Submarine drainage distribution and main sediment transfer pathways along the Brazilian continental margin

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ABSTRACT

The characteristics of the Brazilian submarine drainage systems and their distribution along the continental margin are still poorly known. We mapped the main drainage systems using the available regional bathymetric datasets in order to understand the canyon and channel distribution along the margin and identify the preferential pathways for sediment transfer to the nearby ocean basins. In total, 431 submarine canyons, 168 submarine channels and 7 deep-sea channels were identified on the continental margin. Canyons were classified into three types according to their characteristics. They tend to concentrate on the margin's North sector and are absent from a large section in the South sector. Submarine channels were classified into two types, either straight and/or sinuous and were organized into three different patterns, convergent, distributary, or single isolated channels. Some convergent networks formed by channels are linked down-dip to deep-sea channels that reach the nearby abyssal plains. All mapped drainages fit into eight drainage areas that form large source-to-sink areas along the margin. The large convergent networks observed on the margin present common characteristics. They: 1) are fed by small to medium river systems 2) are located in regions with steep slopes; 3) present a relatively narrow continental shelf; and 4) have some degree of initial confinement in the upper part of the system. Due to their characteristics, large deep-sea channels fed by up-dip convergent networks may be responsible for large amounts of the terrigenous sediments delivered to the nearby abyssal plains.

Keywords: Submarine canyons, Submarine channels, Drainage patterns, Sediment pathways, Source-to-sink

1. INTRODUCTION

Studies using regional and global bathymetric compilations have provided important information on how turbidite systems distribute along the continental margins and how these systems transfer sediments to the deep ocean (Heap and Harris, 2008; Harris and Whiteway, 2011; Harris et al., 2014; Huang et al., 2014; Nyberg et al., 2018).

On the continental margins, depositional systems formed by canyons, channels and distal lobes are among the most important systems transferring sediment to the deep-ocean basins (Lastras et al., 2009; Covault, 2011; Mulder, 2011). Submarine canyons are deeply-incised, V-shaped features that can be originated by different processes (Shepard, 1981; Pratson et al., 2007). They capture important amounts of sediment from terrestrial and shallow marine systems through time and transfer it down slope to the deep-water systems at the base of the slope (Normark and Piper 1991; Piper and Normark, 2009; Lastras et al., 2011; Puig et al., 2017). The different canyon types can be put on an evolutionary context and two end members are recognized: (1) small, slope-confined canyons (or immature canyons) and (2) large, shelf-indented canyons (or mature canyons), each one characterized by a different set of dominating erosional processes (Twichell and Roberts, 1982; Farre et al., 1983; Harris and whiteway, 2011; Puga-Bernabéu et al., 2011).

Some canyons develop submarine channels at their mouths forming a coupled canyon-channel system (Babonneau et al., 2002; Covault, 2011; Amblas et al., 2017). Submarine channels develop through both erosional and depositional processes and have sinuous plan form geometry (Janocko et al., 2013; Deptuck and Sylvester, 2017). Channel characteristics such as sinuosity and length are variable and are usually related to the sediment source characteristics and basin morphology (Flood and Damuth, 1987; Piper and Normark, 2001). Channels may also form large submarine fans on the basin floor. These features are the largest accumulations of genetically related detritus on Earth (Barnes and Normark, 1985; Curray et al., 2003) and are considered important sinks on source-to-sink systems (Bouma et al., 1985; Somme et al., 2009).

Some submarine channels are linked to deep-sea channels. Deep-sea channels have been recognized on the seafloor since the early works on deep-sea physiography (Menard, 1955; Heezen, 1959). These channels are excavated by turbidite currents and are considered as important agents in the transferring of sediments to the abyssal plains (Menard, 1955; Carter, 1988; Carter and Carter, 1996). Morphologically, they are characterized by wide U shaped channels, normally down dip turbidite systems in water depths up to 4000 m. Examples of deep-sea channels distributing sediments to the abyssal plains are also observed on the west North American margin (Griggs and Kulm, 1973), on the West African margin (Wynn et al., 2000) and on the New Zealand continental margin (Carter and Carter, 1996).

The first systematic studies on the Brazilian continental margin were carried out in the late 60's and 70's by the REMAC (Reconnaissance of the Continental Margin) project (Chaves, 1979). Despite the low resolution of the dataset, these works unveiled the main structural and sedimentological patterns throughout the margin and highlighted the main sediment dispersion routes, including the characterization of some of the largest canyons and channels. Using data from the REMAC project, Gorini and Carvalho (1984) further characterized the main sediment routes along the margin. Since the REMAC project, however, studies on deep-water sedimentary systems have been focused on the Southern Brazilian margin mainly because of the exploratory success in the region. More recently, studies using high-resolution bathymetric data have shown some of the complexity of the Brazilian slope sedimentary systems both channelized and non-channelized on specific sections of the margin (Almeida et al., 2015; Reis et al., 2010, 2016). Nevertheless, since the REMAC project, the Brazilian margin lacks integrated studies on a regional scale. The aims of this study are therefore to, (1) map and characterize the margin submarine drainage systems; (2) identify the main sediment routes throughout the margin; (3) understand how submarine channel networks organize; and (4) determine the main controls and morphological constraints on large submarine drainage systems.

2. REGIONAL SETTING

The Brazilian continental margin corresponds to a large section of the East South American margin, extending for more than 6000 km. It is subdivided into three sectors: North (or Equatorial), East, and South (Chaves, 1979; Palma, 1984; Gorini and Carvalho, 1984). This subdivision was established during the REMAC project that also determined the Fernando de Noronha and Vitória-Trindade seamount chains as the limits between North and East, and East and South margins, respectively (Fig. 1).

The North margin sector extends for more than 2100 km from Cape Orange in the west to the Fernando de Noronha seamount chain in the east. This sector has a general E-W orientation and originated from a dominant transform tectonic setting established during the separation between Africa and South America (Matos, 2000). Three sections of the margin are parallel to the main transform faults in the region: Romanche, São Paulo and Fernando de Noronha (Figs. 1 and 2). The North margin sector has a relatively narrow shelf in the Eastern part, next to the Fernando de Noronha seamounts and a wide shelf in the west, next to the Amazon River mouth. On the eastern part of the shelf, large, partially-filled incised valleys are present (Gomes and Vital, 2010) and large sediment wave fields are observed on the central part of the shelf, close to the Maranhense Gulf region (Palma, 1979). On the outer shelf (as on the entire margin) carbonate sedimentation dominates (Martins and Coutinho, 1981). The main sedimentary construction on the North margin sector slope is the Amazon fan (Fig. 2). It is one of the largest fans in the world and extends for more than 1000 km from the shelf-break to the nearby abyssal plain. The Amazon fan area is also affected by gravitational tectonics with the northern and southern parts of the fan being affected by megaslide events (Reis et al., 2016). The Equatorial Atlantic Mesoceanic Channel - EAMOC is the best studied deep-sea channel in this sector. It is a relatively meandering deep-sea channel located north of the Fernando de Noronha seamount chain and is considered a relict feature (Damuth and Gorini, 1976).

The East margin sector extends for more than 1900 km with a N-S orientation (Fig. 1). A short and flat continental shelf (<30 km and <1°) and a relatively steep and deep continental slope characterize this margin sector (Martins and Coutinho, 1981). The main structural features on the continental slope and rise are the marginal plateaus of Pernambuco, Bahia and Rio Grande do Norte and the presence of fracture zones (Gorini and Carvalho, 1984). The Pernambuco and Rio Grande do Norte plateaus originated from structural highs caused by volcanic activity (França, 1979). The Bahia plateau, on the contrary, is located on the subsalt domain (Rodovalho et al., 2007) and its morphology is probably the result of intense salt tectonics. The seamount chains of this sector are normally associated with regional fracture zones (Palma, 1984). Large unfilled incised valleys and carbonate sedimentation on the outer shelf are also common features on this sector (Dominguez, et al., 2013; Fontes et al., 2017). On the continental slope and upper continental rise, the main sedimentary features are the São Francisco deep-sea fan, linked to the São Francisco river (Cainelli, 1992; Fontes et al., 2017), and the Boca do Rio and Joanes megaslides on the central part of the margin (Cobbold et al., 2010; Dominguez et al., 2011). On the continental rise, the largest and most important features are the Vales da Bahia deep-sea channel (a turbidite-excavated feature) and the Pernambuco contourite channel. The Pernambuco channel extends for more than 800 km in a N-S direction and is the result of excavation by the Atlantic bottom water that migrates from South to North (Gomes and Viana, 2002).

On the South margin the continental shelf is wider (> 70 km) and large unfilled incised valleys are observed mainly on the northern part of the sector in the region close to the Paraíba do Sul and Doce rivers (Conti and Furtado, 2009). This margin sector extends for almost 2000 km from the Vitoria-Trindate seamounts in the northern part to the Chuí megaslide in the southern part of the Rio Grande Cone (Fig. 1). The most important structural feature on this margin sector is the São Paulo plateau which extends for more than 1000 km in a N-S direction and is the result of intense salt tectonics (Kumar and Gamboa, 1979). Canyons are absent from large sections of slope in this sector (Harris and Whiteway, 2011) and on the continent, only small river basins drain to the coastline. The Columbia and Carioca deep-sea channels located on this margin are the best-studied deep-sea channels on the Brazilian margin (Bhreme, 1984; Gorini and Carvalho, 1984; Lima 2009). The continental rise on this part of the margin presents at least three large contourite channels (Faugères et al., 1998; Duarte and Viana, 2007).

3. MATERIALS AND METHODS

3.1 Bathymetry

We studied the “Brasil LEPLAC” bathymetric grid provided by the Directorate of Hydrography and Navigation of the Brazilian Navy. It covers the entire Brazilian continental margin from the continental shelf to the nearby abyssal plains with a spatial resolution of 1.5 km (Fig. 3). The final bathymetric grid was derived from multiple single-beam, multi-beam and seismic surveys and from several institutions/projects such as LEPLAC (Brazilian Continental Shelf Survey Program), DHN (Directorate of

Hydrography and Navigation), PETROBRAS (Petroleo Brasileiro S.A), ANP (National Petroleum Agency), GEODAS (Geophysical Data System), and GEBCO (General Bathymetric Chart of the Oceans). The SRTM30_Plus V7.0 (Shuttle Radar Topographic Mission) grid was used to fill the data gaps in distal areas. Data integration and processing was carried out on OASIS – MONTAJ software. Processing steps involved filtering for spike removal and a previous careful cross-over error analysis between surveys from different sources in order to eliminate the low quality surveys. The final bathymetric grid is on WGS84 datum (False N=0, False E=0, Latitude Origin=0, Longitude Origin=0 e scale Factor=1). In addition to "Brasil LEPLAC" grid, the SRTM3D_plus_V11 and the Global Multi-Resolution Topography (GMRT) grids were also used in order to help with the drainage mapping process.

3.2 Mapping methods

The submarine canyons and channels were manually mapped using a combination of two bathymetry-derived grids: (1) Planform Curvature (plan curvature) and (2) Drainage Depth Surface (DDS) (Fig. 3A, B). The curvature is a second derivative function that is related to the concavity and convexity of a surface. In plan curvature grids, flow-lines converge when cells have a concave plan curvature (such as in canyons and channels) and diverge when cells have a convex plan curvature (such as on ridges) (Olaya, 2009). The plan curvature grid was automatically calculated using the spatial analyst tool in ARCGIS 10.5. The DDS is the difference between an ideal surface without canyons and the bathymetric data. The DDS was calculated in three steps: (1) invert the bathymetric data, (2) extract the intercanyons and interchannel ridges from the inverted data and (3) interpolate the points along the ridges and highs. The DDS and the plan curvature grids were then combined in ARCGIS 10.5 via transparency (Fig. 3C).

In order to reduce uncertainty in the mapping process, slope, shaded relief and automatically extracted flow-lines were also obtained from the original "Brasil_LEPLAC" grid using the spatial analyst tool in ARCGIS 10.5 (Fig. 3D). Automatically extracted flow-lines were used to locate the thalweg axis and the slope and shaded relief grids were combined to enhance the canyons and channels limits.

The mapping products were two vector files: (1) a polygon representing the feature area and (2) a line representing the feature thalweg. These vector files were then used to extract further parameters from the drainage systems by sampling different grids (slope, valley depth and the feature depth related to the sea surface) along the thalweg lines every 500 m. The parameters obtained are shown in Tables 1 and 2, and Figs. 4 and 5.

3.3 Continental margin limits and subdivisions

This study follows the Brazilian margin division into three sectors (North, East and South) suggested by the REMAC project (Chaves, 1979; Gorini and Carvalho, 1984).

For the base of slope boundary, we established that where such a limit is not clearly visible on the slope maps, the down dip slope value of 1.5 degrees marks the limit, as suggested by Heezen (1959). The continental shelf-break line also follows the limits established by the REMAC project (Chaves, 1979). The 100 m isobath is considered the shelf-break in the western part of the North sector and the 70 m isobath for the rest of the North sector, the entire East sector and the northern part of the South Margin sector. The 150 m isobath marks the shelf-break for the rest of the South Margin.

Although the term “base of slope” used in this study and in the UNCLOS (United Nations Convention on the law of the Sea) is the same, the base of slope mapped in this study follows a very different methodology from that established in the UNCLOS. Thereby the limits presented here cannot be used as a reference for any international legal study.

3.4 Drainage classification

This work includes only the submarine canyons and channels excavated on the continental margin. Canyons on seamounts and guyots were excluded due to the distinct morphology of these features. These morphological differences could introduce distortions in the statistical analysis performed in this study.

The position of the drainage relative to the base of slope line was used as reference to classify canyons and submarine channels. Canyons were considered to be mostly shallower than the base of slope line and submarine channels mostly deeper. The exact base of slope limit was used only when it was not possible to easily determine the limit between the two features on the bathymetric data. This classification implies that only channels located at the lower slope and continental rise were mapped.

