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Research paper

Morphology of submarine canyons along the continental margin of the Potiguar Basin, NE Brazil

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ABSTRACT

New insights into equatorial slope morphology were acquired through analysis of the continental margin of the Potiguar Basin (NE Brazil). In this paper, we present the first full data coverage of the seafloor between the upper and middle continental slopes (100–1300 m) adjacent to the Brazilian equatorial margin, developed using multibeam bathymetric data. Some of the submarine canyons mapped in this study have wall gradients greater than 35°. Wide (~1700 km) and deep (~250 m) incisions are present on the continental slope and can be linked to incised valleys that are underfilled or incised only on the outer shelf at depths up to 60 m. Two different types of canyons were identified. Canyons of one type are characterized by heads that indent the shelf edge, association with incised valleys and large fluvial systems, high sinuosity, 'V' shapes, and terraces along margins, in addition to erosive features such as landslides and gullies. These characteristics suggest that canyons of this type are associated with the deposition of submarine fan systems, which are considered permeable hydrocarbon reservoirs, on the base of the continental slope. The presence of gullies and sediment waves illustrates the role of bottom currents in the shaping of the slope. The enlargement of the canyons in the study area and the changes in their courses where they cross an important fault suggest that tectonic activity has probably also influenced the morphology of the deep-water environments of the Potiguar Basin. The results of this study constitute initial steps in describing and understanding submarine canyons as part of the equatorial continental Brazilian margin.

1. Introduction

Submarine canyons, which are significant morphological features on the continental slope (Pratson et al., 2007), incise most of the edges of the world's continental margins (Shepard, 1972; Shepard and Dill, 1966) and commonly reflect the structural control on the active margins (Carlson and Karl, 1988; Mountjoy et al., 2009). Furthermore, investigations of submarine canyon geomorphology may support the installation of cables and pipelines, as well as naval submarine operations (Piper, 2005; Piper et al., 1999).

Submarine canyons are important conduits able to transport large amounts of sediment from the continental shelf to the abyssal plain via gravity flows (Gardner, 1989; Shepard and Dill, 1966). Submarine fans, which are fan-shaped or lobate deposits located in front of submarine canyons or channels, have been studied in detail as analogues for ancient deposits of economic significance (Clark et al., 1992; Walker, 1992; Weimer and Slatt, 2004). According to Normark (1970) and Shepard (1972), submarine fans are considered to be formed primarily by turbidity currents that originate from a point source, forming turbidites that are the main reservoirs of the giant oil fields of the world (Bouma et al., 1985; Weimer and Link, 1991; Weimer and Slatt, 2004). The general characteristics of the depositional lobes of submarine fans include the following: (1) they are considered to develop at or near the mouths of submarine-fan channels analogous to distributary mouth bars in deltaic systems; (2) they do not exhibit basal channelling; (3) they usually display upward-thickening depositional cycles composed of classic turbidites; and (4) they exhibit sheetlike geometries (Mutti and Ricci Lucchi, 1978).

Some submarine canyons in the Brazilian Continental Margin have been studied previously. Prominent examples are the Amazon Canyon, the São Francisco Canyon, the Salvador Canyon, and the

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canyons of the Campos Basin (e.g., Dominguez et al., 2013; Martins and Coutinho, 1981; Viana and Rebesco, 2007). The Amazon Canyon formed as a result of mass failures that were modified by subsequent erosion due to turbidity currents (Damuth and Kumar, 1975). The associated fan provides examples of the large, sinuous, leveed valleys that are common on delta-fed submarine fans (Normark and Carlson, 2003). The submarine canyons in the Campos Basin have an average depth of 300 m and an average width of 8000 m (Kowsmann et al., 2002; Viana et al., 1998; Viana and Rebesco, 2007).

Despite the extensive shallow-water oil exploration that has been conducted in this area since the 1970s and the recent discovery of oil deposits in the deep waters of the Potiguar Basin (PETROBRAS, 2013), almost no data on the seabed morphology of deeper regions of this margin have been published. This type of data is essential to the characterisation of geohazards (e.g., Chiocci and Cattaneo, 2011). For example, submarine landslides, one of the most destructive types of geohazards, pose significant risks to pipelines and seabed installations. Deep-water pipelines are often laid on the seabed without pre-trenching or cover, which exposes them directly to debris flows (Yuan et al., 2012).

Therefore, it is important to have a good understanding of the seabed, including the geomorphology of submarine canyons, to avoid the installation of submarine structures at unstable locations, to optimise environmental management, and to determine the existence of deposits of economic importance, such as turbidites and contourites.

To address the lack of information on submarine canyons along the continental margin of the Potiguar Basin off the coast of northeastern Brazil, we performed a multibeam bathymetry sonar survey to map these seafloor features (Fig. 1). The selection of the area was related to the presence of two incised valley systems (Apodi-Mossoró and Açu) of the Potiguar Basin. They are called 'incised valleys' because the ancient Apodi-Mossoró River (Lima and Vital, 2006; Vital et al., 2010a) and Açu River (Gomes et al., 2015b; Schwarzer et al., 2006) cut the shelf deposits, forming valleys that are now represented by cut and fill features. These processes are indicative of an erosional surface during lowstand conditions. Gomes et al. (2014) suggest that these incised valley morphologies are directly associated with the geomorphic response to tectonic activity that occurred when faults reshaped the pre-Holocene coast and shelf domains.

In this paper, we provide the first detailed picture of the continental slope adjacent to the Potiguar Basin of northeastern Brazil by presenting the most complete and highest-resolution bathymetric dataset available for the region. The objectives of this study were the following: (1) to provide the first characterisation and analysis of the continental slope morphology of the Potiguar Basin (Fig. 1), focusing on the submarine canyons; and (2) to reconstruct the main shaping processes along the mapped canyons.

We analysed the morphometric characteristics of the submarine canyons and sedimentary features, and in this paper, we discuss the processes involved in their evolution, the controlling factors, and recent sedimentary activity. The results of this study contribute to the understanding of the transport pathways of sediments from the shelf to the deep basin and provide a morphological framework for detailed future research.

2. Geological setting

The South Atlantic opening occurred during the Early Cretaceous (Neocomian– Barremian), whereas the opening in the Equatorial Atlantic occurred later (Aptian–Albian) (Asmus and Porto, 1972; Szatmari et al., 1987). The separation of the Pangaea Supercontinent resulted in the formation of the Brazilian Cretaceous Rift System, forming passive continental margins and the Brazilian marginal basins (Matos, 1999, 2000).

The study area is located in the pull-apart Mesozoic–Cenozoic Potiguar Basin of the Brazilian Equatorial passive margin. The Potiguar Basin has three stages of evolution: rift (Neocamian–Eo–Aptian), post-rift (Neoaptian–Eo–Albian), and continental drift (Albian–Holocene) stages (Bertani et al., 1990). The rift, post-rift, and continental drift stages are characterised by continental, transitional, and marine megasequence deposits, respectively (Matos, 1992).

According to Matos (1992), the basin is controlled by basement faults. East–west-oriented strike–slip faults were reactivated as normal faults in a compressive regime, according to breakout and focal mechanism data that indicate the magnitude of the maximum horizontal E–W stress (Assumpção, 1992; Bezerra et al., 2007, 2011; Castro et al., 2012; Ferreira et al., 1998; Gomes et al., 2014; Reis et al., 2013). Bezerra et al. (1998) identified neotectonic events that affected the quaternary rocks.

With respect to the oceanographic setting, trade winds arise in the E–NE, attaining a maximum velocity of 18 m/s (Vital et al., 2010b). The semi-diurnal mesotidal regime dominates, with a maximum spring tide range of 3.3 m and a minimum range of 1.2 m during neap tides (Vital et al., 2010b). The North Brazilian Current flows in a direction relatively parallel to the coast (W–NW). The bottom currents, which reach velocities of 30–40 cm/s on the shelf, are overlain by tidal and wave components (Knoppers et al., 1999; Vital, 2009).

The submerged portion of the Potiguar Basin is composed of mixed carbonate–siliciclastic deposits (Gomes et al., 2015a; Vital et al., 2008), and the shelf physiography is partitioned as an inner, a middle, and an outer shelf (Gomes and Vital, 2010). Several morphological seafloor features have been identified, such as sediment waves, isolated shallow marine sandy bodies, patches of coral reefs, beachrocks, and incised valleys (Lima and Vital, 2006; Schwarzer et al., 2006; Testa and Bosence, 1998, 1999; Vital et al., 2008, 2010a).

The earliest evidence of the shelf submarine incisions associated with the Açu and Apodi-Mossoró Rivers were reported by Pessoa Neto (2003). These rivers were exposed on the continental shelf, acting as a source of the siliciclastic influx and its distribution in the shelf and slope. According to (Pessoa Neto, 2003), incisions were active on the shelf during the Miocene, as demonstrated by the occurrence of coastal clastic wedges on the seismic sections and the well samples.

Lima and Vital (2006) studied the evolution of the Apodi-Mossoró Valley during the Pleistocene–Holocene. During the Pleistocene, the continental shelf was exposed, and the valley was formed. This channel was partially buried during the sea level rise that occurred during the Holocene. These authors identified tectonic activities in the Apodi-Mossoró Valley, suggesting the uplift of this shelf portion.

The main river systems of study area are the Açu River and Apodi-Mossoró River. The Açu River is an intermittent river in natural conditions. However, the continuity of its flow is ensured by two built reservoirs. It is 405 km long and reaches a drainage area of almost 44,000 km^2 (AESA, 2011; CBHPA, 2011). Its flow discharge and velocity reach 434 m^3/s and 0.6 m/s, respectively (Soares, 2012). The Apodi-Mossoró River is the second most important river in the study area. It is 220 km long, ~80 km wide, and reaches a drainage area of 14,270 km^2 (Maia and Bezerra, 2013). The climate of the area varies from tropical dry to semi-arid (Vital et al., 2010b).

