

DETERMINATION OF THE FOOT OF THE SLOPE IN A TERRACED CONTINENTAL SLOPE

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Abstract

This paper deals with the argumentation used to support the location of the base of the slope in a margin characterized by a large Contourite Depositional System (CDS) that is developed by the interaction of different water masses with seafloor. As a result of this interaction, and the CDS occurrence, the margin sets apart from the typical continental margin types, and could be defined as a contourites dominated continental margin.

In this type of margin, many contourite terraces are extended from the upper slope to the abyssal plain. Over these terraces some large contourite channels are developed. Because of the occurrence of the CDS there is no evidence of any continental rise, since the slope changes progressively to the abyssal plain. An outstanding characteristic of the CDS is the development of giant contourite drifts. Fossilized contourite drifts can determine the present morphology of the CDS. After considering all the morphosedimentary evidence, the base of the slope region is identified at the base of the deepest terrace.

1. Introduction

The classic morphological profile of a continental margin includes the continental shelf, the slope and a wedge shaped sedimentary body called continental rise. The seaward limit is found where the regional gradient decreases until it becomes horizontal, defining the beginning of the abyssal plain (Figure 1A). Paragraph 5.4.4 of the Scientific and Technical Guidelines (the Guidelines) of the CLCS recognizes that

many continental margins depart from this ideal picture and that geological and geophysical data can be submitted to support the location of the base of the slope.

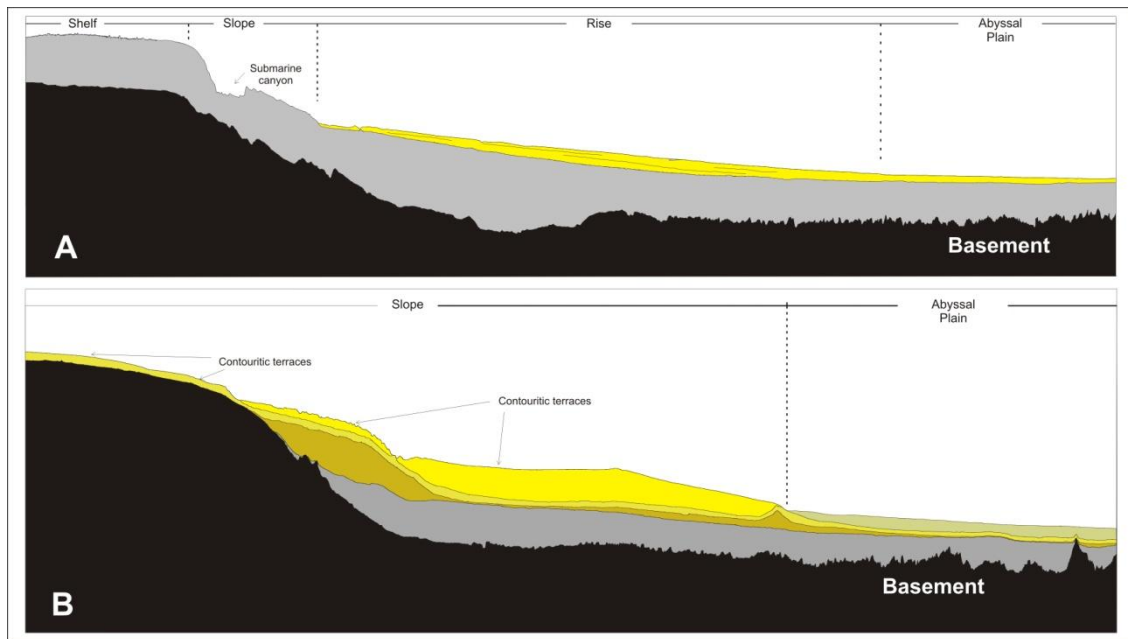


Figure 1: A) classic morphologic section of a continental margin. B) terraced slope connecting the continental shelf with the abyssal plain in the Southern passive volcanic Argentine Margin.