The submarine canyons were grouped into three classes or types according to the degree of incision and connection with the continental shelf, which is similar to the canyon types of Harris and Whiteway (2011) and Puga-Bernabéu et al. (2011). Type 1 canyons show a considerable degree of incision in the continental shelf. These canyons have large head areas (>30 km²) and in some cases they are clearly associated with rivers (Table 3). Type 2 canyons are also linked to the continental shelf but do not develop large canyon heads. These canyons indent the shelf more than 1 km from the shelf-break and have less than 30 km² of head area. Some of these canyons may also be linked to rivers. Type 3 canyons are canyons that do not incise the shelf and therefore they are either shelf independent or much less affected by shelf processes.

Submarine canyons were considered to occupy a limited size range. The dimensions normally accepted for gullies (less than 10 km long and a few tens of meters deep) were considered as the lower size limit for canyons (e.g. Prelat et al., 2015; Shumaker et al., 2017). For the upper limit, the Amazon canyon (91 km long and hundreds of meters deep), which is the largest canyon on the Brazilian margin, was used as reference. Submarine channels were considered as the continuation of canyons on the lower slope and continental rise and should have either similar or smaller dimensions than the associated canyons. Given the cell size resolution (1.5 km), the submarine channels mapped in this work should be equivalent to the channel-levee complex scale (e.g. Deptuck et al., 2003). Deep-sea channels are large U-shaped features located on the continental rise and abyssal plains that up dip merge with regional submarine drainage systems (Carter, 1988). On the Brazilian Margin, they are normally found at >4000 m depth.

River systems were classified according to the river basin area. Large river basins cover more than 150000 km²; medium river basins are between 150000 km² and 7000 km²; and small river basins cover less than 7000 km² in area.

4. RESULTS

A total of 431 canyons, 189 submarine channels and 7 deep-sea channels were mapped (Figs. 6, 7, 8 and 9), with a total cumulative length of 27743 km. From the total length, 12102 km correspond to canyons, 13117 km correspond to submarine channels and 2524 km correspond to deep-sea channels. Incised valleys on the continental shelf were also mapped in order to better understand the preferential sediment pathways.

4.1 Shelf valleys

Shelf-incised valleys were observed on the entire margin. They are mainly located on the outer shelf and, at least one, can be clearly related to a large submarine canyon head (the Tocantins-Araguaia incised valley on the North margin sector) (Fig. 6). Some of the mapped valleys have been previously studied in detail (Vital et al., 2010; Dominguez et al., 2013) but others remain largely unknown. Among the mapped valleys, the Tocantins-Araguaia valley is the longest (Fig. 7). This valley extends for more than 110 km and has a mean width of 8 km. Due to its position and orientation, it likely linked the Tocantins -Araguaia (or Pará) river, the second largest Brazilian river system, to the Pará Canyon on outer shelf during periods of low sea level.

4.2 Submarine canyons

4.2.1 Classification and distribution

Type 1 canyons (pronounced shelf incision, large head) are the least common type of canyon, with only 12 canyons (or 2.8%). Type 2 canyons (less shelf incision, small head) are the second most common type, with 69 canyons (or 16%). Type 3 canyons (no shelf incision, slope confined) are the most common type of canyons, with 350 canyons (or 81.2%). Types 2 and 3 occur on the three margin sectors and Type 1 canyons are absent from the south margin sector (Fig. 10).

The canyon distribution and density are not homogeneous throughout the Brazilian margin (Figs. 10, 11). The North sector comprises 229 submarine canyons that correspond to 53.5% of the total canyons on the Brazilian margin (4 canyons Type 1, 28 Type 2 and 197 Type 3) but no clear distribution by canyon type was observed. The canyon density is high throughout the entire North sector and the continental slope located south of the Amazon fan presents the highest canyon density on the entire Brazilian margin. Three out of the four larger Type 1 canyons (Amazon, Mearim and Pará) have aspect ratios >1 (i.e. they are elongated), are located next to large rivers on the present-day coast and pass to sinuous channels at their mouths, suggesting an association with large rivers (Table 3). The Marajó canyon is the only Type 1 canyon that is not related to a major river. Furthermore, in the North sector there is no clear relationship between the slope gradient and canyon distribution as well as no clear alignment of the canyons to regional structures.

The East margin sector includes 161 canyons that represent 37% of the total canyons. In this sector, 8 canyons (or 5%) are Type 1, 36 canyons (or 22%) are Type 2 and 117 canyons (or 72%) are Type 3. Throughout the East margin sector, the canyon density is not homogeneous. Canyons are closer together on the northern part of the sector and further apart in the southern part (Fig. 11). The majority of the Type 1 canyons (8) on the Brazilian margin are located on the East Margin sector between the Royal Charlotte bank and the Rio Grande do Norte Plateau (Figs. 8 and 10). However, only three (Jequitinhonha, São Francisco and Potengí) are close to large rivers on the coast (Table 3). In this sector, Type 1 and 2 canyons concentrate on the continental slope located between the Pernambuco and Rio Grande do Norte Plateaus (Fig. 8). This large canyon density is unique on the entire Brazilian margin and forms a very distinct slope section. Regional strike-slip faults on the continent are parallel to the submarine canyons in this slope section and no clear distribution pattern was found in the rest of the margin sector. Slope gradient variations do not relate to canyon density in this sector.

The remaining 41 canyons, which correspond to 9.5% of the total number of canyons, are located in the South Margin. Type 1 canyons are absent in this margin sector and only four Type 2 canyons are present (9.7% of the total). The northern part of the South margin sector concentrates 39 canyons and only two canyons are located on the other 2/3 of this sector (Figs. 9 and 10). Canyons are absent from two continuous sections of the South margin continental slope, one spanning more than 400 km near Rio de Janeiro (Fig. 3) state and a second one, spanning more than 1000 km between the Rio de Janeiro state and the Rio Grande Cone in the south (Figs. 3 and 9). In this margin sector, the canyon density has a positive correlation with the slope gradient. The slope sections without canyons have average slope gradients of $< 3^{\circ}$ while the average slope gradient of sections with canyons is $>3^{\circ}$. Despite the absence of large canyon heads, two Type 2 canyons are located close to river systems on the coast: the Doce (Do) and Paraíba do Sul (Pb) rivers (Fig. 9). Furthermore, no clear relationship was observed between regional structures and canyons in this sector.

4.2.2 Submarine canyon characteristics

Submarine canyon characteristics vary according to its type, location and margin sector. The area occupied by canyons on the entire Brazilian continental margin is 42210 km², which represents 7.7 % of the 325743 km² total slope area (Table 1; Fig.4). On average, the Brazilian canyons are 28 (+/-16) km long, 142 (+/- 103) m deep and their average thalweg gradient is 4° (+/- 2.5°). The East margin comprises 44% (18979 km²) of the total canyon area and includes the longest (32 km) and the deepest (182 m valley depth) canyons with the steepest thalwegs on the entire continental margin (4.1°). These canyons are also located at greater depths than other canyons. In the North margin, canyons cover the largest area, 47% of the total or 19917 km². Canyons on this margin are less developed than those on the East margin (26 km long and 115 m deep) but they have similar thalweg gradients. Canyons on the South margin cover an area of 3,314 km² or 8% of the total and are the least developed canyons. They are 24 km long, 91 m deep and have gentler thalwegs (2.7°).

Type 1 canyons are the most developed canyons. On average, they have greater individual areas (260 km²), have greater mean valley depth (266 m), are the longest (48 km), and have gentler thalweg slopes. The characteristics of Type 1 canyons also differ by margin sector. Canyons of this type located on the East margin sector are deeper and have steeper thalwegs than those on the North margin. On the contrary, canyons on the North Margin are the longest and extend over greater areas. Type 2 canyons have intermediate characteristics between Types 1 and 3. These canyons are 191 m deep and 35 km long on average and their thalweg is steeper than Type 1 canyons (4.1°). Type 3 canyons are the least developed canyons. They are on average 121 m deep, 25 km long and have similar thalweg gradients to Type 2 canyons (4°).

It was also observed that canyons located on marginal plateaus have different characteristics than those located outside these areas. Canyons located on plateau areas tend to be less incised, less extensive and have gentler thalweg slopes than other canyons (Table 1).

4.3 Submarine channels

4.3.1 Submarine channels types and networks

Two distinct submarine channel patterns were observed on the Brazilian Margin: straight and sinuous (Fig. 12).

In total, 158 straight submarine channels were mapped on the Brazilian margin: 69 are located on the North margin sector, 63 are located on the East margin sector and 26 on the South margin sector. From the total, 7 channels occur as isolated features (not connected to canyons or channels up dip) and therefore are considered abandoned. Straight submarine channels are linked to all types of canyons but the longest submarine channel networks have at least one or more Type 1 or 2 canyons as the main feeders.

Sinuous submarine channels are much less common than straight submarine channels. In total, 31 sinuous channels were mapped and of them, 10 are active channels (mainly during lowstand stages) and 21 are abandoned. The majority of these features are located on submarine fans, like the Amazon and Mearim on the North margin and the São Francisco in the East margin (Fig. 12). However, single sinuous submarine channels were also observed on the North and South margin sectors (Figs. 7 and 9). Most of the sinuous submarine channels are associated with Type 1 or 2 canyons that may be linked to large or to medium-sized river systems and all canyons feeding sinuous submarine channels on submarine fans are Type 1 canyons (Figs. 7, 8 and 9).

Some canyons do not present or present only short channels at their mouths. Other canyons, however, develop long submarine channels that create two different network patterns down dip: (1) convergent network, which are the most common type and (2) distributary network, which are observed mainly in submarine fan areas (Fig. 12). The distributary networks are formed by one active and several abandoned channels whereas convergent networks are composed of many active channels that merge down dip and a few abandoned channels. The presence of some abandoned channels in the convergent network indicates that avulsion of the main channel can also occur.

On the North margin, the longest submarine channel networks are located on the Amazon fan, on the Maranhense Gulf margin (MGM) (next to Maranhão state; Figs. 2 and 3) and on the Eastern part of the sector, next to the states of Ceará and Rio Grande do Norte margin - RNCEM (Figs.2, 3 and 12). There, the longest straight channels extend for more than 315 km in the Maranhense gulf, where it almost reach the abyssal plain, and for more than 350 km on the RNCEM. On the East margin, extensive and dense submarine channel networks occur over marginal plateaus (Bahia and Pernambuco Plateaus) where channels have greater dimensions and are easily identifiable (Fig. 8). The longest submarine channels in this margin sector are located near the state of Bahia where they extend for more than 205 km. On the South margin at the northern São Paulo plateau, a dense and extensive channel network is present. There, a central sinuous submarine channel converges with straight channels forming a convergent network that points to the Columbia deep-sea channel (Fig. 9). In the rest of the sector, only one channel is present.

4.3.2 Some submarine channel characteristics

The mean straight channel length is 57 (+/-70) km, which is almost twice the mean canyon length. Mean straight channel length varies from 51 km on the North margin to 72 km on the South margin (Table 2; Fig. 5). Sinuous channels are longer (132 km) than straight channels and channels located over marginal plateaus show similar lengths to those located outside the plateaus. Although the North Margin has some of the longest submarine channels on the Brazilian margin, it has the lowest mean channel length.

The mean valley depth considering both straight and sinuous channels is 63 (+/-76) m. The East margin channels are the deepest (95 m) and the North margin channels are the least incised (36 m). Sinuous channels have a mean valley depth of 48 m and a great difference is observed between channels on plateau areas (90 m) and those outside the plateaus (54 m).

In general, the thalweg is gentler in channels than in canyons and no significant difference was observed between sinuous and straight channels, in both cases < 1° (-/+ 0.6°). Among margin sectors, the channels on the East Margin and on plateaus have the steepest thalwegs (mean of 1.2°). No relationship was observed between changes in regional slope gradient and any of the channel parameters.

4.4 Deep-sea Channels

Deep-sea channels are aligned with long, dense submarine channel networks at their upper parts. These channels are very long and reach (or almost reach) the nearby abyssal plain at up to 4000 m depth (Fig 13). In total, five single deep-sea channels (Carioca, Columbia, Paraíba, Rio Grande do Norte and Equatorial Atlantic Mid-Oceanic channel - EAMOC) and a group of two connected deep-sea channels called “Vales da Bahia” were mapped (Fig. 14). These deep-sea channels are almost perpendicular to the margin and, except the “Vales da Bahia”, all point to the Brazil abyssal plain. The *Vales da Bahia* deep-sea channels were the only deep-sea channels mapped in this study that end in a contourite channel, the Pernambuco contourite channel (Fig. 8). Deep-sea channels have a mean length of 454 km and a mean width of 13 km. The longest of these channels is the Columbia deep-sea channel which extends more than 800 km on the continental rise and abyssal plain and has a mean width of 11 km. At its mouth it bifurcates indicating a likely recent change of position. In contrast, the Paraíba deep-sea channel is the shortest with an extension over the seafloor of only 159 km and a mean width of 8 km. The studied deep-sea channels present low sinuosity and only the EAMOC, and the Rio Grande do Norte channels have some degree of sinuosity.

4.5 Submarine drainage areas

All mapped canyons and channels on the Brazilian margin may also be grouped into eight large, areas referred to here as "submarine drainage areas" and named from 1 to 8. These areas act as basins and are defined by the sea-floor morphology and the presence of submarine features such as the presence of plateaus, seamount chains or other morphological obstacles on the margin. Each of these areas may also be related to a certain number of shelf valleys and rivers on the continent forming eight broad source-to-sink systems on the Brazilian margin. The limits between the drainage areas defined in this study are the Rio Grande Cone, the Jean Charcot seamounts, the Vitória-Trindade seamounts, the Abrolhos seamounts, the Pernambuco Plateau, Fernando de Noronha seamounts, the North Brazilian seamounts and the Amazon fan (Figs.7, 8, 9 and 15).