3. Dataset and methods

High-resolution bathymetry data were collected along the study

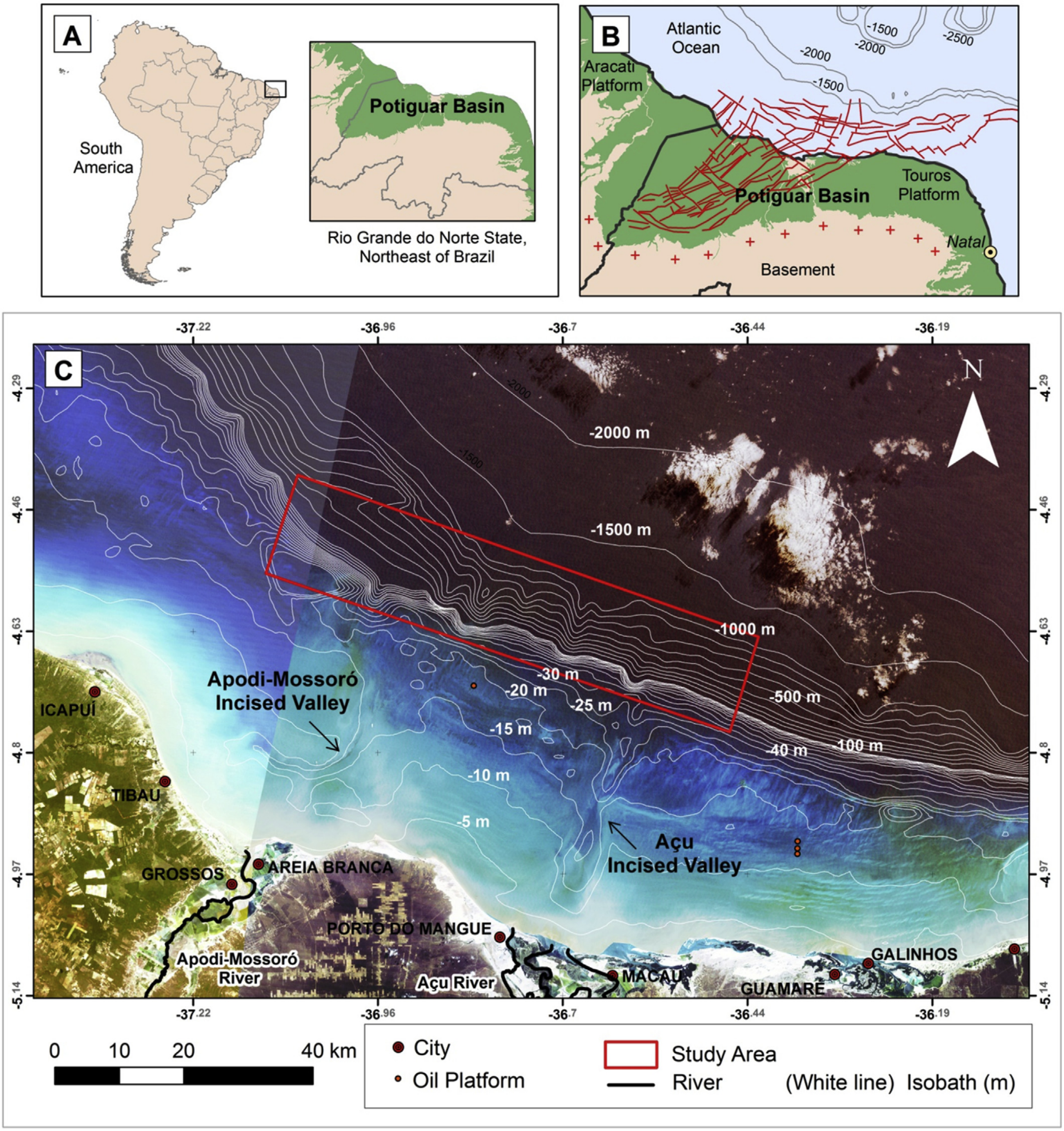

Fig. 1. A) Location of the study area. B) Structural map with tectonics lineaments in red. C) Multibeam bathymetry of the Potiguar Basin, northeastern Brazil. Contours of water depths up to 60 m are shown at 5-m intervals. For water depths from 70 to 100 m, contours are shown at 10-m intervals; for water depths from 100 to 1000 m, contours are shown at 100-m intervals; and at water depths greater than 1000 m, contours are shown at 500-m intervals. The study area is adjacent to the two main incised valley systems of the region: Apodi-Mossoró and Açu. The compilation of Landsat and bathymetry data is from Gomes and Vital (2010). The Potiguar Basin map is based on the work of Bertani et al. (1990). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area in May 2011 with a Kongsberg model Simrad EM 302 multibeam echosounder, using the Brazilian Navy Hydrographic Ship Sirius (NH21) (Fig. 2A). This multibeam echosounder uses a frequency of 30 kHz and has a depth range of 10–7000 m. The swath angle was 150°. The spacing between the survey lines was calculated by considering the swath range to be equal to 3.5 times the water depth.

The Seafloor Information System (SIS) survey software was used for automatic acquisition of the bathymetric data on the WGS-84 datum (Fig. 2C). A Seatex Seapath 200 motion sensor provided the roll, pitch, yaw, and heading information. The angle ranges were ±10° for yaw, ± 10° for pitch, and 15° for roll. The sound

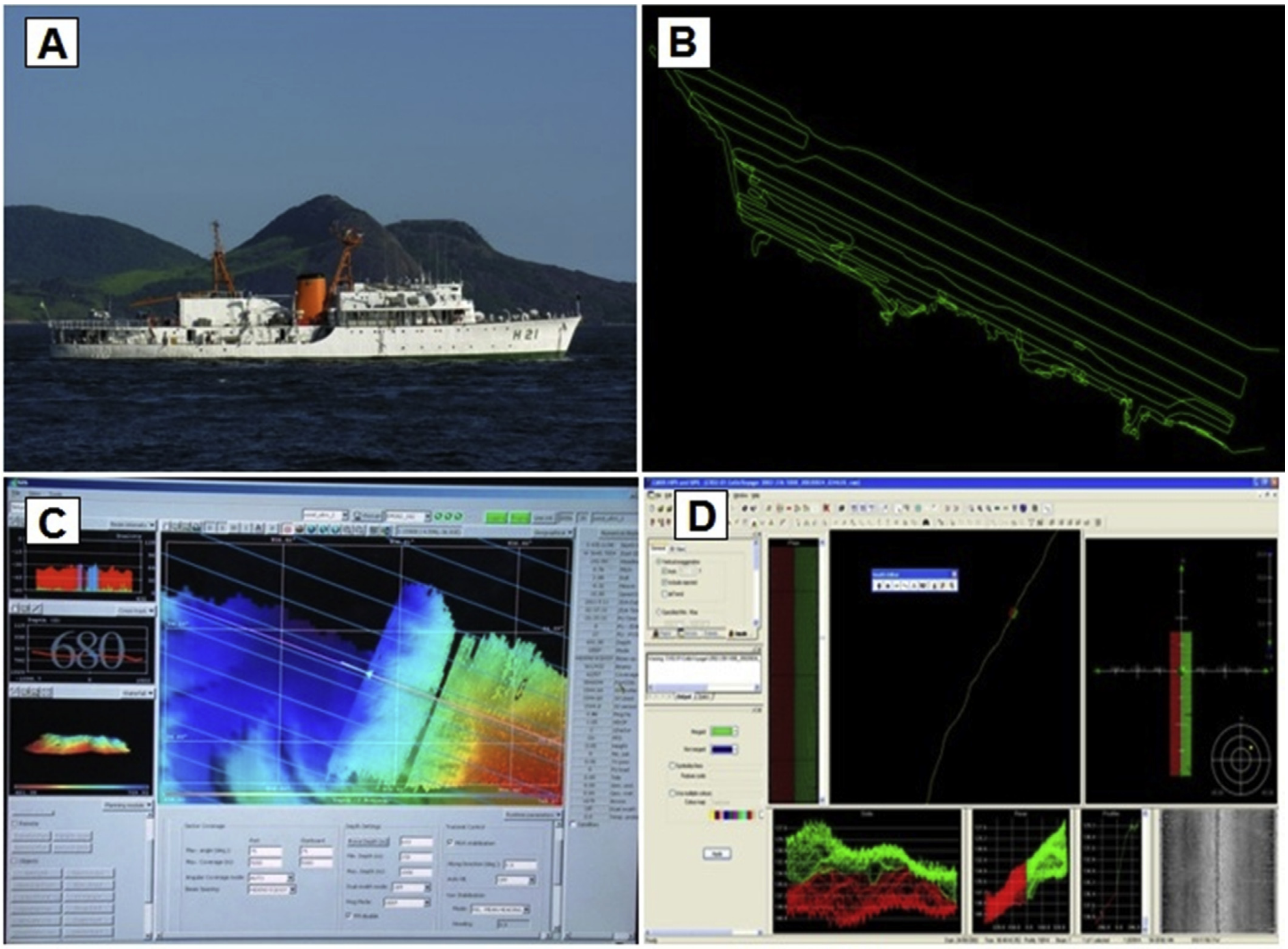

Fig. 2. A) Hydroceanographic Vessel Sirius (NH21) from the Brazilian Navy used for data acquisition. B) Acquisition lines of the bathymetric data. C) SIS software used for automatic acquisition of the bathymetric data. D) Example of multibeam echosounder data processed using Caris HIPS (INFOMAR, 2013).

velocity profiles within the water column were performed by launching an expendable bathythermograph (XBT). The SIS software was used to perform real-time correction of the data. The geographic position was determined using a differential global positioning system (DGPS).

The multibeam data were processed using the Caris HIPS & SIPS software (Fig. 2D). The Combined Uncertainty and Bathymetry Estimator (CUBE) automatic processing method was used with a 50-m-resolution grid. This method uses multiple hypotheses to represent the potential depth variances along the seafloor. Where the statistical method presented 'doubt' with respect to hypothesis acceptance, the information considered to be noise was rejected. The bathymetric models were edited using the Base Editor extension of the CARIS software. The measurements and calculations of the morphometric characteristics of the submarine canyons (e.g., their lengths, widths, depth ranges, slopes, and spacing) were based on the definitions given by Harris and Whiteway (2011).

Single-beam data for the shallow shelf available from previous research (Gomes and Vital, 2010) served as a general bathymetric base for the study area. The data were collected using an Odom Hydrographic Systems HYDROTRAC echosounder, operating at a frequency of 200 kHz. The dataset consists of N–S bathymetric profiles spaced at 1-km intervals perpendicular to the coast.

4. Results

4.1. Continental slope

The continental slope in the study area is approximately 10 km wide. It is characterised by a steep (7° on average) and complex morphology incised by canyons and gullies (Fig. 3). The slope consists of an upper slope (from the shelf break at 70 m to a 300-m depth) and a middle slope (300–1300 m). The upper and middle slopes differ in their gradients (6–16° with a mean of 15° for the former and 4–10° with a mean of 6° for the latter), with the upper slope being steeper overall than the middle slope (Figs. 4 and 5).

The depth profiles across the continental slope present different curvatures. The profiles 3–3′, 6–6′, 7–7′, and 8–8′ have convex shapes (Fig. 5). The profiles 4–4′ and 5–5′ have concave shapes.

4.2. Submarine Canyons

Some submarine canyons of varying morphology and size incise the shelf edge and continental slope of the study area (Fig. 3). These canyons were grouped (A, B, C, and D) on the basis of their locations and morphologies (Fig. 3).