In the Southern passive volcanic Argentine Margin, between 43° S and the Malvinas Escarpment, this classic configuration is not observed, as a very active contourite processes determines the formation of a CDS which prevents the development of a continental rise (Hernandez-Molina *et al.*, 2009). The result is the presence of a broader and smoother slope formed by both depositional (drifts) and erosive (terraces, moats and channels) elements which connect progressively the continental shelf with the abyssal plain (Figure 1B). This is a unique configuration that is not considered in the Guidelines. This paper deals with the description and the geologic framework used to understand this non-classic margin.

2. Database and Methodology

This area is covered by an important grid of geophysical data that was acquired in different cruises (see Figure 2): COPLA 2008, 2009, 2010, 2001-2002/ COPLA-BGR 2004 and BGR 87, 93, 98. In this context, several geophysical data was acquired and compiled, including, approximately 11,000 km of single beam bathymetry, magnetic and gravity measurements and multichannel seismic (MCS) reflection profiles, spaced every 55 km. Airguns capacities used ranged between 4,000–5,200 in³, shooting interval was 50 m, streamers 6 km long, sampling rate 2 ms and record length was 12–15 s.

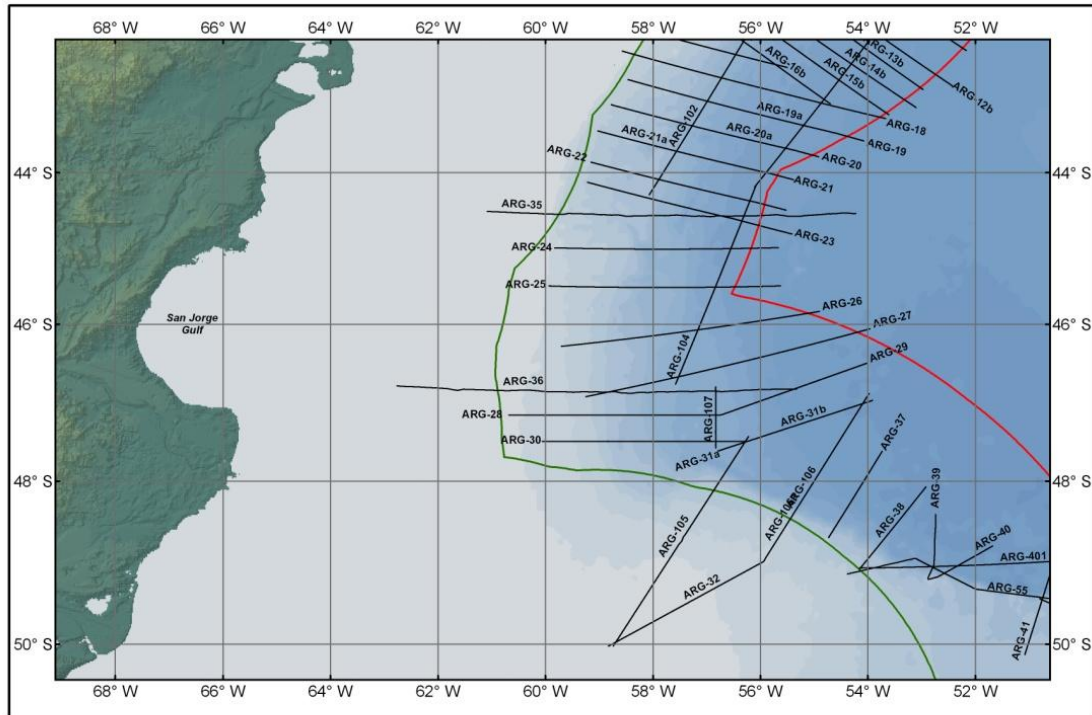


Figure 2: position of geophysical profiles used in this study.

This work is based in three important data sets and results of the Southern Passive Volcanic Argentine Margin, which are the present-day seafloor bathymetry, the oceanographic scenario and the MCS profiles interpretation. Considering all these information both the morphology of the margin is interpreted and the evolution decoded.