On the continent, drainage area 1 includes only small river basins, just two canyons and one submarine channel on the margin. On this part of the Brazilian margin, major rivers drain to the continent interior (to the Paraná River basin). Drainage areas 2, 4, 5 and 6 have a similar configuration with medium-sized river basins on the continent (the São Francisco River is the only exception), high canyon and submarine channel density on the slope and rise, and large deep-sea channels on mid and lower rise. Drainage areas 3 and 8 have small river basins on the continent, a relatively high canyon density on the slope and a few submarine channels on the rise. Finally, drainage area 7 is the largest drainage area and comprises most of the North margin sector. Drainage area 7 has the largest river basins on the continent, a high canyon and submarine channel density on the slope and rise and despite having some of the longest submarine channels, no deep-sea channel on the rise or abyssal plain was observed.

5. DISCUSSION

5.1 Controls on the submarine drainage

5.1.1 Submarine canyons

This study has increased the number of submarine canyons on the Brazilian margin from 61, counted in Harris and Whiteway (2011), to 431 and it also confirms the lack of canyons on the South margin. The increase in canyon number is the result of an updated bathymetric dataset with high resolution. Future works with even higher resolution are expected to further increase the number of existing canyons in this margin.

Large submarine canyons, such as Type 1 canyons, are common features on both passive and active margins (Harris and Whiteway, 2011). Many Type 1 canyons are linked to large rivers, mainly during periods of lower sea levels (Bouma et al., 1985; Michels et al., 2003; Popescu et al., 2004; Harris and Whiteway, 2011; Jobe et al., 2011). However, some of them may present large shelf-indented heads and are not linked to significant fluvial sources (Mitchel et al., 2007; Lastras et al., 2009; 2011). On the Brazilian Margin, according to their characteristics (elongated heads, proximity to river mouths on the coast, and the presence of sinuous submarine channels at their mouths), only five Type 1 canyons are considered linked to a medium or large river system on the continent (Table 3). On the North Margin, the link to a fluvial source controls the development and location of three large canyons: Amazon, Mearim and Pará, which correspond to the rivers of the same names on the adjacent continent. Only the Marajó canyon is not related to a medium or large river (Fig.7) but is close to the Paŕa-Maranhão megaslide (Reis et al., 2010, 2016), a very unstable area, suggesting that slope instability could be the main controlling agent in the development of this canyon. The majority of the Type 1 canyons are located on the East margin. On this margin sector, only the São Francisco and Jequitinhonha canyons are linked to medium or large river systems on the continent. The remaining six canyons seem to be related to the internal structure of the margin, small rivers and local instability processes acting on the canyon head. On the slope located between the Pernambuco and Rio Grande do Norte plateaus (Fig. 8), the activity of Neogene-Quaternary strike-slip fault (Bezerra et al., 1998; Lima et al., 2017; Bezerra et al., 2006) suggests that structural control and instability processes may be important agents in modeling the canyons (including four Type 1 canyons). Further south, the Japaratuba canyon is the largest canyon on the East margin but it is not connected to a medium or large river (Fig. 8). Some authors have suggested that the location of this canyon and the changes in its orientation are controlled by basement faults (Summerhayes et al., 1976; Cainelli, 1994; Fontes et al., 2017), although the connection to small rivers also occurs (Cainelli, 1994). The overall East Margin configuration favors the development of Type 1 canyons. This section of the Brazilian margin has a narrow (< 30 km), flat, and shallow continental shelf

(Chaves, 1979; Harris and Macmillan-Lawler, 2016), which allows a rapid connection between river systems and canyon heads during low sea level. This morphology is due to the establishment of carbonate platforms on the shelf-edge that can be unstable due to oversteepening or interaction with contour currents, as on the Little Bahama Bank (Mulder et al., 2018).

Types 2 and 3 canyons were mapped on the three margin sectors but no regional distribution pattern was observed for these canyons as with other margins (Amblas et al., 2006; Puga-Bernabéu et al., 2013). Despite their smaller size compared to Type 1 canyons, Type 2 canyons can be important regional conduits for sediments when connected to river systems. The connection of these canyons to medium river systems and the control by internal basin structures are expected to be the main controling factors of these canyons on the Brazilian margin. On the northern part of the South margin sector, for example, the Almirante Câmara and Doce canyons (both Type 2 Canyons) are the main feeders of long submarine channel networks (Machado et al., 2004; Almeida and Kowsmann, 2015) (Fig. 9). Types 3 canyons are the most common type of canyon in the Brazilian margin. As observed on the Australian margin (Huang, et al., 2014), the high number of Type 3 canyons on the slope highlights that mass wasting processes are widespread throughout the Brazilian margin where canyons are present.

According to the main models for canyon evolution (Twichell and Roberts, 1982; Farre et al., 1983; Pratson et al., 1994; Orange et al., 1994; Pratson and Coakley, 1996; Puga-Bernabéu et al., 2011; Micallef et al., 2014), Type 1 canyons are considered mature canyons (or in late stage of evolution), Type 2 are in an intermediate stage of evolution and Type 3 canyons are in the early stages. The canyon characteristics on the Brazilian margin are consistent with these models. Type 3 canyons are the smallest canyons and are steeper than Type 1 canyons (Table 1). These characteristics are expected for young, less incised canyons that tend to follow the regional slope. On the contrary, Type 1 canyons are the largest and have gentler thalweg gradients. These characteristics are also expected for mature canyons deeply incised into the continental slopes. Type 2 canyons have intermediate characteristics and are considered to be in transition between types 1 and 3, sharing, in some cases, characteristics of both types.

The distribution of canyons in the Brazilian margin shows that canyons are abundant on the North margin and absent from large sections of slope on the South margin, where the largest section without canyons is found, and according to Harris and

Whiteway (2011), the largest section of slope without canyons on Earth. Three factors can explain the lack of canyons in this part of the Brazilian slope: (1) the uplift of the Serra do Mar mountains in the Cenozoic (Modica and Brush, 2004) which has left this part of the margin absent of large river systems as major systems drain towards the continent interior; (2) the presence of strong contour currents on the upper slope (Viana et al., 1998), that create terraces and could prevent sediment from efficiently entering and incising the continental slopes and (3) the overall gentle slope gradient (< 3°) which is associated with the absence or great canyon spacing on other continental margins (Twichell and Roberts, 1982; Harris and Whiteway, 2011, Puga-Bernabéu et al., 2014). In contrast, the high density of canyons on the North margin is also related to three factors: (1) higher slope gradients compared to the South margin; (2) widespread instability processes on the slope and (3) high input of sediments from the larger river systems on this sector.

5.1.2 Submarine Channels

Most canyons on the Brazilian margin have submarine channels at their mouths. Moreover, the low resolution of the bathymetric data in deep waters indicates that only the largest channel-complexes are visible, so submarine channels should be, even more common. Variations in channel extension and plan-form geometry have been attributed to variations in slope gradient, basin morphology (Flood and Damuth, 1987; Clark et al., 1992; Sylvester et al., 2013; Clark and Cartwright, 2009), characteristics of sediment input, flow frequency and triggering mechanism (Stow et al., 1985; Reading and Richards, 1994; Clark and Pickering, 1996; Bouma, 2000a,b; Piper and Normark, 2001; Piper and Normark, 2009, Azpiroz-Zabala et al., 2017). According to these models, turbidity currents with high mud content have longer duration and contribute to create long (and often sinuous) channels (and fans) while sandy turbidity currents (and fans) contribute to create more straight, shorter, erosive channels due mainly to the formation of short-lived flows. Throughout the Brazilian margin, numerous straight and sinuous single submarine channels fed by one canyon and located side by side may present very different lengths (Fig. 12). Although the variation of the channel lengths (and other channel parameters) in this study may also be attributed to variation in data quality along the channel axis (which is reflected in the higher standard deviation of channel parameters) the lateral variation in channel type and length may also reflect variations in flow frequency, sediment content and sediment characteristics due to lateral variations in triggering mechanisms. Variations in continental slope morphology and gradient can also be responsible to some degree for these variations. An example of sediment source type affecting channel plan-form geometry is observed in canyons with sinuous channels at their mouths. Such canyons are normally related to river systems, which indicates that the high sediment input from an often steady, sediment rich source, such as from rivers, is one of the key prerequisites for developing sinuous channels. A significant difference was also observed in the way straight and sinuous submarine channels organize spatially on the margin. Straight submarine channels are the main type of channel on convergent networks, forming a complex and sometimes dense pattern, while sinuous submarine channels tend to create distributary networks, which are very common on submarine fan areas (Fig. 12).

The structural context along the Brazilian margin may also influence submarine channel development and morphology. On the North margin, the slope sections parallel to the transform faults have shorter channels than neighboring areas not affected by these faults (Fig. 7). These areas also lack thick sediment wedges at the base of slope (Fig. 2) which is expected for transform margins (Ingersoll, 2011). The abrupt change in gradient between the slope and the continental rise in the transform sections, due to the lack of a sediment wedge and the resultant rapid energy loss, could be the reason behind the lower channel extension in these areas. In this study, it is not possible to assess the degree of influence of strike-slip tectonics on submarine channel development in these areas but the marked changes in channel length suggests that they are at least influenced to some degree. Channel size is also affected by margin structures. Submarine channels are deeper and easily identifiable on plateau areas (Table 2 and Fig. 5). This pattern is due to the tendency of channels to follow the troughs and bathymetric lows related to either underlying salt tectonics and/or volcanism, both common in the Brazilian marginal plateau areas (Kumar and Gamboa, 1979; Winter et al., 2007; Almeida and Kowsmann, 2015).

5.1.3 Deep-sea channels

Deep-sea channels are the ocean-ward continuation of a contiguous continental-margin sedimentary transport system (Menard, 1955; Carter, 1988). On the Brazilian margin, the connection between deep-sea channels and up dip turbidite systems has been suggested for the Columbia channel (Brehme, 1984; Massé et al., 1998; Lima et al., 2009) in the South margin, the EAMOC (Damuth and Gorini, 1976; Baraza et al., 1997; Belderson and Kenyon, 1980) on the North margin and for the "Vales da Bahia" (Gomes and Viana, 2002) on the East margin.

Among the deep-sea channels mapped in this study, the Columbia and the EAMOC channels are the best studied; thereby they may provide the best view on the processes controlling this type of channel on the Brazilian margin. Turbidites, recovered from the Columbia channel thalweg and levees, indicate that this feature is eroded by turbidite currents and is probably active today (Massé et al., 1998; Lima et al., 2009). At the Columbia channel mouth, in the Brazil abyssal plain, high seismic amplitude anomalies have been interpreted as terminal lobe deposits (Gorini and Carvalho, 1984) and more recent seismic studies showed that the location of the channel and its morphology is controlled by regional faults (Lima et al., 2009). The EAMOC was also excavated by turbidite currents. However, it is abandoned today due to recent tectonic changes at the nearby Fernando de Noronha fracture zone (Damuth and Gorini, 1976; Baraza et al., 1997). Morphologically, the EAMOC channel presents relatively high sinuosity and its up and down dip extremes are currently buried (Belderson and Kenyon, 1980; Baraza et al., 1997). The presence of large underlying structures controlling the Columbia deep-sea channel location suggests that the great morphological differences between long, normal submarine channels and the large, U-shape deep-sea channels can also be attributed to the interaction of submarine channels with large regional structures located down dip.

5.2 Long convergent networks development and maintenance

On the modern seafloor, long convergent drainage networks that are able to deliver sediments to the abyssal plains are composed of several turbidite systems that merge down dip (Menard, 1955; Carter, 1988; Hesse et al., 1987; Klaucke and Hesse, 1996). On the Brazilian margin, long convergent networks occur at drainage areas 2, 4, 5, 6 and 7 on the Maranhense Gulf margin (Figs. 12 and 15). These five areas have some common characteristics that help to understand some controlling factors of the development of these long networks. On the continent, linked to these drainage areas, at least one river system (presenting variable sizes) acts as the main sediment source, indicating that river system size alone, is not a key element. The continental shelf extension in these areas is less than < 65 km. On the continental slope, the mean slope gradient is >3° and at least one of the canyons is a Type 1 or 2 connected to the main river system. The continental slope and rise morphology is also important. On the drainage areas listed above, some degree of initial confinement up dip, either on the slope or rise, was observed. This confinement can be caused by the presence of a seamount chain, a marginal plateau/morphological high or the continental slope orientation which can form an embayment focusing the flow to a specific point down dip. Most of the drainage areas presenting long convergent networks are fed by medium river systems, which suggests that smaller river systems are more efficient in delivering sediments to the abyssal plain than larger river systems. This could be related to the suspended sediment concentration, which is higher in small to medium river systems, and thus making them more prone to initiate hyperpycnal flows (Mulder and Syvitski, 1995; Mulder et al., 2003). The initial confinement seems to be a key factor in these large networks, causing reduction in accommodation space and forcing channels to converge to one single point. This convergence creates one main channel that captures all turbidite flows originated up dip in different canyons. The capture of events from different canyons can in turn help to keep system activity, even when environmental changes occur on the source slope section (such as sea-level variations).

5.3 Brazilian margin submarine drainage model

Based on the results of the present study, the mapped submarine drainage systems were grouped into three main organization patterns (Fig. 16).

Pattern 1 includes the convergent networks (Fig. 16A) that can occur at large both and small scales. Large-scale convergent networks on the Brazilian margin are observed in drainage areas 2, 4, 5, 6 and 7 (on the MG margin). These networks drain large sections of slope and continental rise, have a general “funnel” like plan-form geometry and can be considered important sedimentary systems. The main characteristics of the large convergent networks are: some degree of initial confinement, the presence of multiple feeder canyons, and multiple active down dip convergent submarine channels (mainly straight on the Brazilian margin, although sinuous channel convergence may also occur in the MGM) and in areas 2, 4, 5 and 6 a deep-sea channel. In this pattern, all the drainage networks tend to converge down dip reaching, or almost reaching, the nearby abyssal plain. Two types of large network terminations were observed: directly on the abyssal plains and in contourite channels. In smaller convergent networks, multiple canyons also feed multiple submarine channels; however, in these cases, they do not reach the abyssal plain and terminate on the rise. The smaller networks present variable extension.