The 'A canyons' (Areia Branca Canyon, Grossos Canyon, Mossoró Canyon, and Apodi Canyon) are located adjacent to the Apodi-

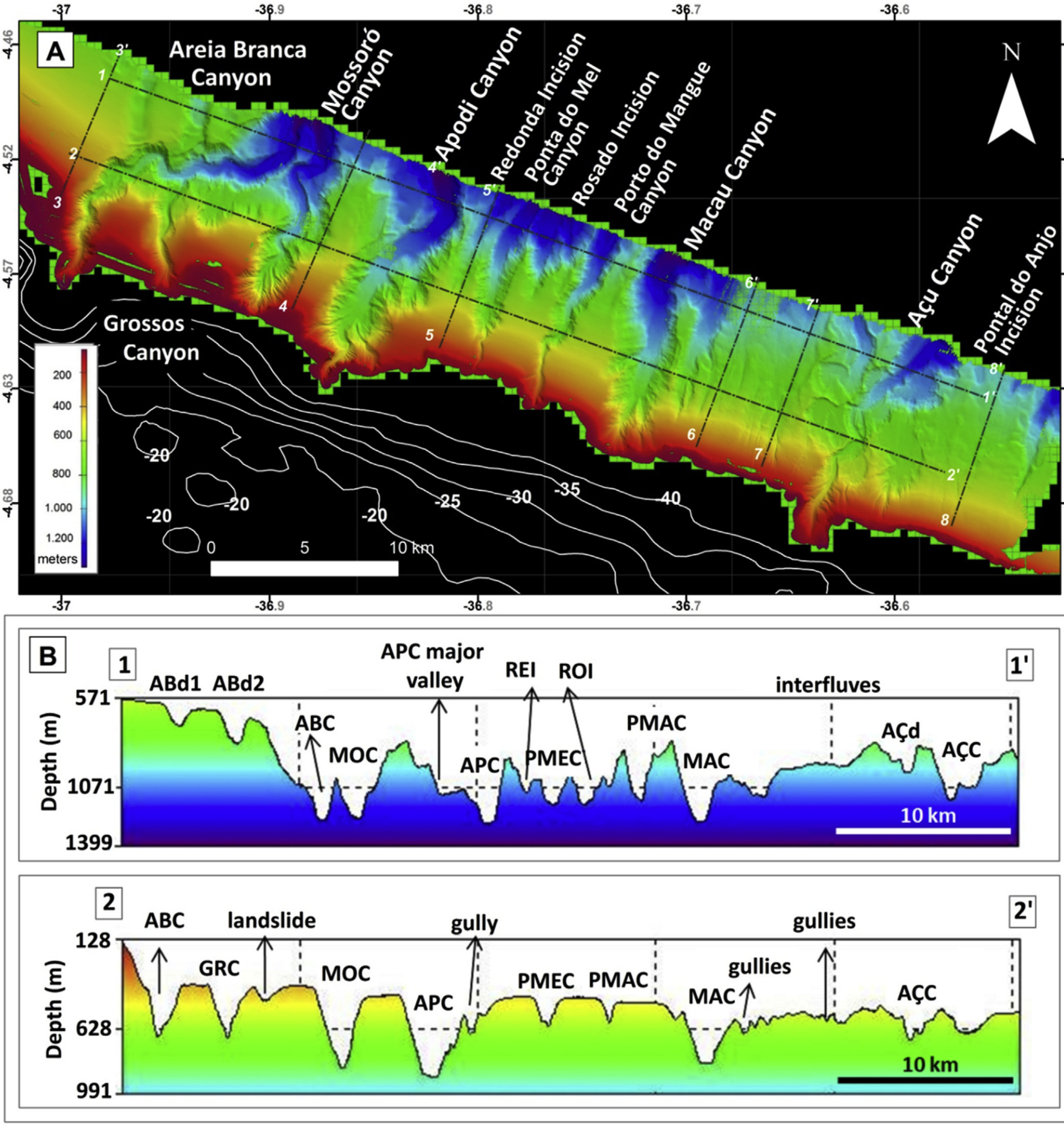

Fig. 3. A) Morphobathymetric map of submarine canyons on the continental slope of the study area. The canyons are essentially oriented perpendicular to the shelf edge, although changes in the orientation are observed in the Areia Branca Canyon. The numbers in italics indicate the ends of the profiles. Regarding the contour lines of the continental shelf, see Gomes and Vital (2010). B) Longitudinal depth profiles to the margin: 1–1′ and 2–2′ (ABd 1 and ABd2 = distributaries of Areia Branca Canyon; ABC = Areia Branca Canyon; GRC = Grossos Canyon; MOC = Mossoró Canyon; APC = Apodi Canyon; REI = Redonda Incision; PMEC = Ponta do Mel Canyon; ROI = Rosado Incision; PMAC = Porto do Mangue Canyon; MAC = Macau Canyon; AÇC = Açu Canyon; AÇd = Açu distributary).

Mossoró-incised valley. In this paper, we use the term 'incised valley' to refer to an eroded fluvial valley on a continental shelf and its depositional fill (Gomes et al., 2014; Nordjord et al., 2006; Payenberg et al., 2006; Zaitlin et al., 1994). Incised valleys can be connected to submarine canyons on a continental slope.

The 'B canyons' (Ponta do Mel and Porto do Mangue Canyons) have narrow heads and valleys on the upper slope and become wider on the middle slope. The 'C canyon' (Macau Canyon) has a wide head on the upper slope and a wide valley on the middle slope. The 'D canyon' (Açu Canyon) is located adjacent to the Açu-incised valley (Fig. 3).

Each canyon consists of three different segments: 1) an upper canyon, which consists of the canyon head and is commonly the area with higher gradients; 2) the middle canyon, where the

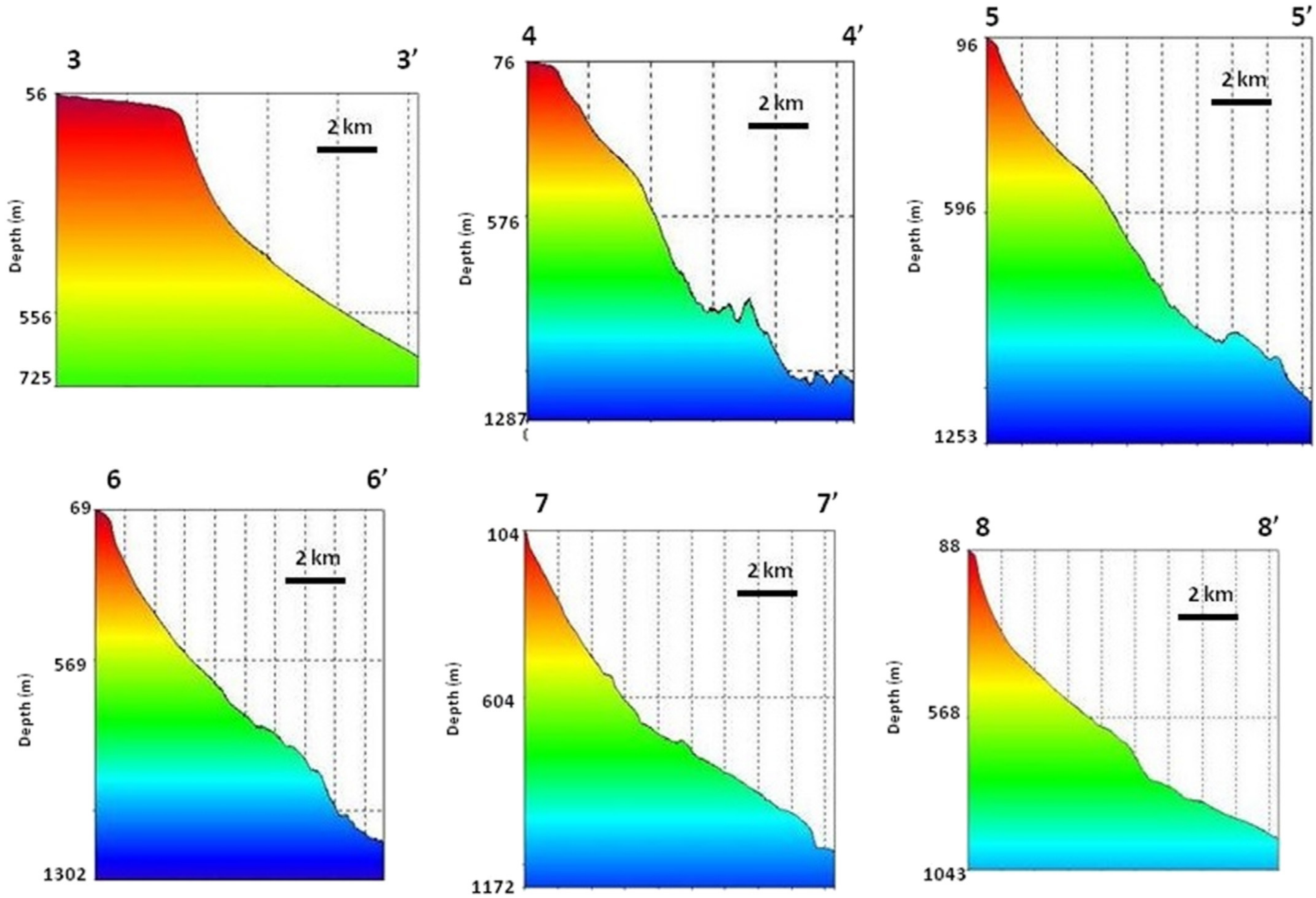

Fig. 4. Depth profiles across the continental slope of the study area. See Fig. 2 for the location.

canyon is deeply incised and the gradient becomes less steep; and 3) the lower canyon, which includes the areas of the lowest gradients and is where the canyons become wider.

The Mossoró, Apodi, and Açu heads had the highest slope values (>50°), and in some locations of the Areia Branca walls, the slope was >35° (Fig. 5). The slope reaches at least 25° on the walls of all of the canyons.

4.2.1. The 'A canyons'

The Areia Branca, Grossos, Mossoró, and Apodi canyons are located adjacent to the Apodi-Mossoró-incised valley. The Areia Branca and Apodi canyons have heads mapped in the shelf break zone at depths of 163 m and 106 m, respectively.

The Areia Branca Canyon (ABC) is the most sinuous canyon in the study area (sinuosity = 1.30) (Fig. 6A). It is also the longest canyon, with a 20-km length, starting at a depth of 163 m at a point 38 km from the coast and ending at a depth of 1383 m. The Areia Branca canyon has an average depth of 331 m, a maximum depth of 390 m, an average width of 1563 m, and a maximum width of 3507 m, including the terraces formed along its margins. The incision reaches a width of 2546 m.