3. Oceanographic Scenario

Termohaline circulation generates strong contour currents that have a profound effect on continental margins. The deposits generated by these along-slope currents are called contourites or contourite drifts. These depositional elements are associated with erosive features like channels, moats and terraces. In general, both depositional and erosive features are elongated parallel to the margin and developed at the same depth range as the contour current that affects the margin (Hernandez-Molina, *et al.*, 2009).

A CDS is commonly developed when along-slope processes dominate and an association of depositional drifts and erosive features. The interaction of one or more water masses with the margin may cause large drifts.

The Southern Passive Volcanic Argentine Margin is characterized by a strong interaction of along-slope processes with seafloor (Hernández-Molina *et al.*, 2009). This margin is one of the most dynamic of the world's oceans (Chelton *et al.*, 1990). The oceanographic configuration is given by the Brazil/Malvinas Confluence (BMC) as well as the interaction of Antarctic water masses: Antarctic Intermediate Water (AAIW), Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW) with the Brazil Current, re-circulated AAIW and North Atlantic Deep Water (NADW) at different depth (Georgi, 1981; Saunders and King, 1995; Piola and Matano, 2001).

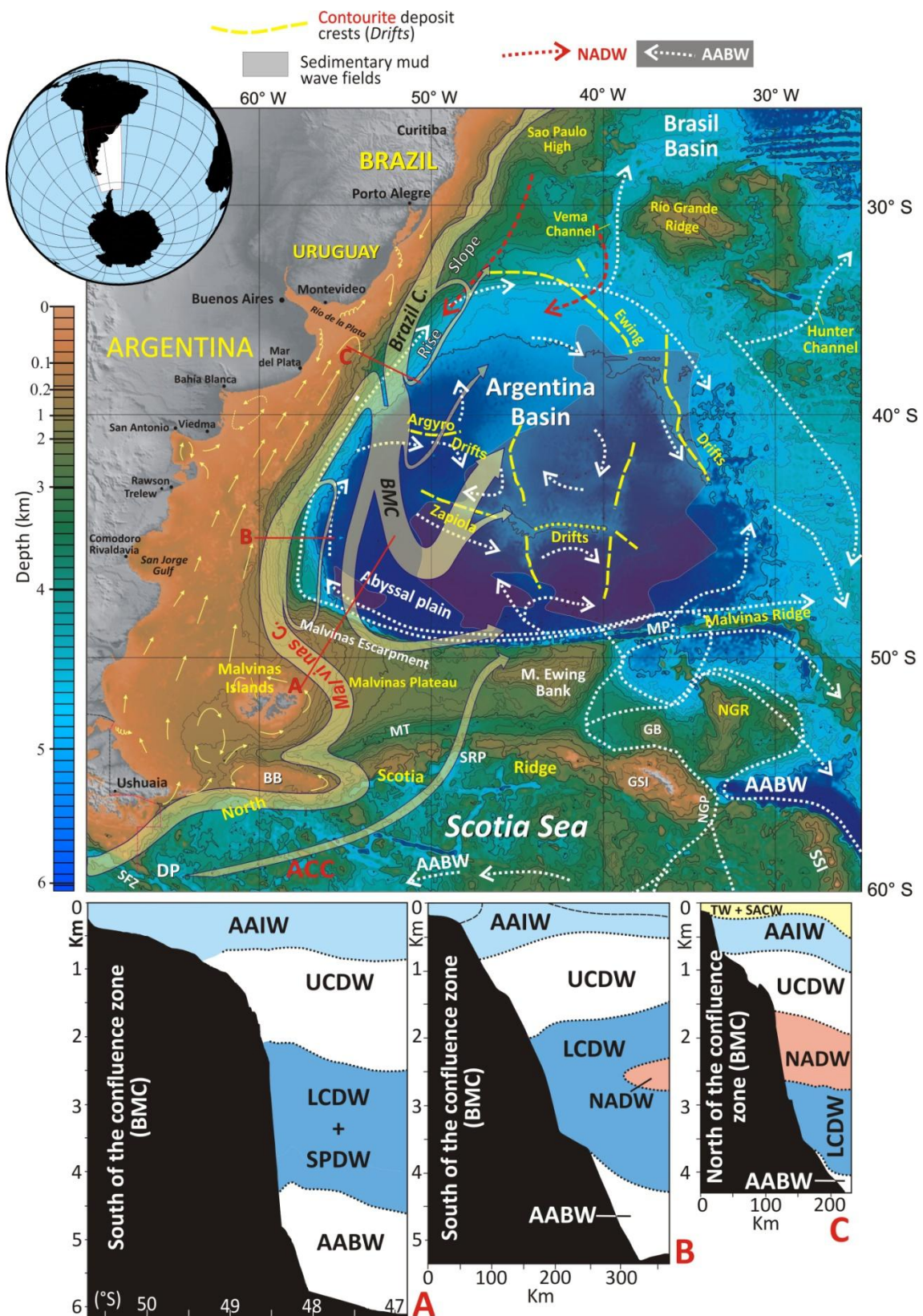


Figure 3: circulation pattern in the Argentine margin and schematic sections showing the depth of the interfaces between the different water masses. From Henández-Molina *et al.*, 2009.

The interfaces between these water masses are determined by changes in density, which at basin scale deepen northward and are vertically displaced by eddies (Piola and Matano, 2001; Arhan *et al.*, 2002 a, b). Locally, where the CDS is developed, these interfaces are shallower due to physiographic changes in the margin from Hernández-Molina *et al.*, 2009.