Pattern 2 corresponds to the distributary networks (Fig. 16B). These networks can also occur at large and small scales. They are typically formed by a large feeder canyon linked to a large river basin and a very long sinuous submarine channel, which change their position through time (by channel avulsion). The Amazon fan area is the only region on the Brazilian margin where a large distributary network was observed. Distributary networks are also located on the surface of small fans, such as São Francisco and Mearim (Fig. 12) where they are also sinuous and have a limited extension when compared to those in the Amazon Fan.

Pattern 3 comprises single and/or short submarine channels (Fig. 16C). These channels can be either sinuous or straight and range from no, or almost no, channel, to long single channels that can reach the deepest parts of the basin. A few events of avulsion may also occur.

The type of convergence observed in Pattern 1 is observed on other continental margins as well. The New Zealand margin, for instance, presents some long convergent networks that reach the nearby abyssal plains (Carter and Carter, 1996; Mountjoy et al., 2018). As in the Brazilian long convergent networks, the initial confinement and, therefore, the convergence of canyons on the continental slope, up dip of the Bounty channel on the New Zealand margin, and its further confinement into the Bounty trough, seems to be an important factor controlling the development of this long system. The presence of multiple feeder canyons helps to always keep a minimum level of activity in these systems. On a larger scale, in the Labrador Sea, the relative confinement of the NAMOC deep-sea channel and its multiple feeder systems is also one of the key elements helping this system to develop its plan form geometry (Klaucke and Hesse, 1996).

Pattern 2 is the most typical pattern on the submarine fans surface worldwide and is the result of high sediment input and multiple events of avulsion (Bouma et al., 1985; Weimer, 1991; Flood and Damuth, 1987; Boubaneau et al., 2002). Although only one channel is active at a time in these networks, the abandoned channels may be reactivated (Deptuck and Sylvester, 2017), which helps to keep the pattern. On the Brazilian margin, only sinuous channels were observed forming this pattern. However, on other continental margins, such as the West American margin, this pattern can be formed by straight channels (Normark et al., 2009).

The single channels on Pattern 3 display variable extension. As discussed above, variations of source type and triggering frequencies are the factors controlling the extension of these channels. The lack of initial confinement forcing channels to converge as in Pattern 1, and the relatively low sediment input when compared to the channels in Pattern 2, are also responsible for the development of this pattern.

5.4 Implications for sedimentation on abyssal plains

Most sediment cores recovered from abyssal plains (including the Brazil abyssal plain) are known to contain siliciclastic turbidite layers (Kuenen, 1964; Wynn et al., 2000; Stevenson et al., 2015), which indicate that turbidite sedimentation is common in these settings. Furthermore, a recent census of sediments in the world's seafloor showed that the Brazil abyssal plain has more siliciclastic clays than previously thought (Dutkiewicz et al., 2015). These observations suggest that the multiple Brazilian long submarine channels and deep-sea channels are important conduits for transferring sediment from the continent to the abyssal plains. Therefore, a significant amount of the Brazilian abyssal plain siliciclastic sediments could have their origins on the Brazilian margin, placing the terminations of these systems on abyssal plains as important sinks for sediments.

The sediment supply from continental sources to the abyssal plains is also important for the development of local benthic communities on these deep-water areas. Recent studies on the Zaire fan lobes observed that some benthic communities prefer organic rich sediments deposited on the distal lobes while others adapt to the distal lobe sediment dynamics (Olu et al., 2017; Sen et al., 2017). This observation suggests that long channel networks capable of reach the abyssal plains, might be important agents supporting benthic marine life.

6. CONCLUSION

The mapping of the submarine drainage systems and their characteristics along the Brazilian margin provide important information on how the sediment is transferred from the continent to the adjacent abyssal plains. The conclusions of this work are:

1) The Brazilian margin has 431 submarine canyons, 189 submarine channels and 7 deep-sea channels. On a regional scale, the North margin presents the highest density of submarine canyons and the South margin presents the lowest density, with large slope sections where canyons are absent. Canyons can be classified according to their characteristics into three types: Type 1, presenting pronounced shelf incision and large heads; Type 2, presenting small heads and less pronounced shelf incision; and Type 3, totally confined within the slope.

2) The submarine channels are within the channel-levee complex scale and can be classified into two types based on their planform geometry: straight and/or sinuous. Straight submarine channels are the most common type of channel and can be linked to all types of canyons. Sinuous channels are less frequent and are observed only linked to Type 1 and 2 canyons

3) Deep-sea channels on the Brazilian margin are fed by dense and long submarine channel networks up dip which helps these features transfer sediments to the abyssal plains. All mapped canyons and channels on the Brazilian margin can be grouped into eight large submarine drainage areas. These areas mark the limits of large source-to-sink systems along the Brazilian margin and on the oceanic part, and their limits are defined by the seafloor morphology.

4) Many submarine channels organize into networks of variable extension that can be classified as convergent or distributary. Convergent networks are typically formed by multiple active and abandoned channels while distributary networks have one active channel and multiple abandoned channels. Five drainage areas present very long convergent drainage networks formed by multiple canyons, multiple submarine channels, and in the majority of the cases, one deep-sea channel. Some margin characteristics that help to form and maintain these large convergent networks are the presence of at least one large Type 1 or 2 canyon connected to a river system, a relatively narrow shelf (< 65 km), a high slope gradient and the existence of some type of confinement of the upper system (for canyons and/or channels).

5) The submarine drainage on the Brazilian margin presents three main patterns: (1) convergent networks formed mainly by straight submarine channels that end either on the abyssal plain or in a contourite channel; (2) distributary networks, common on the

surface of submarine fans and formed by sinuous channels; and (3) single channels that present variable length, are either sinuous or straight and may suffer few avulsion events.

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9. FIGURES

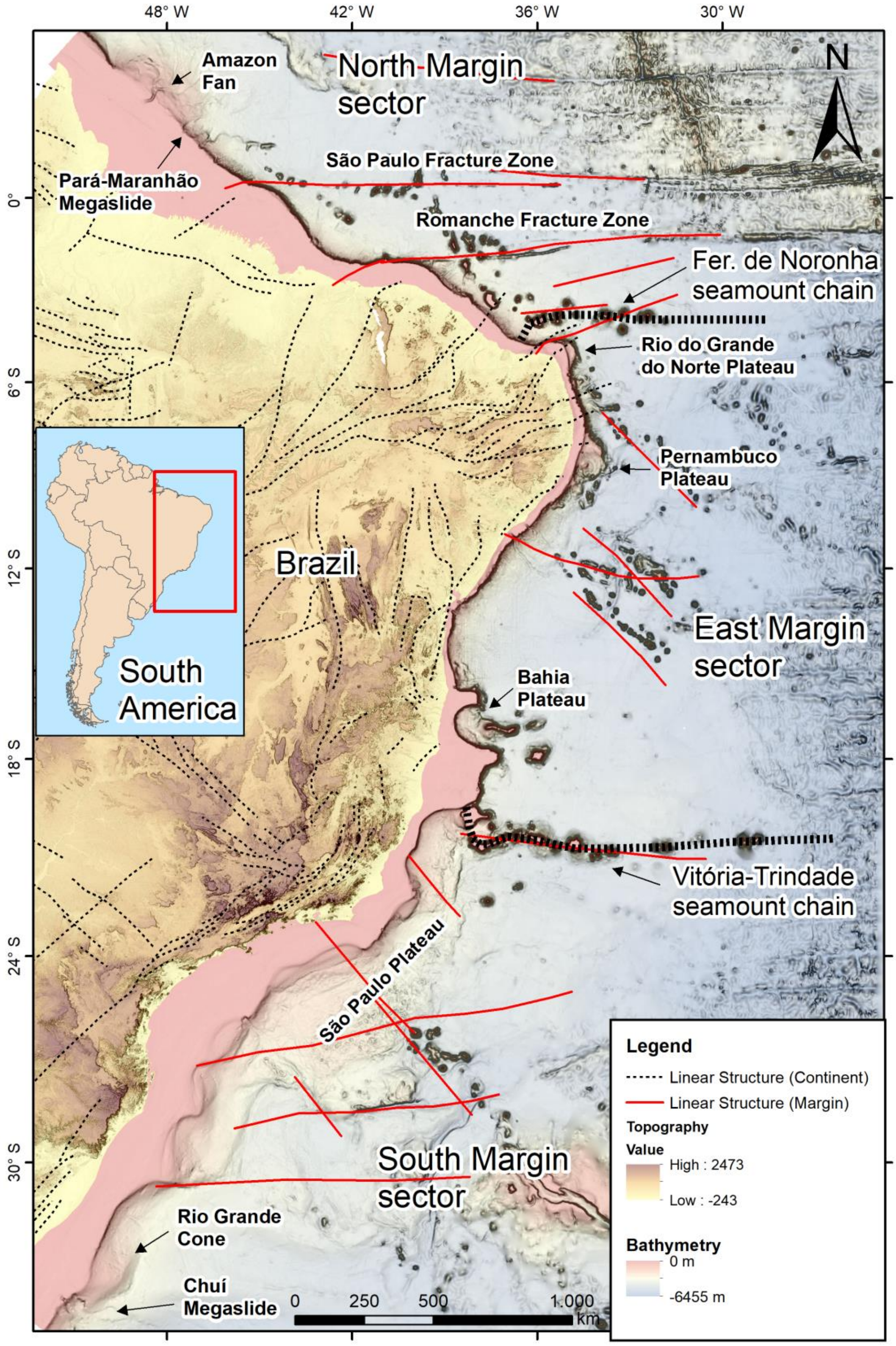

Fig. 1. Study area, margin subdivision and main regional features of the Brazilian margin. The Fernando de Noronha and Vitória-Trindade seamount chains are considered the limits between margin sectors.

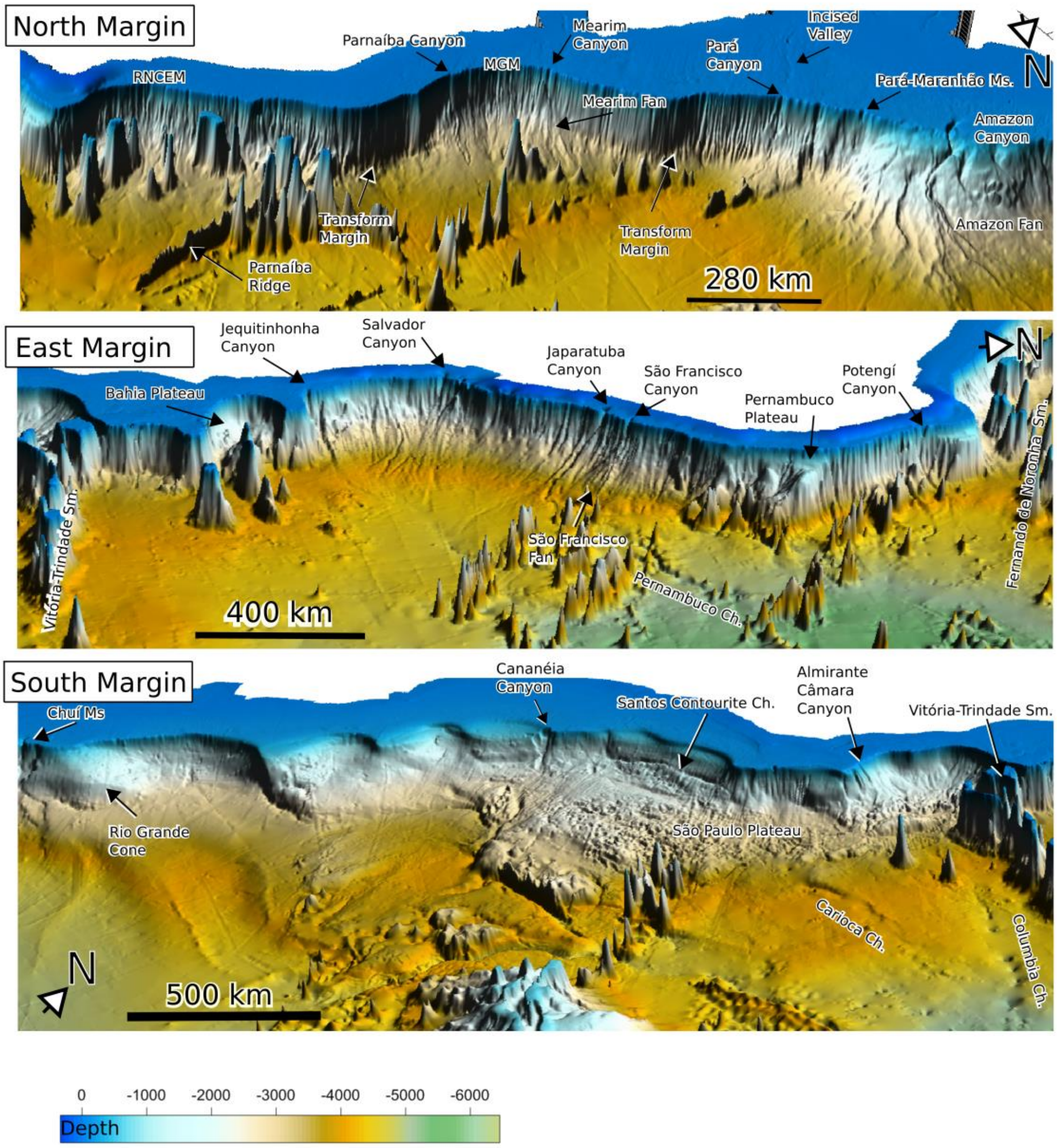

Fig. 2. Tridimentional view (5x vertical exaggeration) of the margin sectors (Brasil_LEPLAC grid). On the North sector, note the sediment wedges on the Maranhense Gulf Margin (MGM), Rio Grande do Norte-Ceará Margin (RNCE) and close to the Pará canyon mouth and the lack of significant sediment wedges on the transform sections. On the East sector, the Pernambuco contourite channel and the marginal plateaus are the most expressive features. On the South Margin, the smooth continental slope, the Rio Grande cone and the São Paulo plateau are the most important regional features. See the difference between the North sector, where canyon density is high, and the south margin, where they are absent. Also note the numerous valleys on the continental rise.