The Areia Branca head is very narrow, with a width of ~480 m. The upper canyon segment has an initial NE–SW orientation that changes to an E–W orientation in the lower canyon and ends with an approximately N–S orientation (Fig. 6A). This drastic change in orientation of the Areia Branca Canyon is probably controlled by the border fault (Fig. 7).

The upper canyon exhibits a V-shaped cross profile, with marginal terraces (Fig. 6B; profiles 10–10′ and 11–11′). The canyon is U-shaped in its middle segment. In its lower segment, an axial incision (200-m depth, 1000-m width) and major valley (430-m depth, 3400-m width) are observed (according to the concepts described by Baztan et al., 2005) (Fig. 6B; profile 13–13′).

The Areia Branca canyon has one tributary (Grossos Canyon) and two distributaries (ABd1 and ABd2) (Fig. 6A). A tributary or affluent is a canyon that flows into a main stem canyon (Pidwirny and Jones, 2009). A tributary does not flow directly into a basin; rather, it feeds another, larger canyon. The opposite of a tributary is a distributary. A distributary is a canyon that branches off and flows away from a main canyon, forming a bifurcation (Pidwirny and Jones, 2009).

The Grossos tributary starts at a depth of 115 m and joins the main canyon at a depth of approximately 950 m. The Areia Branca canyon has a maximum gradient of 8° and an average width of 1357 m. The east wall becomes less steep near the main channel, exhibiting an asymmetric profile. The east wall has an average height of 264 m.

The distributaries (ABd1 and ABd2) become confluent with the main channel (Areia Branca canyon) at depths of 642 m and 796 m, respectively. These two distributaries exhibit average incisions of 142 m and 216 m, respectively. They exhibit U-shape cross profiles (Fig. 6A and B; profile 9–9′) with minimum slopes of 3° and 2°, respectively).

The distributaries located to the north of the main canyon are rectilinear and follow the NNE trend of the Areia Branca Fault System (Fig. 7). These faults may have influenced the locations of the Areia Branca and Grossos canyon heads and the locations of the

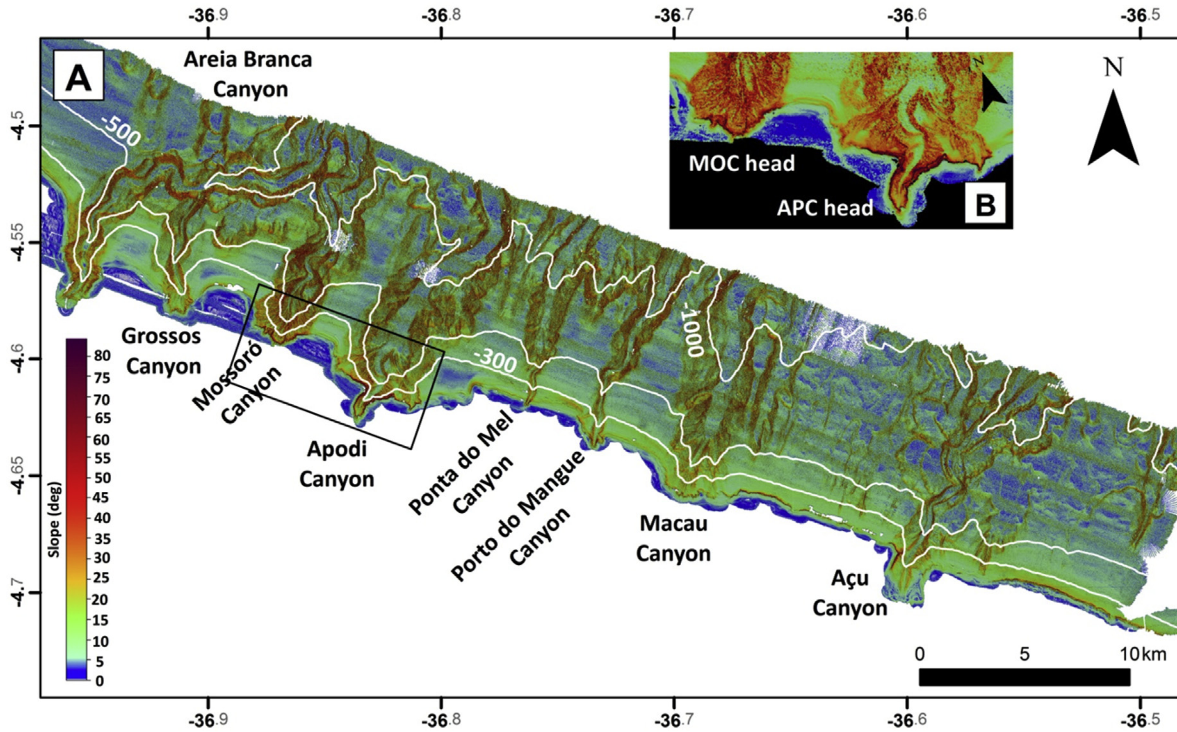

Fig. 5. A) Slope map of the study area, with 300-, 500-, and 1000-m isobaths showing the canyons' morphologies. Note the greenish tones above the 300-m isobath and the more bluish tones below it. The highest slopes are observed in the Mossoró, Apodi, and Açu canyon heads (>50°). In some locations on the Areia Branca walls, the slope is >35°. B) The Mossoró and Apodi heads, which exhibit high slopes (Location in Fig. 5A).

ABd1 and ABd2 thalwegs. Theses canyons are located in front of these faults and have the same orientation and parallelism.

Between the Grossos and Mossoró canyons heads, at the shelf edge, there are semi-circular and circular coral reef buildings that extend from the 60- to 80-m isobaths (Fig. 6) (Gomes et al., 2015a). The Grossos and Mossoró canyon heads both exhibit a smooth relief with a height of approximately 10 m, covering areas of approximately 4 km^2 and 6 km^2, respectively (Fig. 6A).

The Mossoró Canyon (MOC) starts with a 2309-m-wide head, widening to 3445 m. Its thalweg becomes shallower as the channel becomes deeper and joins the Areia Branca Canyon at a depth of 1330 m. In the transition between the middle and lower segments, there is a sediment ridge along which the canyon meanders downward. The Mossoró Canyon has a length of 13.2 km and the second largest sinuosity found (1.22). The MOC is characterised by numerous gullies on the walls (Fig. 6A).

The Apodi canyon head reaches the shelf break at 106 m and is very narrow (637 m) in comparison with the canyon width (up to 5010 m) at greater depths (Fig. 6A and B; profiles 1–1′ to 4–4′). Gullies are also present in this canyon (Fig. 6B; profile 2–2′). There is a well-formed gully that incises the shelf edge on the eastern wall (Fig. 6A).

The Apodi canyon head is located at a water depth of 106 m and extends to 1415 m, which is the deepest region of the study area. The average gradient of the thalweg is 6°. As with the Areia Branca Canyon, from the middle to the lower segment, the Apodi Canyon becomes U-shaped. The major valley morphology and axial incision are illustrated in Fig. 6A and B.

4.2.2. The 'B' canyons

The Ponta do Mel (PMEC) and Porto do Mangue (PMAC) canyons start at water depths of 115 m and become wider at the boundary between the upper slope and middle slope, where they intercept a basin border fault (Figs. 7 and 8). Additionally, there is a drastic change from a V-shaped to a U-shaped profile that corresponds to the location of the basin border fault (Figs. 7 and 8). The width of the Ponta do Mel Canyon is initially 387 m and increases to 2260 m, with an average of 1436 m. The width of the Porto do Mangue Canyon is initially 573 m and increases to 1906 m, with an average of 1232 m. The average depths of the PMEC and PMAC canyons are 293 m and 261 m, respectively, but the PMEC canyon reaches a maximum depth of 486 m. The PMEC and PMAC canyons have sinuosities of 1.05 and 1.07, respectively. These values are lower than the average for all of the submarine canyons in the study area (1.10).

There are considerable incisions on the middle slope between the Apodi, Ponta do Mel, and Porto do Mangue canyons (Fig. 8). These incisions are approximately 150 m deep and 1000 m wide and are referred to as Redonda (REI) and Rosado (ROI) incisions.

4.2.3. The 'C' canyon: Macau Canyon

The Macau canyon head is mapped at a water depth of 120 m. It is the widest canyon (with a mean width of 3094 m) and also has the widest head (2413 m). The Macau canyon head follows the predominant orientation of the slope incisions of the study area, which is SW–NE. The sinuosity of the canyon is 1.04. The canyon has no connection to the continental shelf. Gullies are widely present in the upper segment of the Macau Canyon, which has a V-shaped cross section. The middle and lower segments have U-shaped cross sections (Fig. 9; profiles 4–4′ to 6–6′). The average depth of the Macau Canyon is 360 m.

4.2.4. The 'D' canyon: Açu Canyon

The Açu canyon exhibits a very different and complex morphology (Fig. 10A). This canyon is the extension of the Açu-incised valley in deeper waters. The head of the Açu Canyon is