Oceanographic circulation along most of the Argentine continental slope is controlled by the northward-flow of the Malvinas Current which meets the Brazil Current flowing southwest at approximately 40° S (see Figure 3). Both currents determine the BMC (Lonardi and Ewing, 1971, Piola and Rivas, 1997), which is a distinct characteristic of the Argentina Basin. Oceanographic configurations are clearly different North and South of the confluence.

South of the BMC (see Figure 3, section B), where the CDS is located, the intermediate circulation (< 1,000 m) is determined by the northward flow of the AAIW and at 1,000-3,500 m by the two fractions of the CDW, called Upper Circumpolar Deep Water (UCDW) and Lower Circumpolar Deep Water (LCDW) (Piola and Matano, 2001; Hernández-Molina *et al.*, 2009). To the South, the LCDW is divided into two high-velocity cores at 2,500 m depth and the South Pacific Water (SPW) is identified (see Figure 3, section A). North of the BMC, besides the water masses already mentioned, the NADW is recognized (see Figure 3, box C). It circulates towards South close to the slope at depth between 1,500 and 2,800 m (Piola and Mantano, 2001).

The AABW enter the Argentina Basin from the South through the Malvinas Gap and from the East around the Malvinas Plateau, turning West along the Malvinas Escarpment, and finally heading North at the Argentine slope (see Figure 3). The northward displacement of AABW conditions the deep circulation and it is partially trapped in the basin generating a cyclonic gyre up to 2,000 m thick, which influence at depth greater than 3,500 to 4,000 m (Piola and Matano, 2001; Arhan *et al.*, 2002 a, b; Hernández-Molina, *et al.*, 2009). This deep circulation regime is significant in controlling the sedimentary processes and the submarine morphology across the entire ocean basin and particularly on the Argentine margin (Le Pichon *et al.*, 1971; Flood and Shor, 1988; Klaus and Ledbetter, 1988; Reid, 1989; Arhan *et al.*, 2002 a, b; Hernández-Molina, *et al.*, 2009).

4. Morphosedimentary Description of the CDS

Within the CDS, Hernández-Molina *et al.*, 2009; 2010, delineated two major sectors: the Terraces Sector and the Submarine Canyons and Channels Sector.