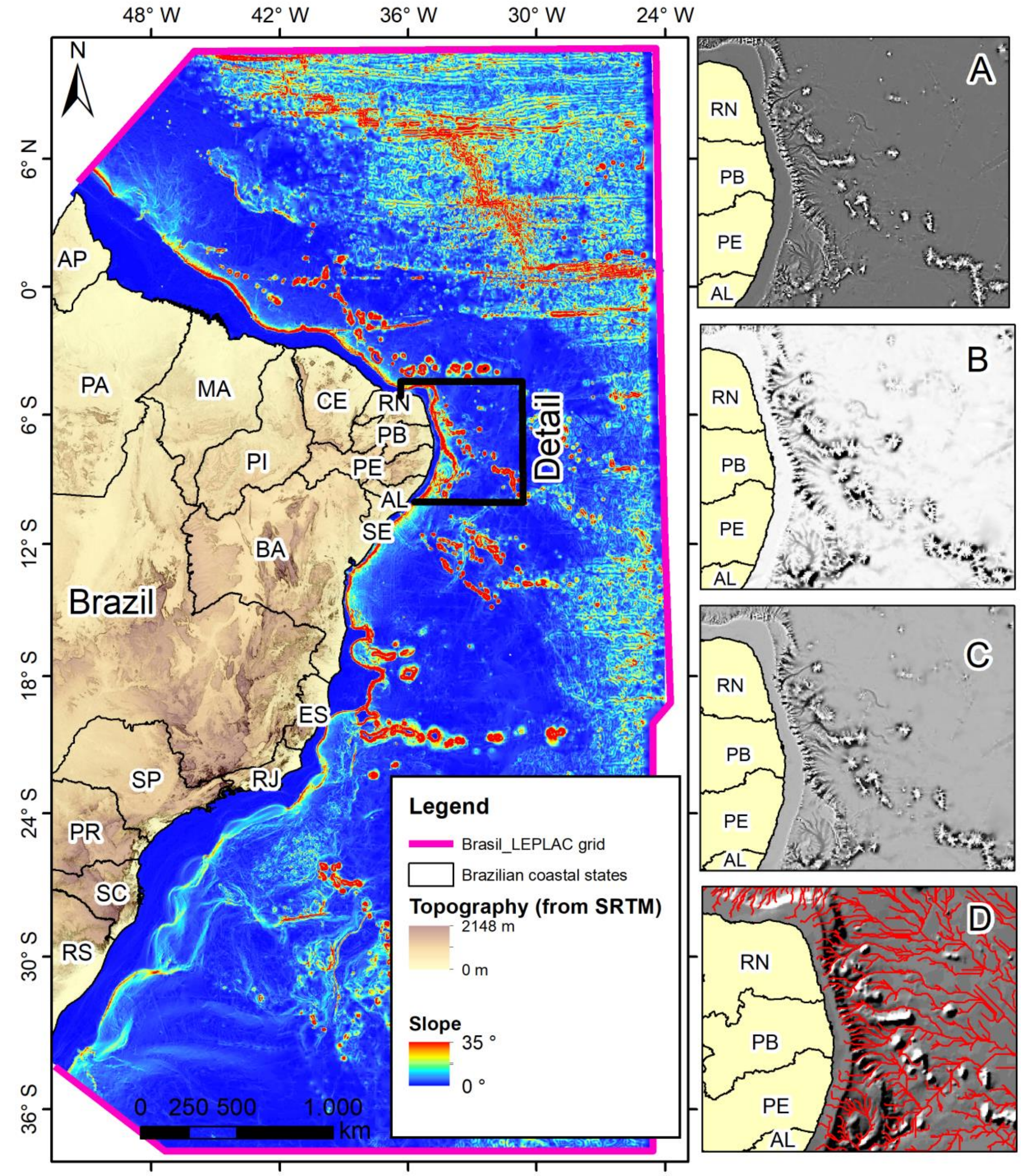

Fig. 3: Limits of the Brasil_LEPLAC bathymetric grid and its gradient variation. On the continent, the Brazilian coastal states are: AP- Amapá, PA – Pará, MA-Maranhão, PI-Piauí, CE- Ceará, RN- Rio Grande do Norte, PB-Paraíba, PE – Pernambuco, AL- Alagoas, SE –Sergipe, BA – Bahia, Es – Espírito Santo, RJ – Rio de Janeiro, SP – São Paulo, PR – Paraná, SC – Santa Catarina and RS – Rio Grande do Sul. The detail shows a region where canyons are best viewed on low resolution grids. (A) Plan curvature grid (white colors represent convex features). (B) Valley depth grid. (C) Combined Valley depth and Plan curvature Grids. (D) Automatic extracted drainage on Brasil_LEPLAC grid.

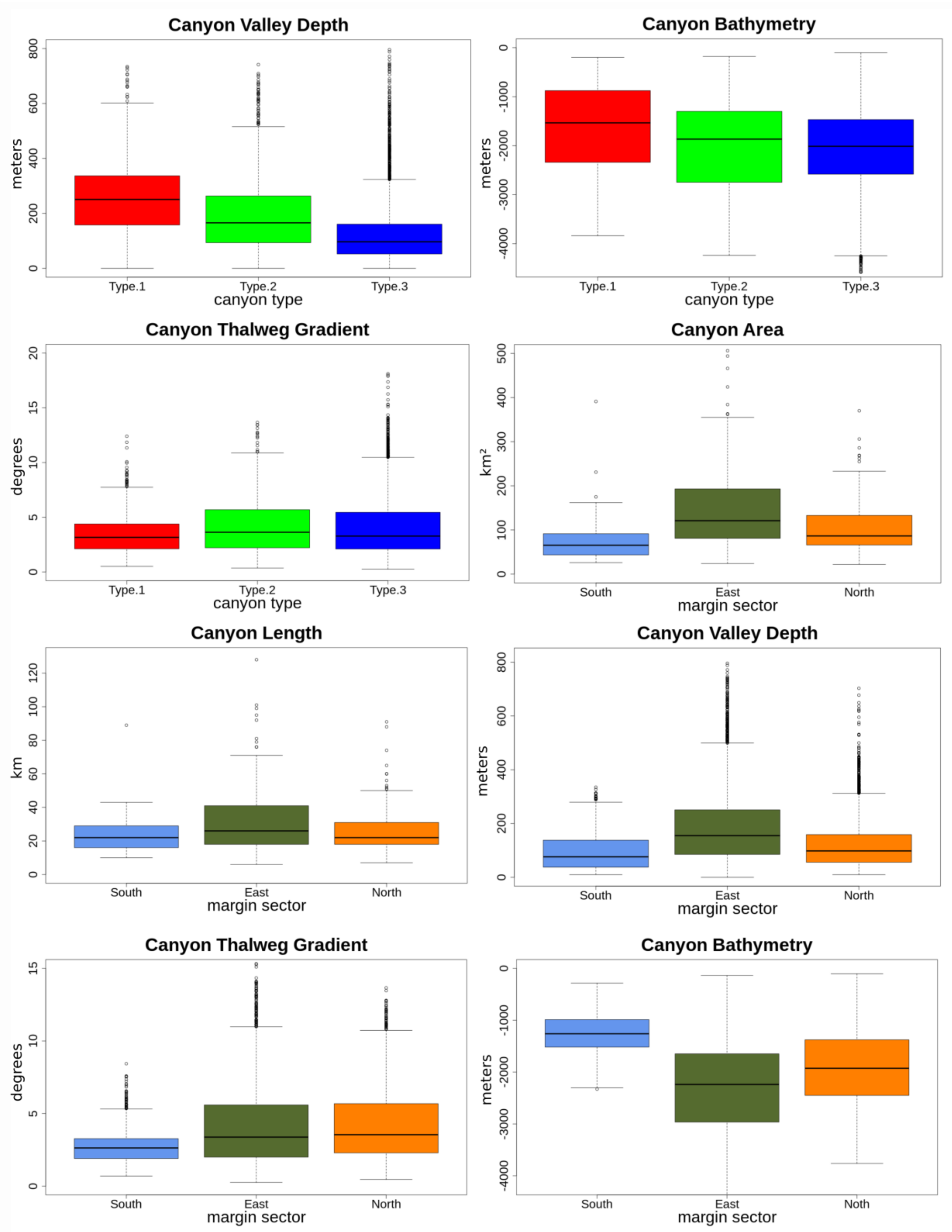

Fig. 4: Box plots of the morpholmetric parameters measured for canyons. (A) Canyon valley depth – Depth difference between the canyon margin and canyon thalweg by canyon type. (B) Canyon Bathymetry - Depth of the canyon thalweg related to the sea surface by canyon type. (C) Canyon thalweg gradient – Gradient on the canyon thalweg by canyon type. (D) Canyon area – Area occupied by the canyon from head to mouth by margin sector. (E) Canyon Length – mean length of the canyons by margin sector. (F) Canyon valley depth by margin sector. (G) Canyon thalweg gradient by margin sector. (H) Canyon bathymetry by margin sector.

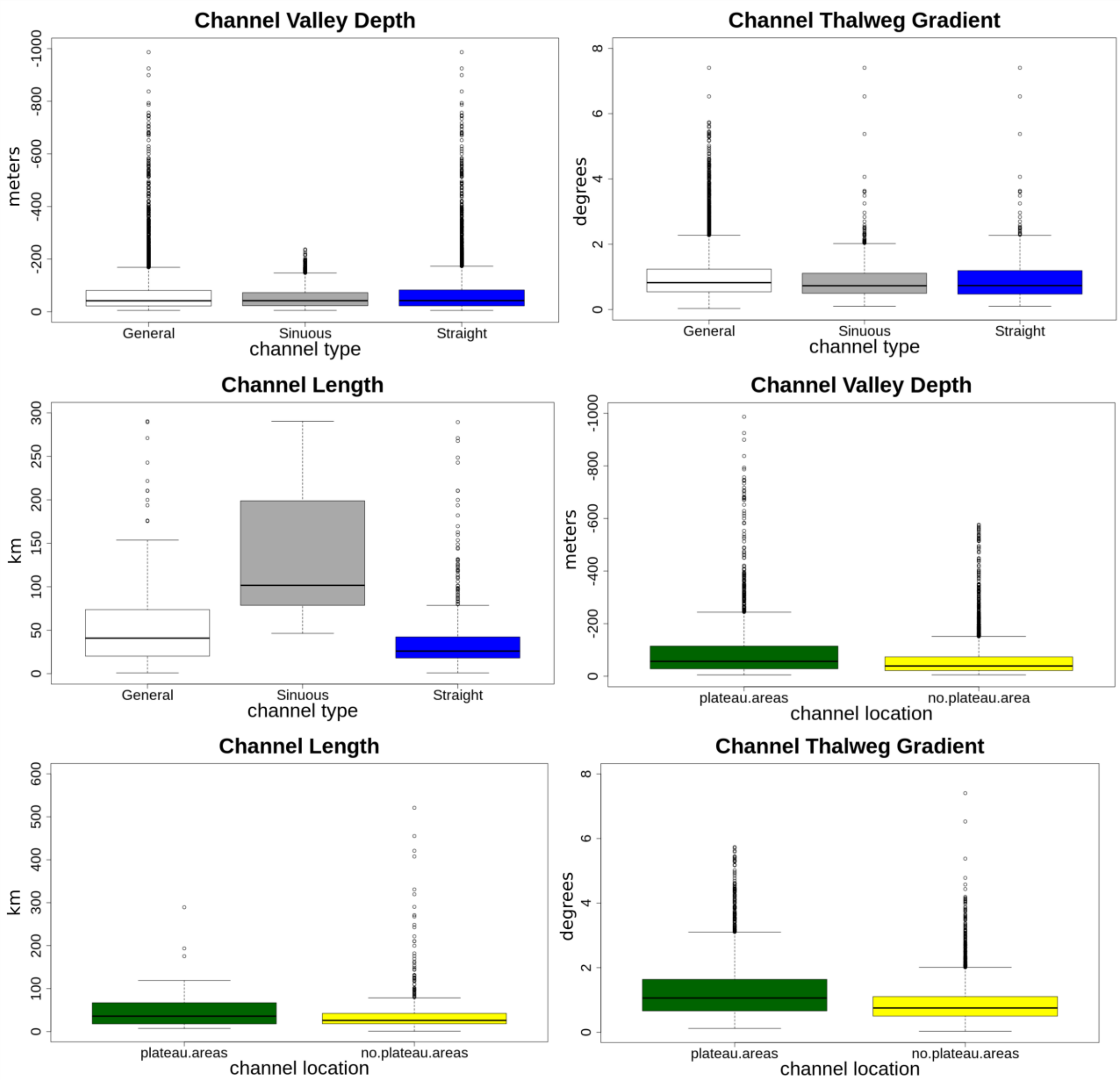

Fig. 5: Box plots of the morphological parameters measured for channels. (A) Channel valley depth – depth difference between the channel margin and channel thalweg by channel type. (B) Channel thalweg gradient – Gradient on the channel thalweg by channel type. (C) Channel length - mean length of the channels by channel type. (D) Channel valley depth on plateau and no plateau areas. (E) Channel length on plateau and no plateau areas. (F) Channel thalweg gradient on plateau and no plateau areas.