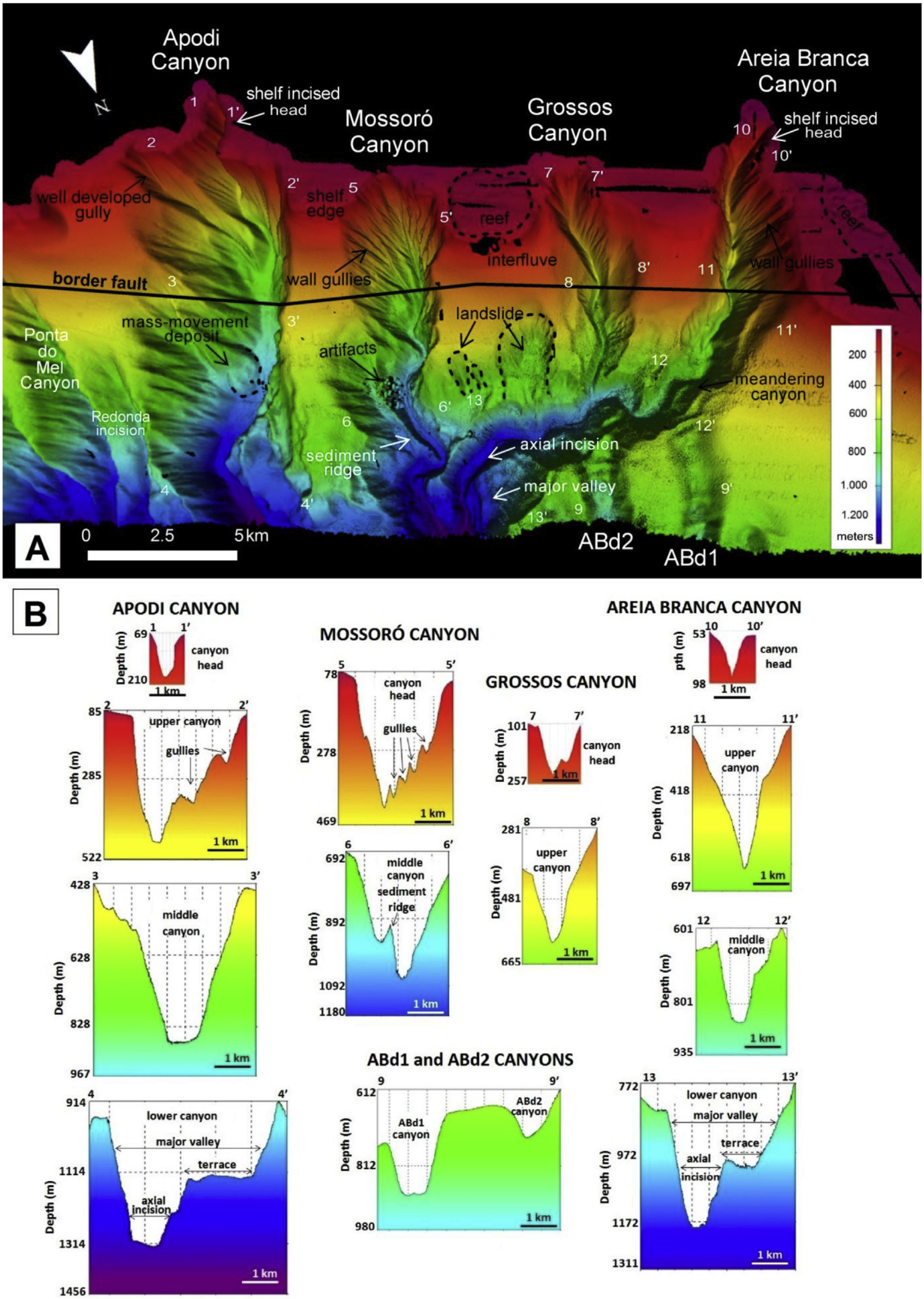

Fig. 6. A) Morphobathymetric map of 'A submarine canyons' (Vertical exaggeration: ~10). The smaller white numbers indicate the position of the cross-sectional profiles. Seabed morphological features are interpreted. B) Cross-sectional profiles of the canyons (ABd1 and ABd2 = distributaries of Areia Branca Canyon).

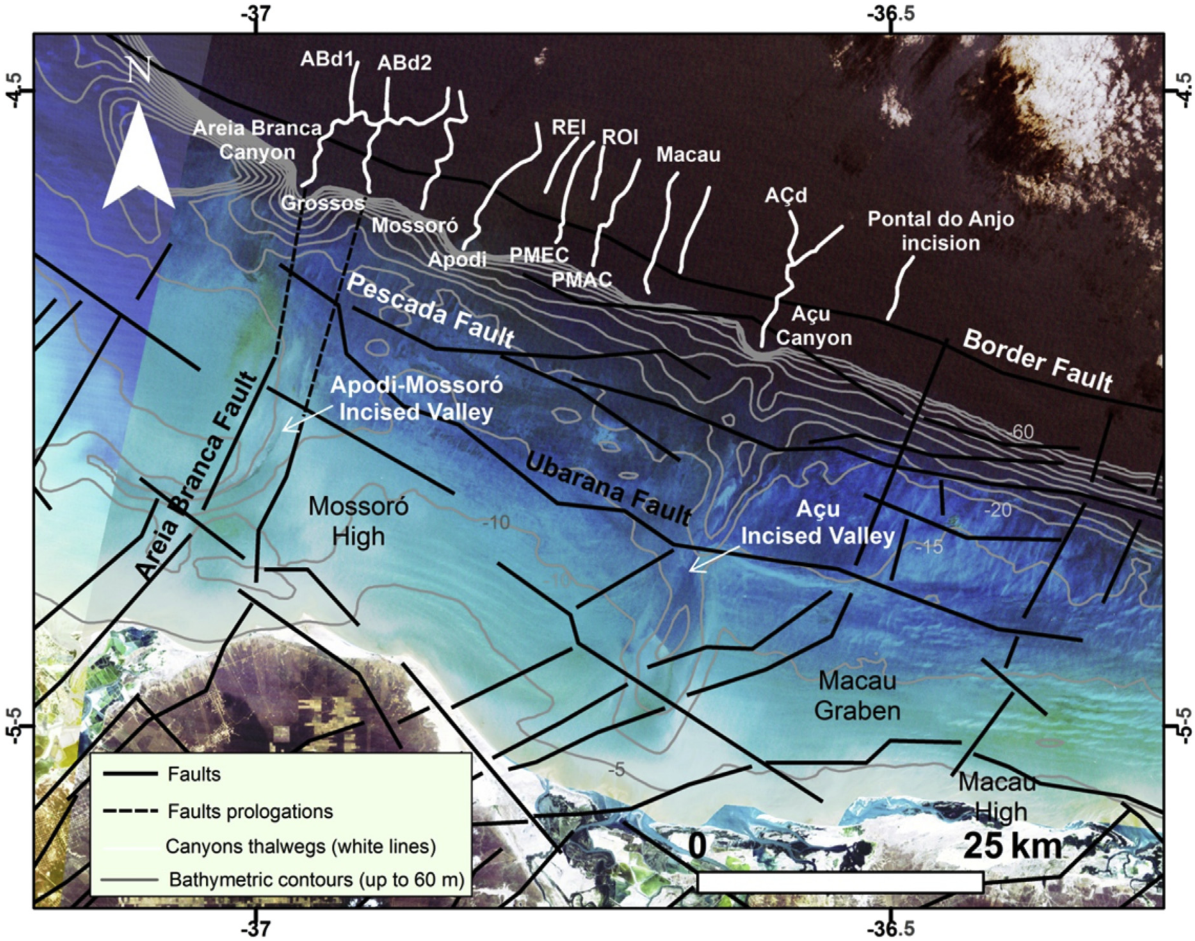

Fig. 7. Compilation of the structural data of the study area (Angelim et al., 2006). The dotted lines are the possible extensions of two parallel faults that may have controlled the head and thalweg positions of the Areia Branca (ABC), Grossos (GRC), ABd1, and ABd2 canyons tectonically. Note the influence of the border fault in the Açu canyon (AÇC) (REI = Redonda Incision; PMEC = Ponta do Mel Canyon; ROI = Rosado Incision; PMAC = Porto do Mangue Canyon).

mapped in the continental shelf edge at a water depth of 108 m and has a width of 1000 m. The incision reaches 319 m deep. The Açu Canyon is the second longest canyon (14,502 m) in the study area and has the third highest sinuosity (1.15). The Açu Canyon stands out due to the extensive terraces along its margins, which form flat, gently sloping surfaces. If these terraces are considered, the canyon's maximum width is 6210 m. Scarps separate these terraces from the non-excavated slope (Fig. 10A).

The orientation of the canyon changes from N–S to SW–NE where the basin border fault occurs (Fig. 7). At a water depth of 858 m, there is a bifurcation that forms another canyon (AÇd) (Figs. 6 and 10).

The Pontal do Anjo incision (PAI) starts on the middle slope (613 m) (Fig. 10). It has a length of 6198 m, a maximum depth of 191 m, an average width of 903 m, and a sinuosity of 1.02. This incision is a potential canyon.

The morphometric characteristics of the canyons in the study area are summarised in Table 1.

4.3. Deep-water morphological features

4.3.1. Submarine landslide and slump failures

Landslides were mapped in the interfluve between the Grossos and Mossoró canyons. The largest landslide is approximately 990 m wide (Figs. 6 and 11H).

At the Porto do Mangue canyon head, triangular landslide scars are present over a large area (~0.4 km^2) (Fig. 8). In addition, next to the Pontal do Anjo incision, there is a slump failure marked by a scarp approximately 60 m high (Figs. 10 and 11B). This scarp limits the toe slump.

4.3.2. Gullies

Almost all of the canyons of the continental slope of the Potiguar Basin exhibit gullies, primarily at their heads (Figs. 6, 9 and 10). The gullies are more numerous in the upper segment of the Mossoró Canyon, where they are 70 m deep and 740 m wide (Fig. 6). In the Apodi head, there is a very well-developed gully that incises the shelf edge (Fig. 11E).

The gullies of the Macau Canyon can be divided into two groups (Fig. 9). The first group consists of feeding gullies, which are shallower and narrower than those in the other group. The feeding gullies range in depth from 10 to 60 m and in width from 50 to 540 m. They converge at a water depth of 760 m. The second group consist of wall gullies, which are wider and deeper than the feeding gullies. The wall gullies range in depth from 120 to 200 m and in width from 890 m to 1100 m (Fig. 9).

East of the Macau Canyon, there are important gullies that start at the middle slope (475 m) (Fig. 9A). These gullies have an average depth of 144 m and an average width of 1507 m (Fig. 9; profiles 1-1′ to 3-3′).

