted Margin.

Its formation is associated with a basinward dipping, large-scale fault that bounds it to the west along its entire length. In and seaward of the SEMA, geophysical data evidence an increasing amount of volcanic and intrusive rocks and a distinct crustal morphology and structure. It represents a specific and well-defined tectonostratigraphic compartment, characterized by sparse rift-related structures, altered pre-salt sequence, basement shallowing and density increase. Furthermore, the SEMA marks the transition to a distinctive salt domain, characterized by intense halokinesis with evidence of compression, forming a salt-sheet riding over the oceanic crust. The SEMA Volcanic Outer High is structured as a linear ridge that seems to constitute the external limit of the Campos Rifted Margin. Its understanding provides new clues on the geodynamics of the Brazilian margin and insights into the breakup process, with potential impact on the external frontier for hydrocarbon prospects.

ACKNOWLEDGMENTS

We would like to thank CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the scholarship and to ANP (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis) for the dataset. The authors are grateful to the reviewers for their useful comments that improved the paper.

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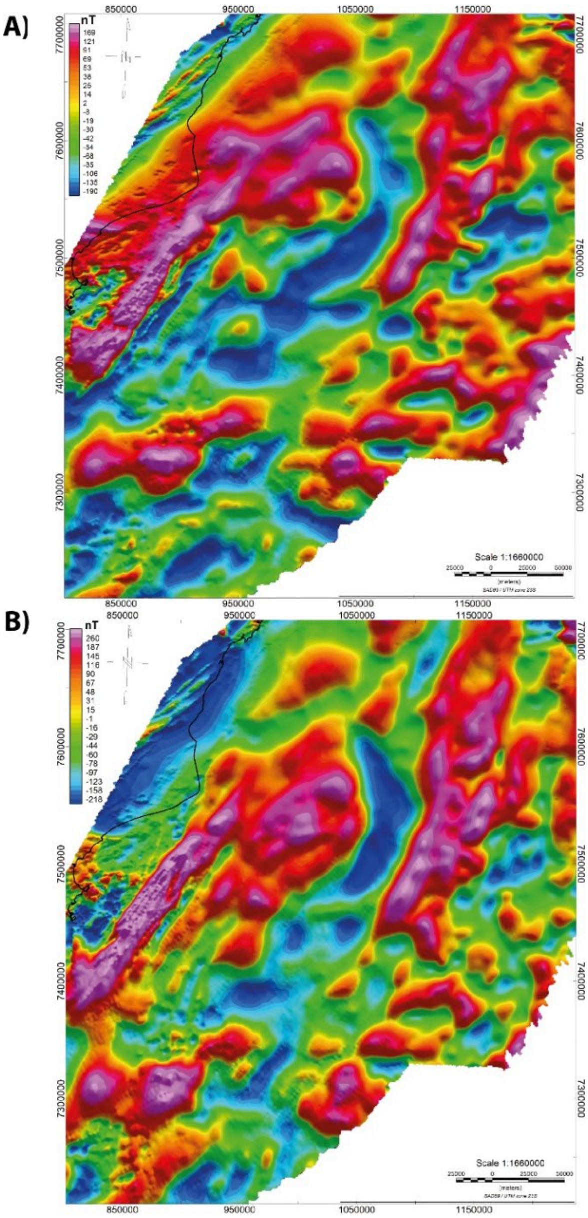
Supplementary Material



Graça M.C.: Conceptualization, Writing, Methodology; **Stanton N.S.G.**: Supervision, Writing, Methodology, Conceptualization, Visualization; **Gordon A.C.**: Conceptualization, Writing - review & editing.

Received on December 30, 2021 / Accepted on May 6, 2022