4.1 The Terraces Sector

This region is characterized by four sub-horizontal morphological elements (terraces) identified at the present-day seafloor. Their limits and lateral continuity can be imaged in the first derivative map (Figure 4). Terraces are about 300 km long and 50 km wide. They are developed at different depths: Nágera, at 500 m; Perito Moreno, at 1000 m; Piedra Buena, at 2500 m; and Valentin Feilberg, at 3500 to 4000 m (Figure 4). For each terrace, the proximal part is 0.25 to 0.5° seaward, whereas the gradient is slightly steeper (0.5 to 1°) across the distal part.

Erosive features dominate the slope in this sector, being the terraces the most distinct features, but also contourite moats and channels are recognized (Figure 4). A large moat with good lateral continuity runs parallel to the Northwest end of the Malvinas Escarpment. At ~48° S/~57° W this moat is subdivided into two contourite

channels: the Keninek contourite channel (Channel-1) and the Kolenten contourite channel (Channel-2). To the East another contourite channel is recognized (Channel-3). These erosive channels run northward along the Valentin Feilberg Terrace.

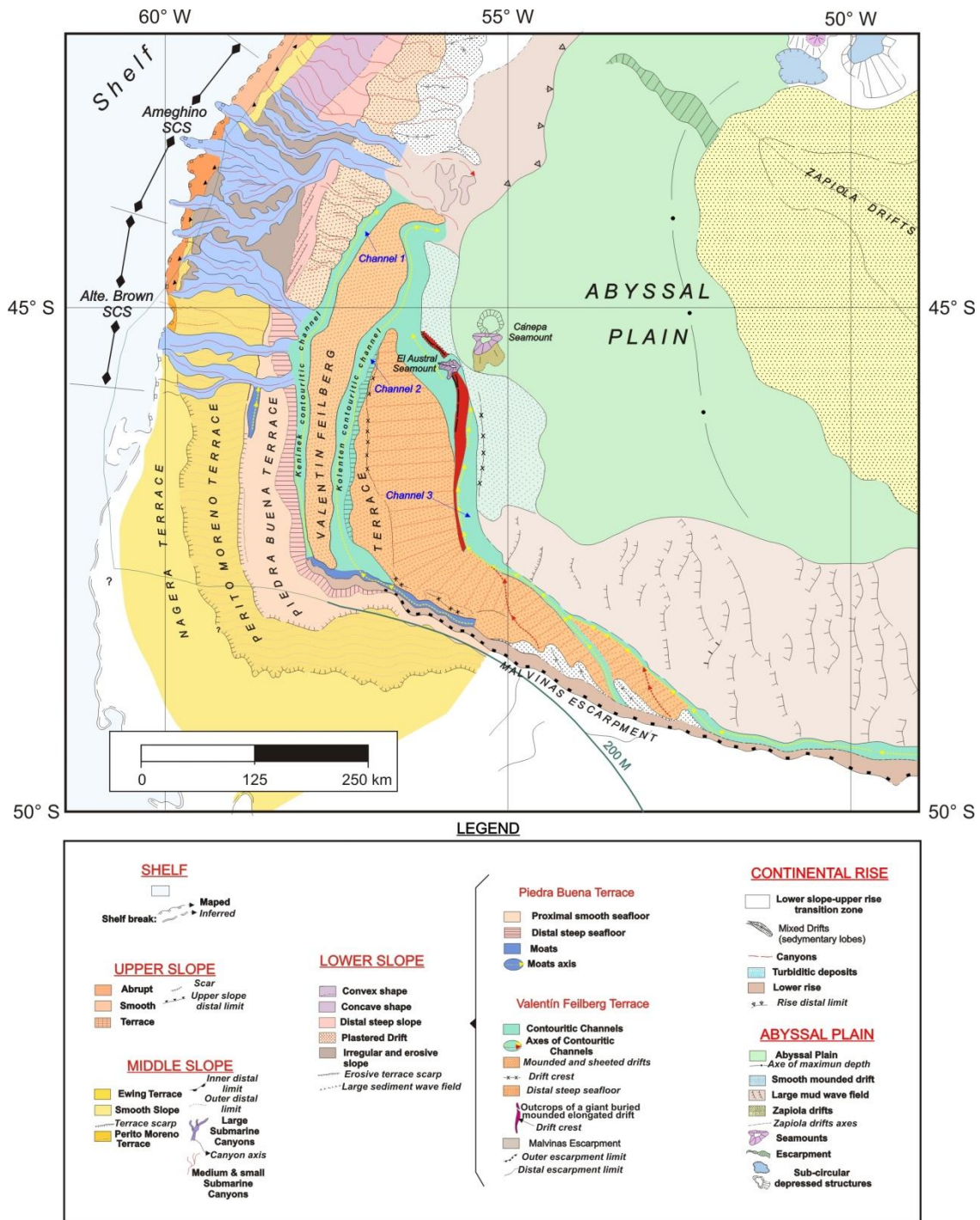


Figure 4: Morphosedimentary map. From Hernandez Molina *et al.*, 2010.

The present-day terraced morphology of the slope is the result of the development over time of constructional (depositional) and erosive phases that controlled the CDS. This configuration is clearly imaged in Figure 5 where the Piedra Buena paleoslope is clearly buried by younger drifts that resulted from the evolution of the CDS.