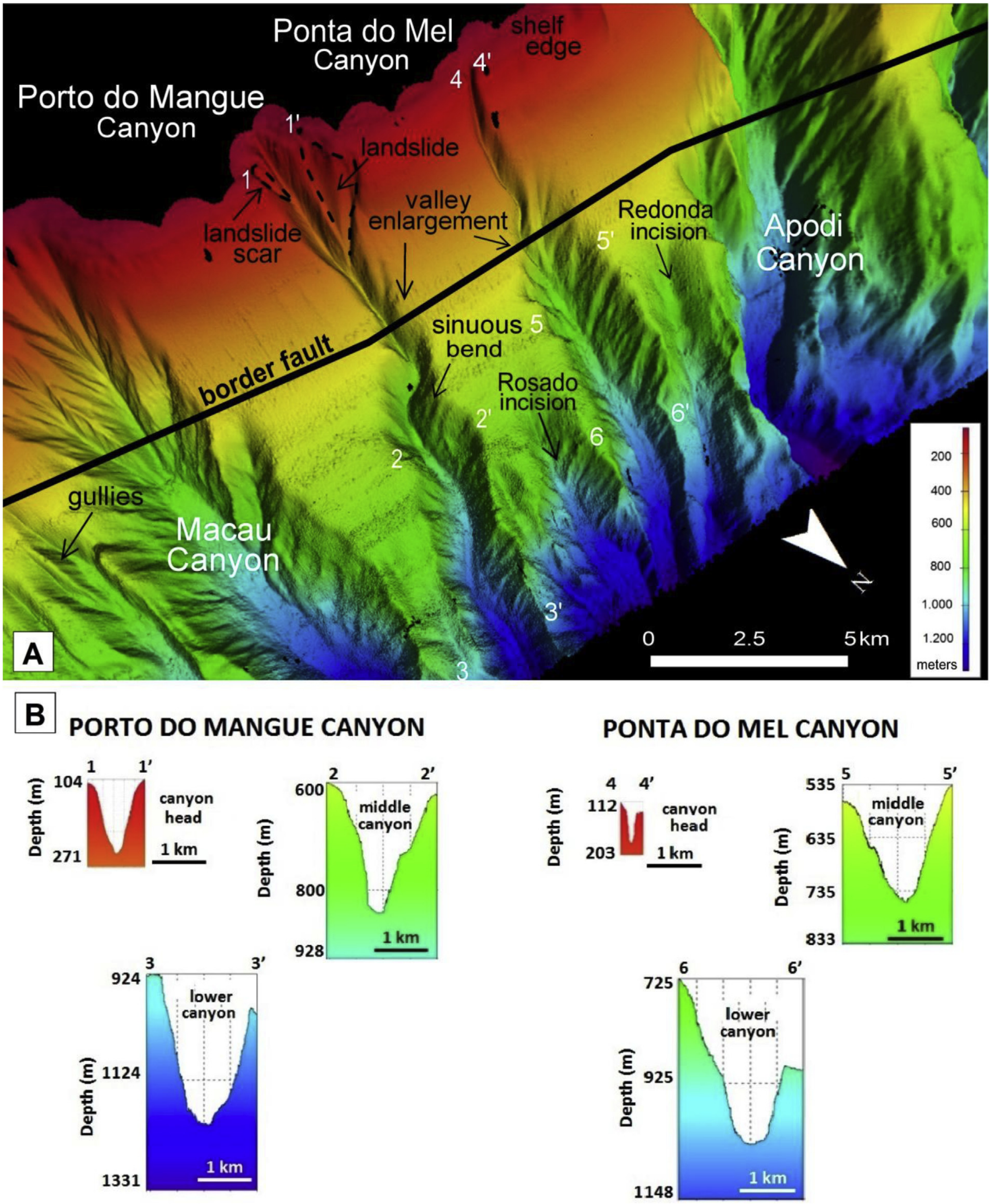

Fig. 8. A) Morphobathymetric map of 'B submarine canyons' (vertical exaggeration: ~10). The smaller white numbers indicate the positions of the cross-sectional profiles. Seabed morphological features are interpreted. B) Cross-sectional profiles of Ponta do Mel (PMEC) and Porto do Mangue (PMAC) canyons.

Gullies were also identified in the continental slope between Macau and Açu canyons and between the Açu Canyon and the Pontal do Anjo incision (Figs. 9, 10 and 11D). These gullies are a series of regularly spaced and parallel grooves that can be up to 3.5 km long (Figs. 9, 10, and 11D). The spacing of these gullies ranges from 200 to 500 m, the width ranges from approximately 40 to 120 m, and the depth ranges from approximately 10 to 20 m.

4.3.3. Sediment waves

Sediment waves with SW–NE crest orientations occur next to the bifurcation of the Areia Branca Canyon and the ABd1 Canyon (Fig. 11I). The sediment waves are approximately 50 m in length and between 10 and 20 m in height. The field covers an area of approximately 0.2 km^2. The orientation of the crests of the sediment waves suggests a NW orientation of their potential genetic flows.

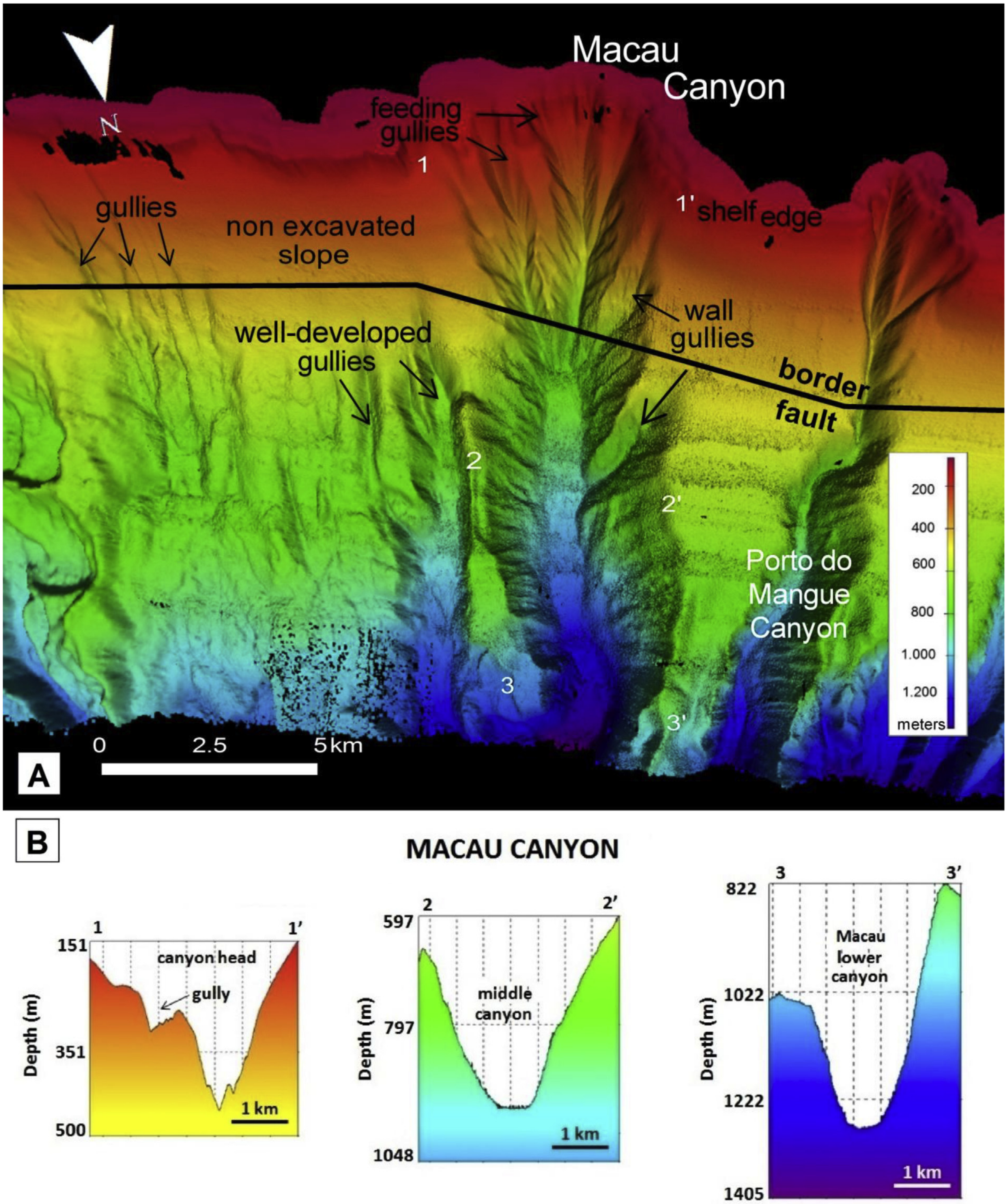

Fig. 9. A) Morphobathymetric map of the Macau Canyon (vertical exaggeration: ~10). The smaller white numbers indicate the positions of the cross-sectional profiles. Seabed morphological features are interpreted. B) Cross-sectional profiles.

4.3.4. Sediment ridge

There is a curved sediment ridge in the Mossoró Canyon between the 750-m and 1150-m isobaths (Figs. 6 and 11G). The orientation is SSE–NNW. It is possible that this ridge constricts the middle canyon segment and constrains the meander in the NW direction, diverting the course of the canyon. The ridge is 150 m high and 260 m wide.

In the Açu Canyon, the ridge ranges in height from 40 to 100 m and has an average width of 230 m (Figs. 10 and 11C). The ridge prevents a direct connection between the Açu Canyon and its distributary (Fig. 10).

5. Discussion

Based on the geometry and morphological patterns of the continental slope of the Potiguar Basin, as determined from

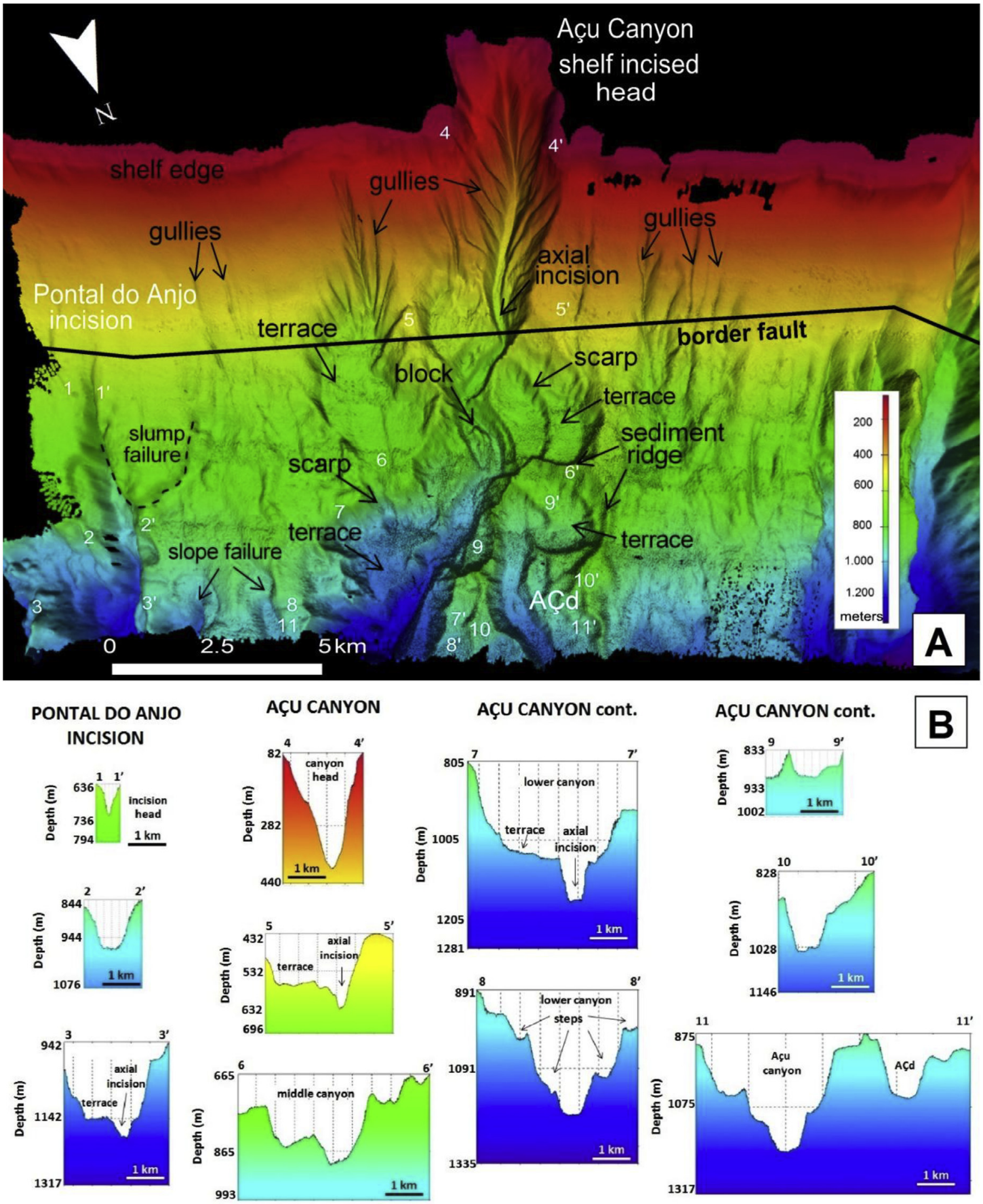

Fig. 10. A) Morphobathymetric map of 'D submarine canyons' (vertical exaggeration: ~10). The smaller white numbers indicate the positions of the cross-sectional profiles. Seabed morphological features are interpreted. B) Cross-sectional profiles (AÇd = Açu distributary).