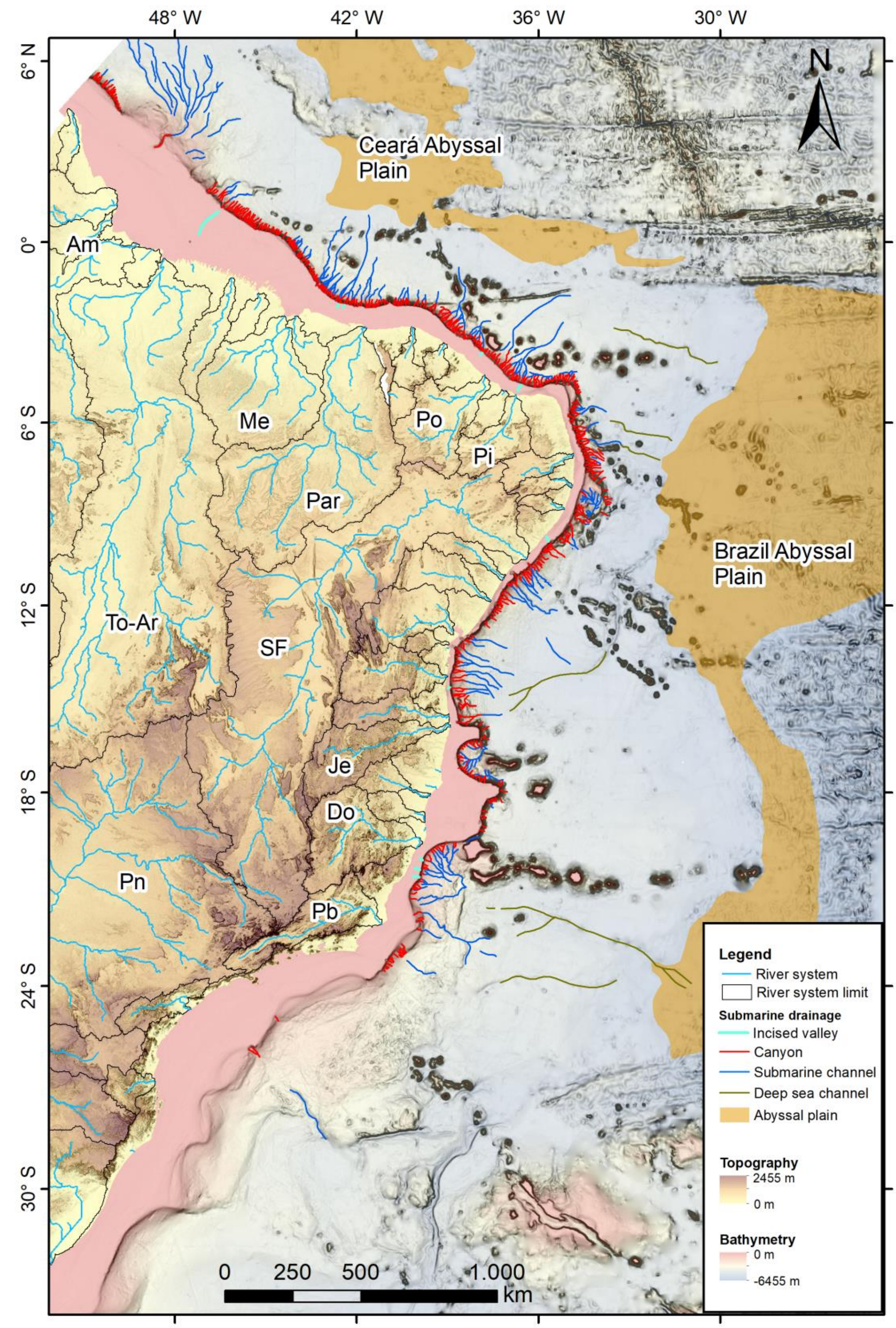

Fig. 6: Mapped submarine drainage on the Brazilian continental margin and their classification by type. On the continent the main river basins are: Am – Amazon, Me – Mearim, Par – Parnaíba, Po- Potengí, Pi – Piranhas, To-Ar – Tocantins-Araguaia, SF – São Francisco, Je – Jequitinhonha, Do – Doce, Pn – Paraná and Pb – Paraíba do Sul.

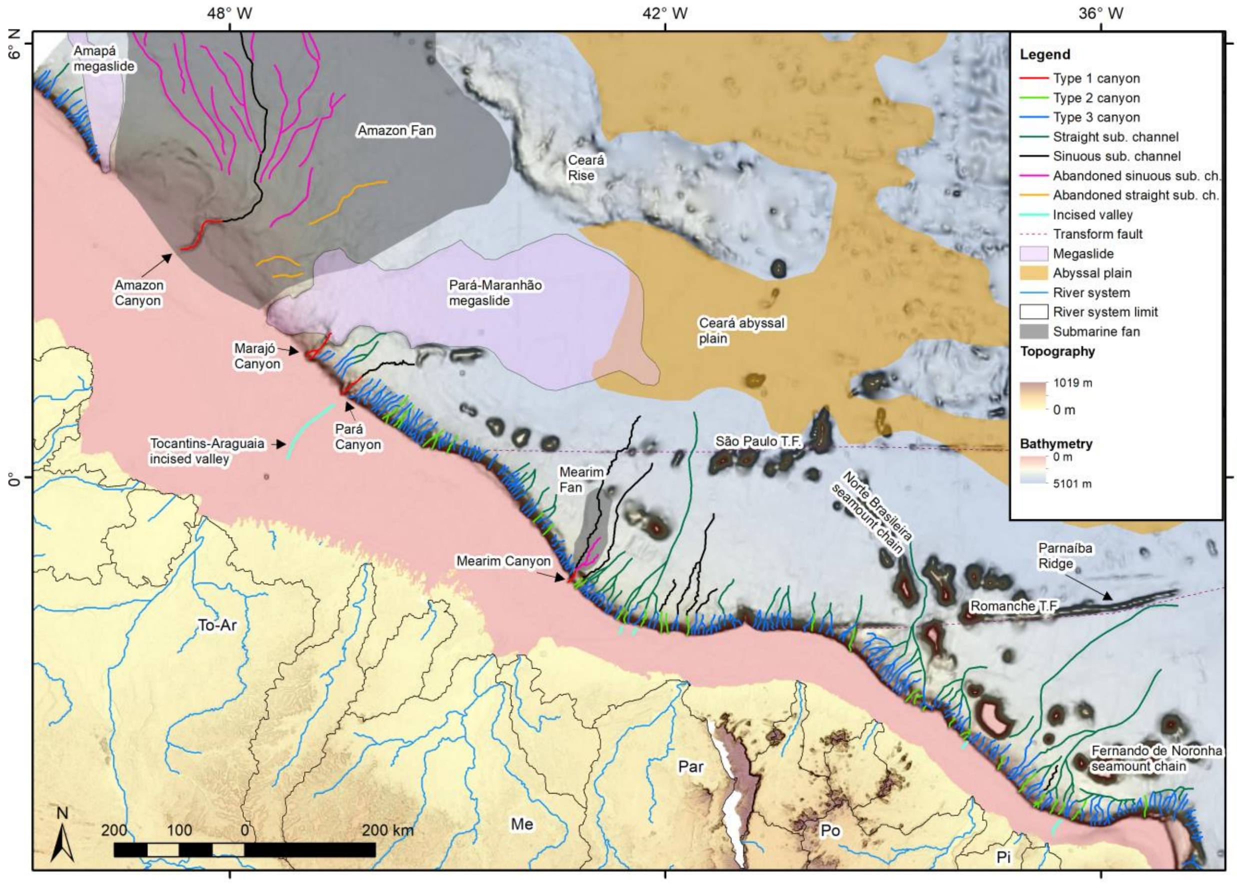

Fig. 7: Distribution of the main morphological features on the North margin sector and their relationship to the mapped submarine drainage systems. Channels on the transform section (E-W segments) of the margin are shorter than in other areas.

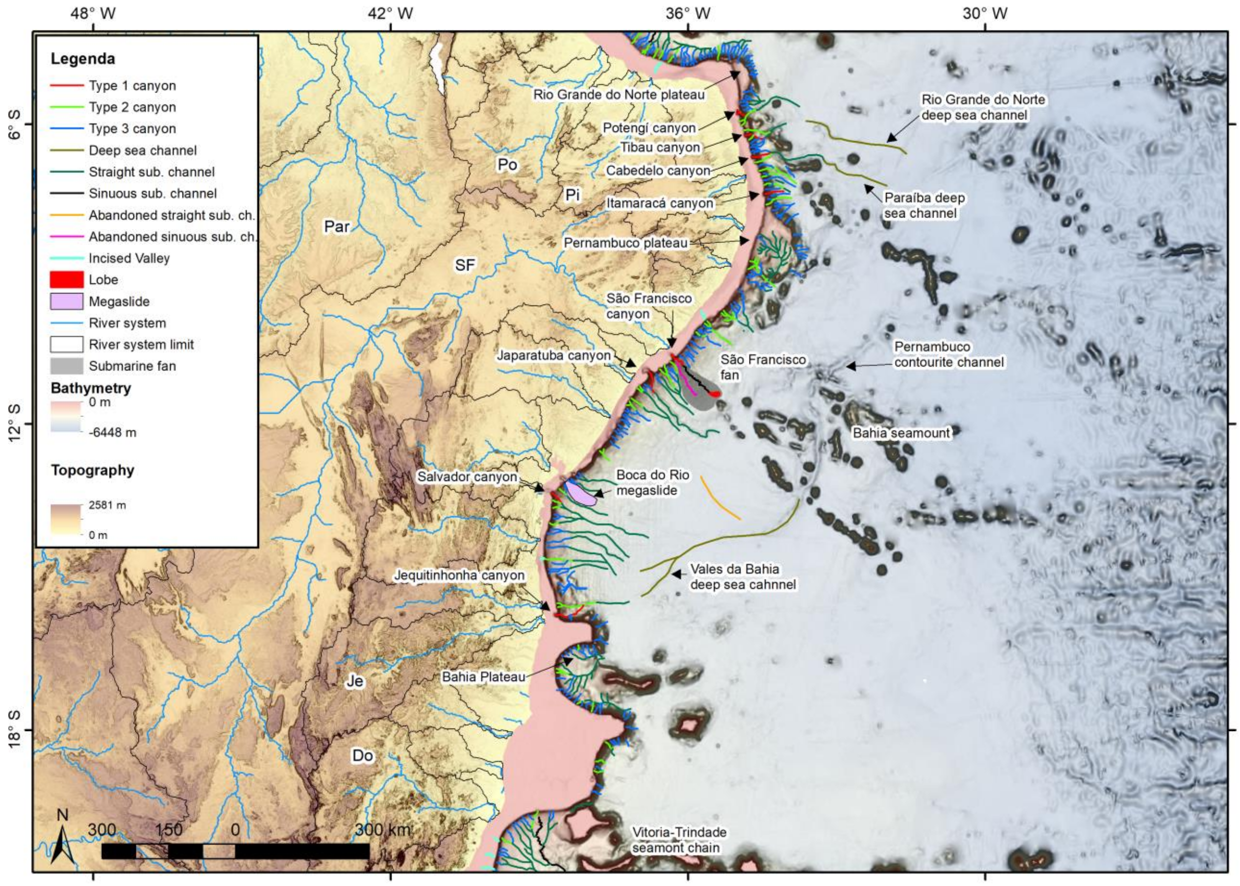

Fig. 8: Distribution of the main morphological features on the East margin sector and their relationship to the mapped submarine drainage systems. Type 1 canyons and medium size river systems on the continent predominate in this sector.

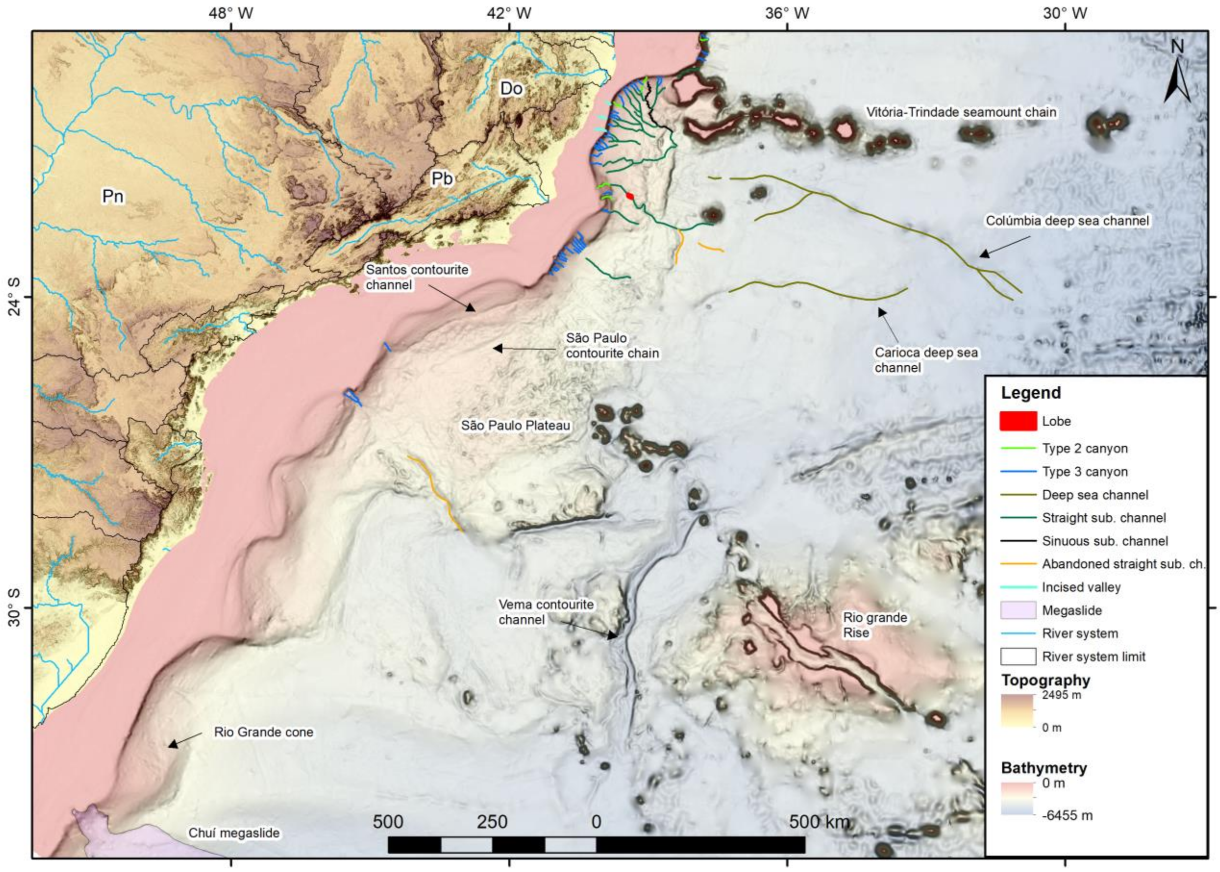

Fig. 9: Distribution of the main morphological features on the South margin sector and their relationship to the mapped submarine drainage systems. Large sections of slope in this sector are devoid of canyons.