Partially outcropping at the base of the slope, there is a relict morphological feature that has been identified by Hernández-Molina *et al.*, 2010 corresponding to the crest of a large contourite deposit which we will refer to as giant-drift (see Figures 4 and 5). This deposit represents a buried mounded and elongated contourite drift with asymmetric morphology, further details can be found in Hernández-Molina, *et al.*, 2010. It is located Southwest of the Cánepa Seamount, between 47° 30' and 45° 15' S, at a depth of 5,300-5,400 m. The giant-drift is divided in two areas (southern and northern) by El Austral Seamount (Figure 4). The crest of the giant-drift outcrops in the present-day seafloor generating a clear bathymetric offset that marks the seaward limit of the CDS.

The depositional features are located at depths greater than 4,000 m at the base of the slope (BOS). In the southernmost part of the Valentin Feilberg Terrace, sheeted drifts are exhibited at depths of 3,800 to 4,500 m and change laterally northward into two mounded, elongated and separated drifts over the Valentin Feilberg Terrace (Figures 4 and 5). Towards the abyssal plain there are sheeted drifts that are marked by flat sea-bottom morphology, containing local progradational bodies, sediment waves and erosive scarps.

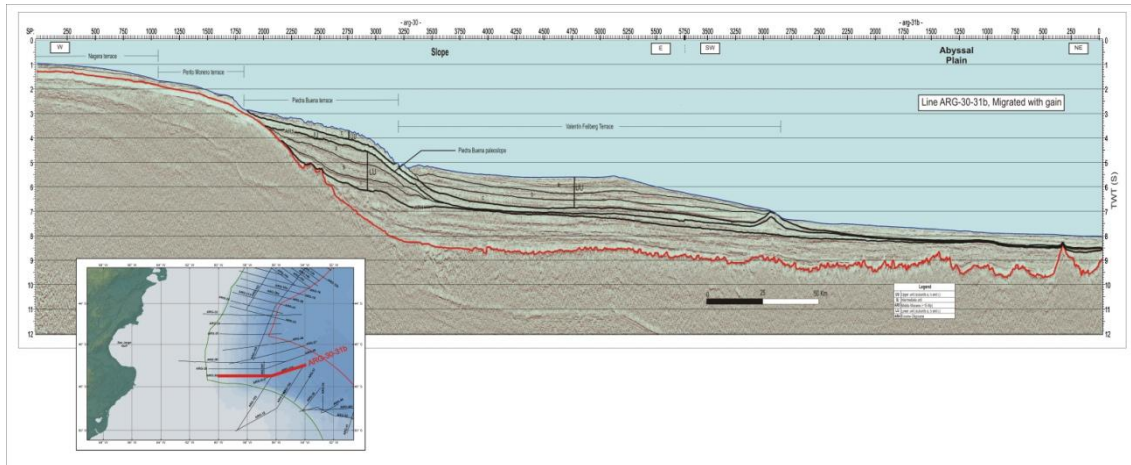


Figure 5: characteristic seismic section of the CDS (composite line ARG-30-31B).