multibeam bathymetric data, some interpretations can be drawn regarding the processes responsible for the development of the submarine canyons and the current continental slope morphology.

5.1. Development of submarine canyons

The origin and development of submarine canyons are generally considered to be driven by two sets of processes: 1) slumping, slope failure, and other mass wasting events; and 2) erosive turbidity flows derived from fluvial, shelf, and upper-slope sources (Farre et al., 1983; Harris and Whiteway, 2011; Piper and Normak, 2009; Pratson and Coakley, 1996; Pratson et al., 1994; Puga-Bernabéu et al., 2011; Puig et al., 2014 Shepard, 1981). These two sets of processes are believed to have acted separately and in combination to influence the origin and development of the submarine canyons of the Potiguar Basin.

Table 1
Summary of the morphometric characteristics of the submarine canyons of the continental slope of the Potiguar Basin.

Canyon	Length (m)	Branch length (m)	Head depth (m)	Confluence depth (m)	Average depth range (m)	Maximum depth range (m)	Head width (m)	Average width (m)	Maximum width (m) [including terraces]	Sinuosity	Average slope (°)	Stage	Type
Areia Branca	20056	–	163	–	331	390	480	1563	2546 [3507]	1.30	5	mature	ident the shelf edge
Grossos	–	6406	115	950	264	313	942	1357	1929	1.09	8	transitional	
ABd1	–	4494	–	642	142	150	1454	1605	1752	1.03	3	initial	slope-confined
ABd2	–	3716	–	796	216	238	1439	1483	1559	1.02	2	initial	slope-confined
Mossoró	13244	–	106	–	369	435	2309	2563	3445	1.22	7	transitional	
Apodi	14462	–	106	–	373	486	637	3193	5010 [5224]	1.13	6	mature	ident the shelf edge
Ponta do Mel	9863	–	115	–	293	486	387	1436	2260	1.05	8	transitional	
Porto do Mangue	10799	–	115	–	261	272	573	1232	1906	1.07	7	transitional	
Macau	11427	–	120	–	360	370	2413	3094	3777	1.04	6	transitional	
Açu	14502	–	108	–	252	319	1000	1508	2722 [6210]	1.15	5	mature	ident the shelf edge
Açd	–	5268	–	858	172	191	779	913	1004 [2421]	1.06	3	initial	slope-confined

Farre et al. (1983) and Puga-Bernabéu et al. (2011) proposed a model for the formation of canyons. We suggest that the formation and development of the submarine canyons of Potiguar Basin have generally followed this model. This model consists of three phases, described below, with downslope and upslope processes interacting to shape submarine canyons.

The initial or youthful stage involves pre-conditioning factors, such as low sediment strength, differential compaction in the sediment, permeability, underconsolidation, oversteepening, and/or the presence of faults and other tectonic structures, that lead to localised slope failures. Triggering factors could include fluid escapes, strong storms, and earthquakes (e.g., Lo Iacono et al., 2014; Puga-Bernabéu et al., 2011).

The slope failures and landslides in the middle slope of the study area (Figs. 8 and 10) may represent the youthful stage of canyon formation. Multiple retrogressive slides occur where progressive failure events and interaction among adjacent slides produce multiple features and the extension of the instability upslope, forming initial submarine canyons (e.g., Lo Iacono et al., 2014; Moore, 1964; Prior and Coleman, 1978). Examples of this scenario in the study area are the Pontal do Anjo incisions and the Açu distributary canyon (AÇd) (Figs. 8 and 10).

Additionally, Pratson and Coakley (1996) point to the existence of precursor gullies formed by downslope erosive flows triggered in the upper slope by sediment oversteepening, which leads to canyon-forming slope failures. Evidence of these features is observed at the head of the Pontal do Anjo incision (Fig. 10) and in well-developed gullies to the east of the Macau Canyon (Fig. 9).

In the transitional stage, initial canyons progress upslope to near the shelf break (Farre et al., 1983), and the canyon growth mechanisms are similar to those in the initial stage. The Macau Canyon is an example of this transitional stage. Morphological evidence for this stage is the head near the shelf break (which does not incise the shelf), numerous gullies in the upper segment, reduced sinuosity, considerable width, and a semi-circular head shape, all of which are morphological products of the upslope erosion process (Fig. 9).

The Ponta do Mel and Porto do Mangue canyons also represent this transitional stage. The upper segments are characterised by the existence of gullies formed by top-down axial incision processes (e.g., Lastras et al., 2011; Pratson and Coakley, 1996) whereas the middle and lower segments were formed by retrograding landslides. They also have heads near the shelf break.

The mature stage involves a change in the erosion style of canyons that may breach the shelf edge. This stage is represented by shelf-incised submarine canyons. The canyon heads act as catchment areas for shelf and river sediments (Green, 2009; Herzer and Lewis, 1979; Mullenbach et al., 2004) that bypass the slope through the canyon valleys and are deposited on the basin floor. Downward sediment flows due to gravity can contribute significantly to canyon excavation and enlargement by a process of axial incision (Baztan et al., 2005; Pratson and Coakley, 1996). Mature submarine canyons become more active due to the increased and probably more frequent sediment supply provided from different areas on the shelf. The mature stage in the study area is represented by the Areia Branca, Apodi, and Açu submarine canyons that incise the shelf.

Low-latitude sea-level records (Peltier and Fairbanks, 2006) reveal that the last glacial maximum (LGM), ~20,000 B.P., placed the coastline 120 m below the present sea level and exposed shelf (shelf break of 70 m). Therefore, the canyons with heads located along the continental shelf (the Areia Branca, Apodi, and Açu canyons) were probably connected to the incised valleys and/or shelf/river drainage systems.

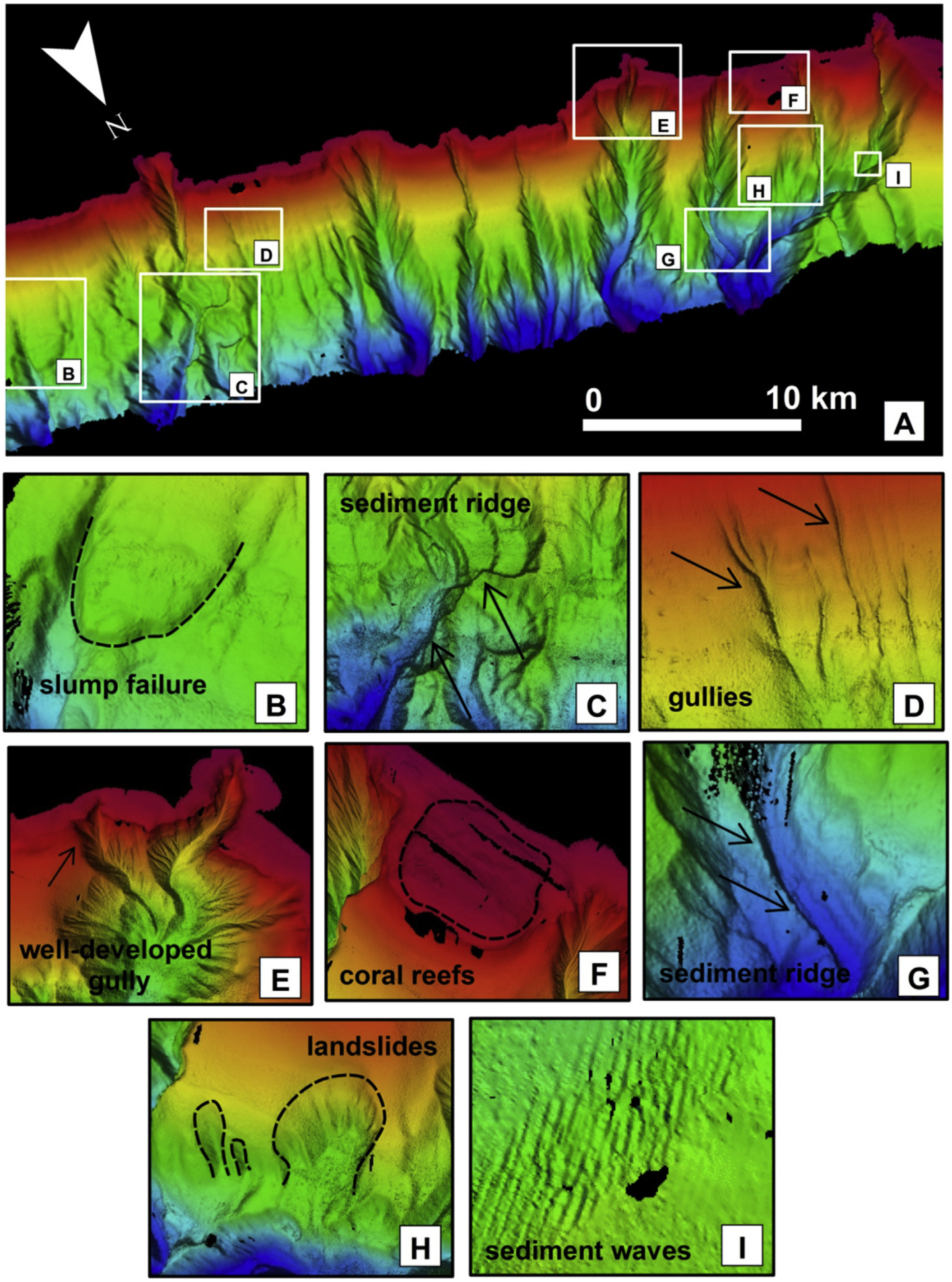

Fig. 11. Summary of deep water morphological features of the study area. A) Continental slope of Potiguar Basin, with the locations of morphological features. B) Slump failure. C) Sediment ridges in the Açu Canyon. D) Gullies. E) Well-developed gully on the shelf edge next to the Açu canyon head. F) Coral reefs. G) Rectilinear sediment ridge in Mossoró Canyon. H) Landslide between the Mossoró and Grossos canyons. I) Sediment waves in the Areia Branca Canyon.