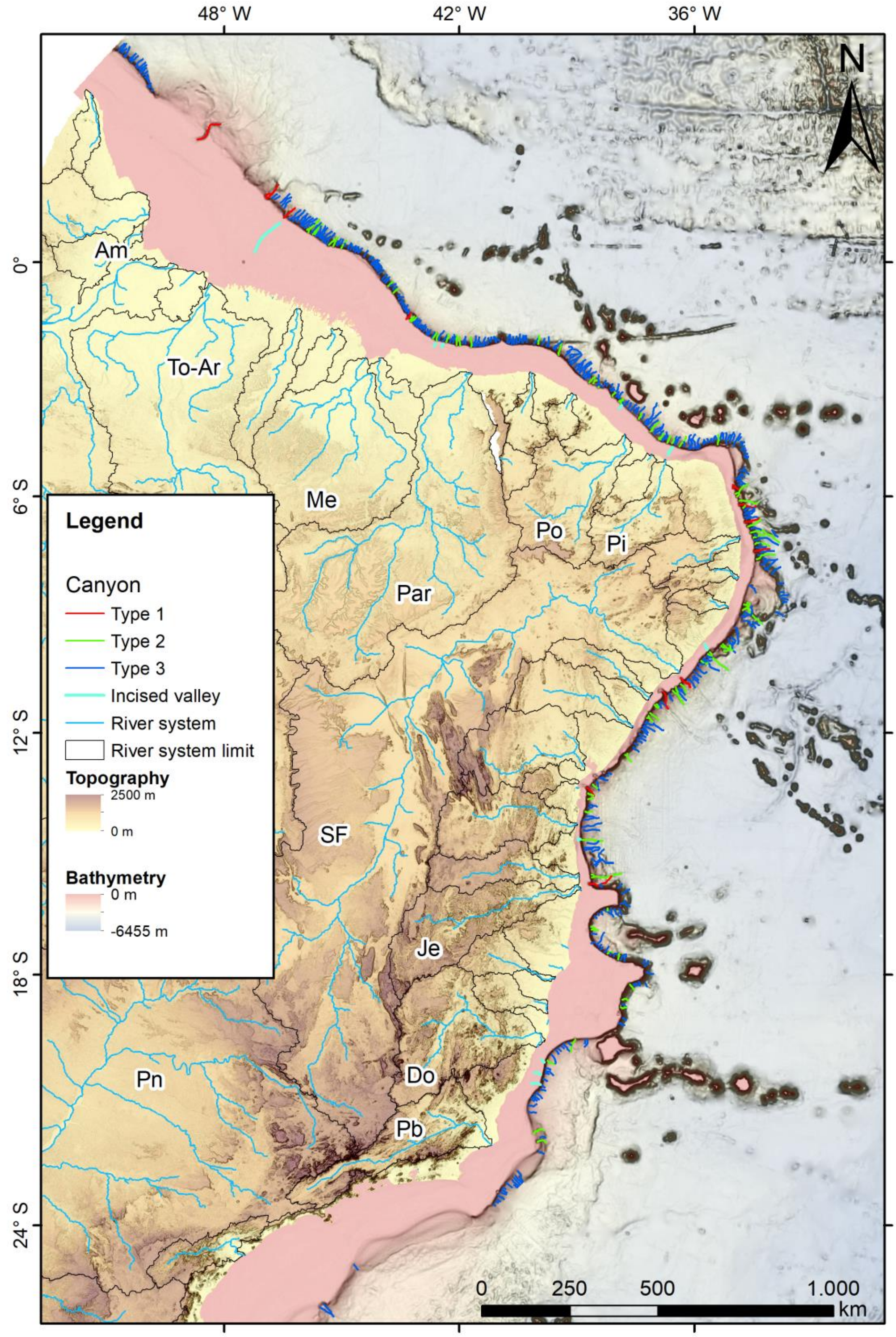

Fig. 10: Classification and distribution of the submarine canyons on the continental slope.

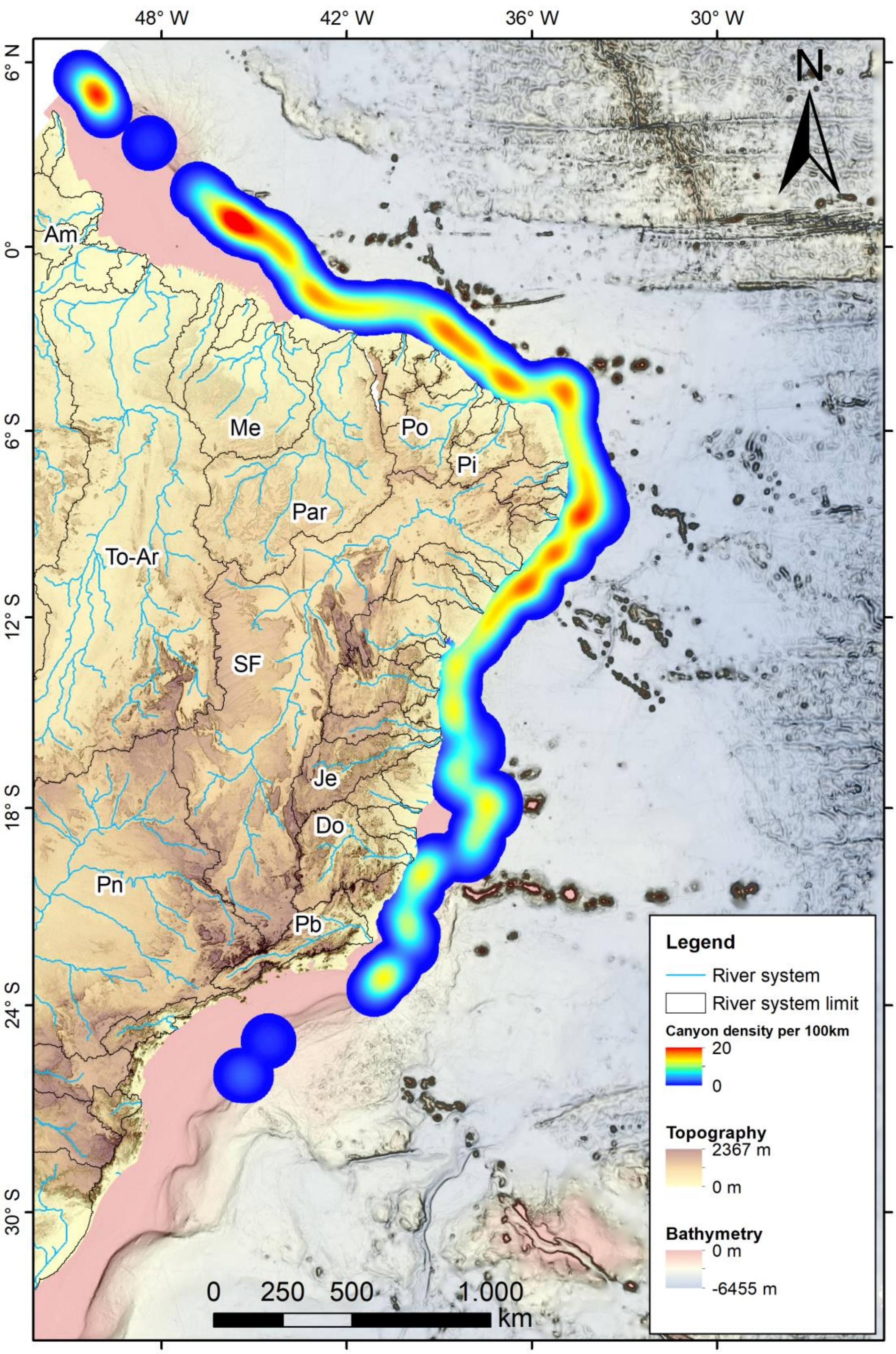

Fig. 11: Variation in canyon density along the Brazilian slope. Canyons are more closely spaced on the North margin and absent on the South.

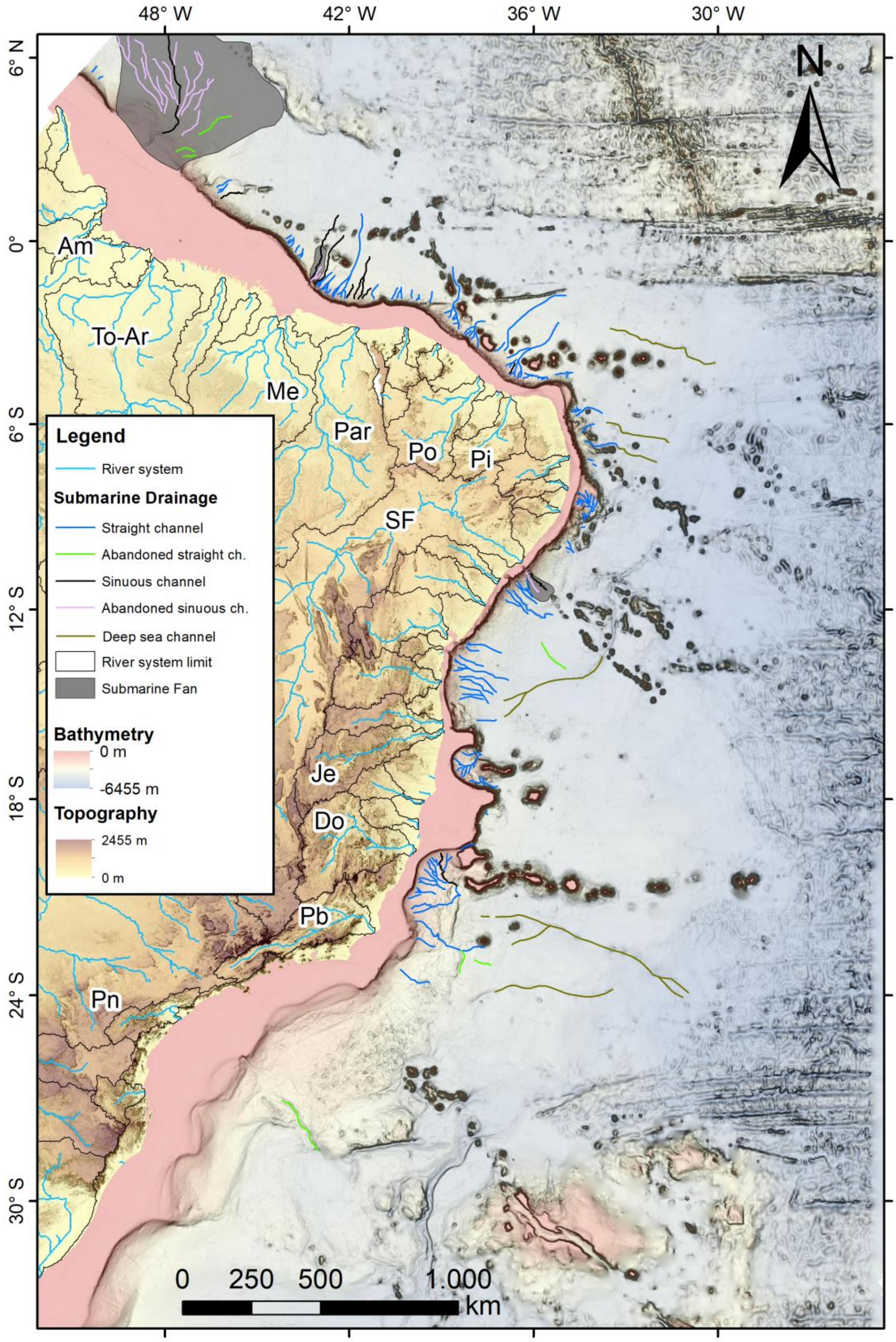

Fig.12: Channel classification and distribution along the Brazilian margin. On the North margin, continental rise sections with long channels are separated by sections with shorter channels. On the East margin, channels are longer between the São Francisco (SF) and Jequitinhonha (Je) river systems. On the South margin, the longest channels are located between the Doce (Do) and Paraiba do Sul (Pb) river systems.

Fig. 13: Location of the mapped deep-sea channels on the Brazilian margin. Two deep-sea channels are considered abandoned: Carioca and EAMOC.