5.2. Sedimentary dynamics and geohazards

The axial incisions along the thalwegs in most of the canyons demonstrate that recent downslope sedimentary fluxes occur along the slope (Baztan et al., 2005). Turbidity and mass transport processes were frequent along the continental slope of the Potiguar Basin, contributing to the evolution of the submarine canyons (e.g., Gomes et al., 2015a).

The presence of sediment waves demonstrates the role of bottom currents on the shaping of the slope. Sediment waves in confined deep-water environments (Fig. 11I) result from the action of downslope sediment flows due to gravity or internal waves along the canyon axis (Karl et al., 1986; Wynn and Stow, 2002).

The sediment ridges (Figs. 6, 10, 11C, and 11G) and blocks (Fig. 10) are obstructions that are probably composed of rocky outcrops, which are difficult to erode (e.g., Lo Iacono et al., 2011), although further investigation is warranted to identify their nature.

Gullies are channelised in the upper canyons and indicate erosional processes. The V-shaped, nearly symmetrical cross sections and relatively high average steepness indices of the gullies suggest the action of gravity-driven erosion processes (Figs. 6, 11D and 11E; e.g., Noormets et al., 2009). In addition, some of the gullies that exhibit circular scars at their heads, terraces, scarps, and landslides (Figs. 6, 9 and 10) may suggest retrogressive mass movements (e.g., Klaus and Taylor, 1991).

According to Harris and Whiteway (2011), the mean slope of the passive-margin canyons is 3.8°, while the mean slope of the canyons in the study area is 7°. Furthermore, high slopes were observed in the Mossoró, Apodi, and Açu heads (>50°), and in some locations of the Areia Branca walls, the slope is >35°. According to Moţoc (1975), cited in Vlad and Alexandru (2012), these walls (with slopes of 35–50°) are extremely strongly inclined and prone to excessive erosion.

These steep gradients, in addition to other conditions, e.g., sediment consolidation and tectonic influence, may have induced sediment instability and favoured the occurrence of frequent mass failure events, in the form of submarine landslides and slope failures. The mass wasting features provide evidence of the instability of the region and indicate that the region can be considered to be prone to geohazards.

In general, mass failure features occur on the continental slope and canyon walls and can pose a significant hazard to offshore infrastructure. The first suspicions of instability of the sediments on the canyon floors arose due to breaking of cables that had been laid across the canyons as long ago as the late nineteenth century (Milne, 1897; cited in Shepard, 1972). On the shallow continental shelf of Rio Grande do Norte, there are submarine power cables that are used to supply electricity to oil production platforms (Costa et al., 2014). If this system is improved and used in deep waters, we suggest that the installation of submarine structures across the canyons be avoided, mainly in the canyons heads and where landslide structures have been mapped, because they exhibit instability that could contribute to submarine accidents and adverse environmental effects.

5.3. Tectonics vs morphology

Some of the morphological patterns of the submarine canyons and the continental slope suggest that tectonic activities have also controlled the morphology of the deep-water environments of the Potiguar Basin (Figs. 6–8 and 10). Some of the tectonic features could correspond to a preferential location and could have influenced the distribution of the submarine canyons. Evidence of tectonic influence on the morphological evolution of the area includes the following:

1. The coincident locations of the Areia Branca, Grossos, ABd1, and ABd2 heads and thalwegs with the Areia Branca Cenozoic faults (Figs. 6 and 7),
2. The change in orientation of the Areia Branca Canyon (NE–SW, E–W, NE–SW), possibly due to the influence of the Pescada fault system or the border fault system.
3. A very rectilinear sediment ridge in the Mossoró Canyon (oriented ~ NW) (Fig. 7). According to Mountjoy et al. (2009), mean faults of limited length facilitate the development of elongated ridges that taper to their ends, reflecting the plunge of the fault propagated. However, we would need seismic data to prove this point.
4. The enlargement of the Ponta do Mel and Porto do Mangue canyons and the change in the canyon profiles from V shapes to U shapes where the canyons intercept the border fault. In addition, a sinuous bend is observed on the Porto do Mangue canyon course (Figs. 7 and 8).
5. The change in the course of the Açu Canyon where it intercepts the border fault (Figs. 7 and 10).

The tectonic framework of the studied margin is related to the Equatorial tectonic regime that has deformed Quaternary cliffs and beachrocks (Bezerra and Vita-Finzi, 2000; Moura-Lima et al., 2010). According to Bezerra and Vita-Finzi (2000), in coastal northeastern Brazil, within the passive margin of the South American plate, focal mechanisms indicate a strike–slip regime, with compression parallel to the west-to west–northwest-trending coastline. This regime may have produced the drastic change in the orientation of the Areia Branca Canyon.

Therefore, the current morphology of these canyons and continental slope is a result of the interplay of the erosional processes with the retrogressive failures, downslope turbidity currents, sediment deposition and transport, and structural inheritance of the region.

5.4. Classification of the canyons

Two main types of submarine canyons are defined, based on their characteristics, mainly on the incision depth. 'Type I' canyons, which have been studied extensively (Jobe et al., 2011; Lastras et al., 2009; Sawyer et al., 2007; Shepard and Emery, 1973), indent the shelf edge (e.g., Harris and Whiteway, 2011; Normark, 1970) and are linked to areas of high sediment supply, such as large fluvial systems (Fildani and Normark, 2004; Gay et al., 2003; Sawyer et al., 2007; Shepard, 1981; Shepard and Emery, 1973), generating erosive canyon morphologies and large downslope submarine fans/aprons. 'Type II' canyons do not indent the shelf edge; they exhibit smooth, highly aggradational morphologies and a lack of downslope fans/aprons (Jobe et al., 2011).

Some typical characteristics of Type 1 canyons are their erosional morphology, their relatively high sinuosity, their V-shaped cross sections, and the presence of tributaries and terraces (Arzola et al., 2008; Jobe et al., 2011; Lastras et al., 2009).

The Apodi and Açu canyons have heads that indent the shelf edge and are associated with large fluvial systems (Apodi-Mossoró River and Açu River, respectively). Lima and Vital (2006) and Gomes et al. (2015b) recognised the directions of the main structural features that connect the Apodi-Mossoró-incised valley to the corresponding rivers on the continent.

Heads that indent the shelf edge, the association with fluvial systems, and other characteristics, such as considerable sinuosities compared to other canyons in the study area, the 'V' shape, and the presence of tributaries/distributaries and terraces along the margins (Figs. 6 and 10), are indications that these canyons (the Apodi and Açu) are Type 1 canyons. Furthermore, these canyons exhibit evidence of erosive features, such as landslides and gullies.

The Type 1 Apodi and Açu canyons have high sediment supplies because of their connection to the two main river systems in the study area, the Apodi-Mossoró River and the Açu River (e.g., Jobe et al., 2011; Normark and Gutmacher, 1988; Normark and Piper, 1991; Shepard, 1981). According to Gomes et al. (2015b), a series of Landsat images of the water column revealed significant amounts of suspended sediments along the Açu-incised valley, flowing down-valley due to the channelised currents. These currents probably reach the Açu canyon as turbidity currents, supplying sediments, producing erosive structures, and depositing lobes of submarine fans.

These canyons (the Type 1 Apodi and Açu canyons) are closely associated with the deposition of the large submarine fan systems that have been considered to be highly permeable hydrocarbon reservoirs (Dailly et al., 2002; Jobe et al., 2011; Normark, 1970; Posamentier, 2003; Stow and Mayall, 2000), such as the

Almirante Câmara and São Tomé canyons (Brehme, 1984; Gorini et al., 1998; Pellizon, 2005; Viana et al., 1998) and the Ceiba canyon (Dailly et al., 2002; Jobe et al., 2011). Nonetheless, our limited dataset does not allow us to confirm this information.

Although the Areia Branca canyon head is mapped at the shelf edge, it could not be classified as a Type 1 canyon because there is no current and direct connection of the Apodi-Mossoró-incised valley with the Areia Branca Canyon. Nogueira (2014) has suggested that another drainage system exists at the outer shelf to the west of the Apodi-Mossoró-incised valley and that this drainage system has a direct connection to the Areia Branca Canyon.

The Redonda, Rosado and Pontal do Anjo incisions (potential canyons) were classified as Type 2 canyons because they are slope-confined, without well-developed heads, and consist of small and immature canyons (e.g., Goff, 2001; Twichell and Roberts, 1982) excavated into the middle slope at deep water depths (>400 m). Type 2 canyons such as these form in areas of low fluvial sediment supply (i.e., with no association with a fluvial system), with no tributaries or distributary canyons, and exhibit morphologies characteristic of low-energy deposition, such as smooth U-shaped morphologies and flat bottoms.

6. Conclusions

The results obtained from an analysis of a multibeam bathymetric dataset made it possible to map for the first time a sector of the Brazilian continental slope – specifically, a sector along the continental margin of the offshore Potiguar Basin. Based on our detailed analyses, we were able to draw the following conclusions:

1. The studied continental slope consists of an upper slope (from the shelf break) ranging in depth from 70 to 300 m and a middle slope ranging in depth from 300 to 1300 m, with the upper slope being steeper than the middle slope.
2. Several submarine canyons intersect the upper and middle continental slopes. Other deep-water features present are landslides, gullies, sediment ridges, and sediment waves. The landslides and gullies indicate a potential erosional/depositional system in the continental slope.
3. Along the continental slope of the Potiguar Basin, submarine canyons display initial, transitional, and mature stages.
4. The canyons were classified according to their morphology. The Apodi and Açu canyons, classified as Type 1 canyons, are associated with the deposition of submarine fan systems.
5. The morphology of the canyons and the continental slope of the Potiguar Basin are the results of erosional processes, sediment deposition, and transport by currents, as well as the influence of tectonic activity. The findings of this study concerning the morphology of the canyons and their formation contribute to knowledge of deep marine depositional environments and environmental management.

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