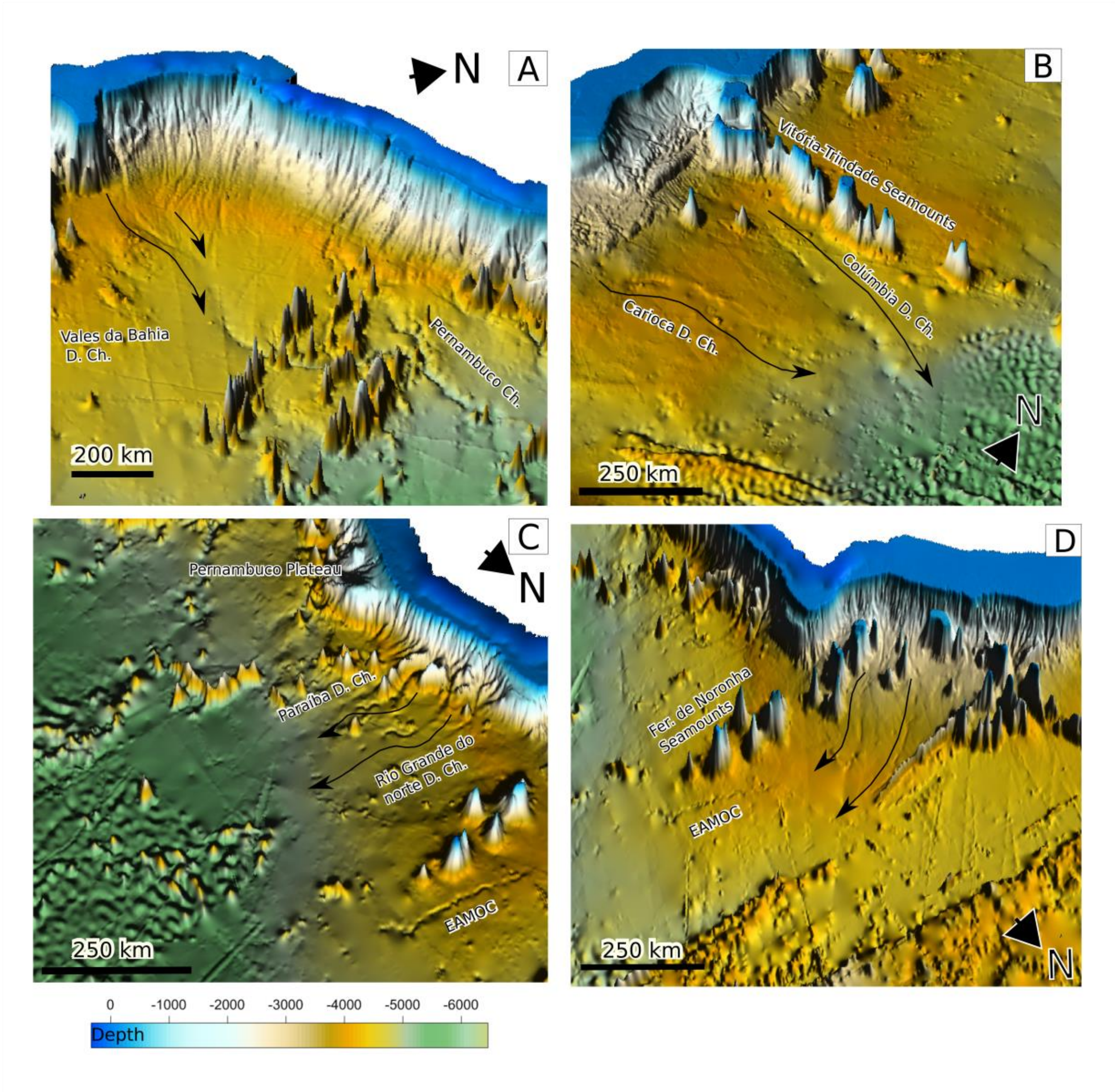

Fig. 14: Three-dimensional view (5x vertical exaggeration) of the deep-sea channels and the associated up-dip network. (A) Vales da Bahia. (B) Colúmbia and Carioca. (C) Paraíba and Rio Grande do Norte. (D) EAMOC.

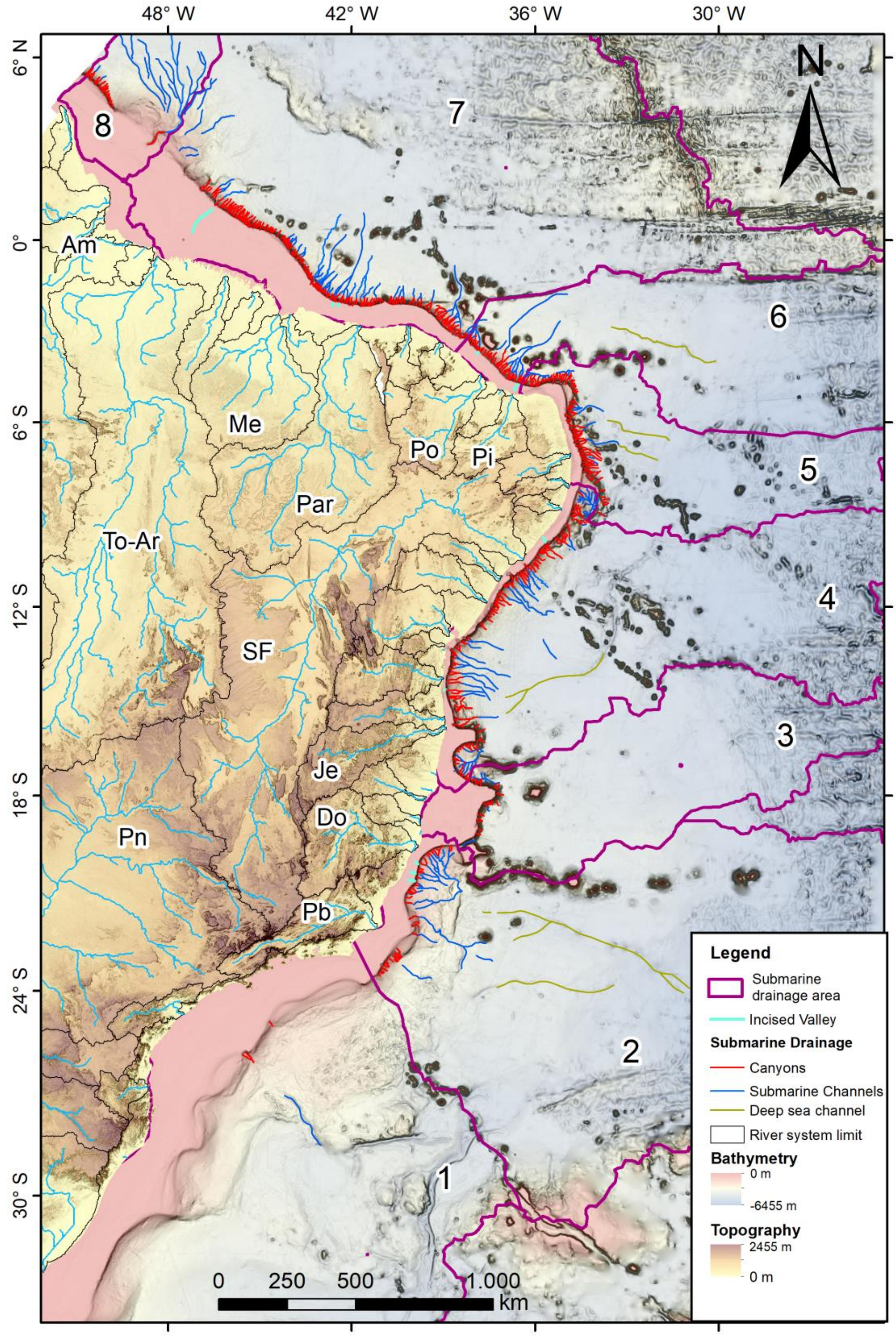

Fig. 15: Drainage areas numbered from 1 to 8 along the Brazilian margin. These areas separate large source-to-sink systems along the margin.

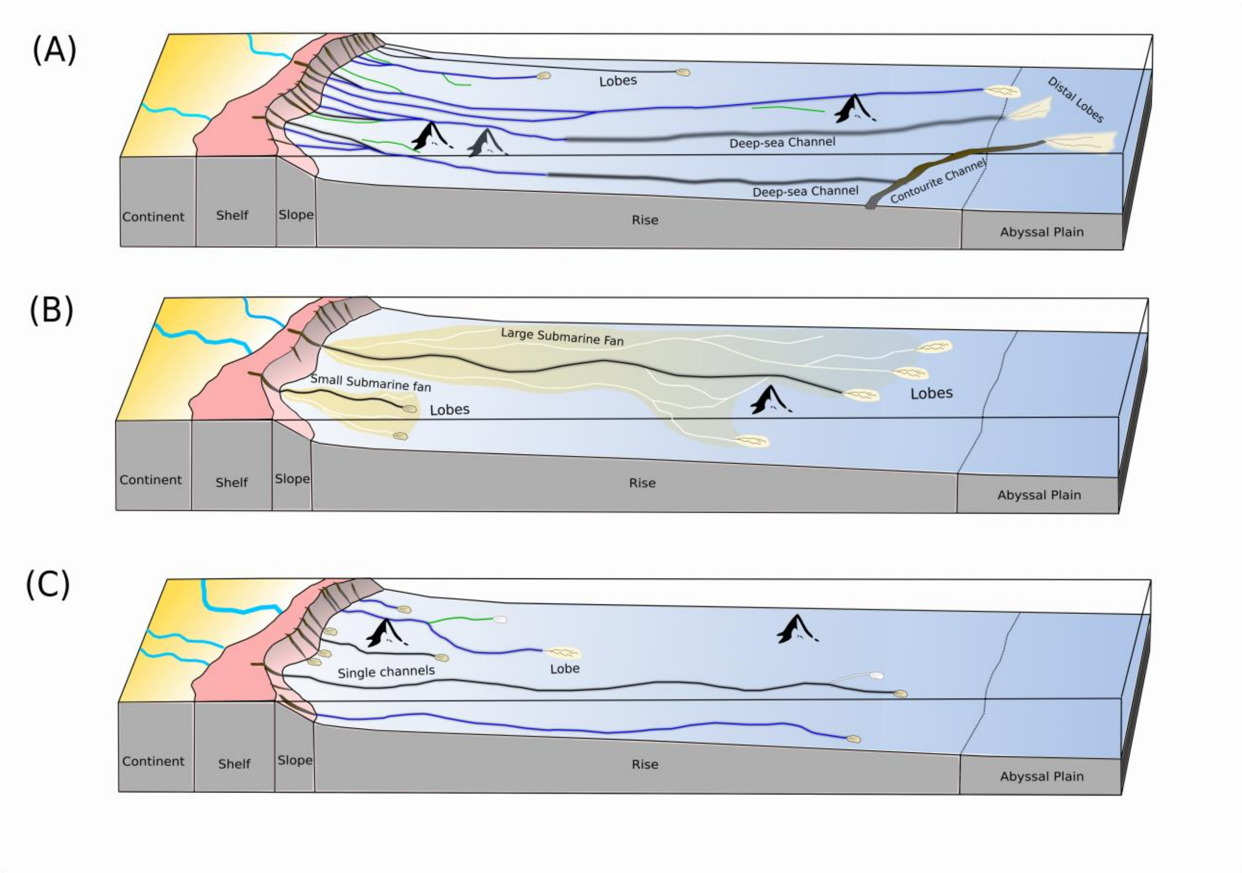

Fig. 16: Drainage organization patterns on the Brazilian margin. Blue channels represent straight channels, black represent sinuous channels, light grey abandoned sinuous channels and green abandoned straight channels. (A) Convergent network pattern. (B) Divergent networks pattern. (C) Single and no channel pattern.

Table 1: Characteristics of submarine canyons on the Brazilian margin. Mean depth (m) – mean depth difference between the canyon margin and canyon thalweg. Max. Depth (m) – maximum difference between the canyon margin and canyon thalweg. Total area (km²) – comulative area of canyons. Mean area (km²) – mean individual canyon area. Length (km) – canyon planform extension. Thalweg slope (º) – gradient of the thalweg of the canyon.

Canyons	**Mean depth (m)**	**Max. depth (m)**	**Total area (km²)**	**Mean area (km²)**	**Length (km)**	**Thalweg slope (°)**
All canyons	142	872	42210	121	28	4,01
North Margin sector canyons	115	651	19917	108	26	4,1
East Margin sector canyons	182	872	18979	151	32	4,1
South Margin sector canyons	91	329	3314	82	24	2,7
Canyons on plateau areas	118	459	5506	96	23	3,2
Canyons on no plateau areas	145	872	36704	126	28	4,1
Type 1 canyons	266	572	3124	260	48	3,4
Type 2 canyons	191	651	9315	182	35	4,1
Type 3 canyons	121	872	30057	105	25	4
North Margin type 1 canyons	235	411	1519	379	52	2,4
East Margin type 1 canyons	275	575	1608	201	47	3,9
North Margin type 2 canyons	153	651	3470	133	30	4,3
East Margin type 2 canyons	220	872	6894	215	32	4,1
South Margin type 2 canyons	131	329	3314	82	22	2,7
North Margin type 3 canyons	104	507	14931	97	25	4,1
East Margin type 3 canyons	155	754	10477	123	28	4,1
South Margin type 3 canyons	84	293	2734	75	23	2,8

Table 2: Characteristics of submarine channels on the Brazilian margin. Mean depth (m) – mean depth difference between the channel margin and thalweg. Max. length (km) – channel planform extension. Thalweg slope (º) – gradient of the on the thalweg of the channel.

Channels	Mean Depth (m)	Length (m)	Thalweg slope (°)
All Channels	63	56	0,9
North Margin sector	36	51	0,7
East Margin sector	95	54	1,29
South Margin sector	66	72	0,8
Channels on plateau areas	90	43	1,2
Channel on no plateau areas	54	44	0,8
Sinuous channels	48	132	0,9

Table 3: Characteristics of the Type 1 canyon heads. The highlighted canyons are those considered to be linked to an important fluvial source.

Canyon	Area (km²)	Distance to the coastline (km)	Aspect Ratio	Proximity to large river	Channel type at the mouth
Amazon	243	189	1,6	yes	sinuous
Japaratuba	227	17	2,5	no	straight
Salvador	171	10	1,8	no	straight
São Francisco	127	8	1,95	yes	sinuous
Potengí	114	17	0,33	yes	straight
Jequitinhonha	93	18	1,5	yes	straight
Cabedelo	84	33	0,5	yes	straight
Itamaracá	81	18	0,45	no	straight
Mearim	53	95	1,5	yes	sinuous
Marajó	50	242	0,3	no	straight
Tibau	37	23	0,2	no	straight
Pará	31	206	1,1	yes	sinuous