4.2 The Submarine Canyons and Channels Sector

The Submarine Canyons and Channels Sector encompasses two submarine canyon systems (SCSs, see Figure 4). In the South, the West-Northwest trend Alte. Brown SCS crosses the slope down to a depth of 3,500 m, where it joins Channel-1. At this point Channel-1 trends North, but after meeting with the Alte. Brown SCS it turns Northeast, deepening and widening down to the BOS. To the North, the Ameghino SCS has a great shift in its trend, Northwest in the upper and middle slopes, Northeast at depths of 3,000 to 3,500 m, and then Northwest again, down to the BOS. Seaward of Channel-1, the depositional and erosive features described for the previous sector are also identified in the Valentin Feilberg Terrace (Figure 4).

The BOS off the Ameghino SCS lacks any rise or large submarine fans, and is closer to the 5,000 m isobath than anywhere else in the margin. These features illustrate the dominance of erosive processes at the depths where Channels 1, 2 and 3 merge in the same area and then turn east (see Figure 4).

5. Seismic Stratigraphy

For the purposes of describing the growth of the CDS, seismic stratigraphic analysis will be focused only in the upper part of the sedimentary record. Three major seismic units will be described (see Figure 5): lower unit (LU), intermediate unit (IU) and upper unit (UU).

A regional erosive discontinuity (D) correlated with AR4 D of Hinz, *et al.*, 1999 is at the base of the LU and its upper boundary is coincident with AR5 D reported by the same author. The LU comprises three subunits c), b), and a). Subunit c) as a lightly mounded external shape, with internal reflections onlapping the AR4 D. Subunit b) is a plastered drift prograding basinward. It is generally lightly deformed, and is deeply eroded in its seaward distal part. It exhibits highly continuous, well-stratified reflections. The upper boundary is an erosive local surface, which marks the morphological onset of the present-day Piedra Buena Terrace. Subunit a) has a weak to transparent acoustic response, and internal reflections onlap its basal boundary. Its upper boundary underpins the well-developed Piedra Buena Terrace. Towards the abyssal plain, all subunits evolve laterally to sheeted drifts, and then to the giant-drift.

The IU is an expansive aggradational unit, with a weak to transparent acoustic response. It has relatively constant thickness and is characterized by the same morphological domains as those of subunit a) of the LU. Toward the abyssal plain, the intermediate unit changes to sheeted drifts and then to the giant-drift.

The UU is mainly developed seaward of the Piedra Buena Terrace and is either very thin over this terrace. Its basal boundary is a key stratigraphic horizon. During UU deposition, the present-day Valentin Feilberg Terrace was developed, and the giant-drift in the abyssal plain was partly fossilized. The UU is internally composed of three subunits, whose reflections have stratified facies with medium amplitude and good lateral continuity. Subunit c), deeply eroded on the Piedra Buena Terrace, forms a sheeted drift below the Valentin Feilberg Terrace. Subunits b) and a) form two mounded and elongated drifts, and sheeted drifts seaward. Internal reflections migrate upslope, exhibiting a downlap termination over the basal limits.

6. Evolution of the CDS

The present-day configuration of the CDS was generated during different evolutionary stages including the depositional and erosive phases. The initial deep-water circulation stage (LU, Figure 6A) started with the development of AR4, representing the onset of Antarctic Bottom Current activity in the Argentina Basin. Hinz, *et al.*, 1999 dated this discontinuity as at the Eocene-Oligocene boundary, which could be related to the Drake Passage opening.

After that, the margin was affected by a major aggradational phase that began with the development of AR5 (early-middle Miocene, Hinz, *et al.*, 1999), marking the onset of IU (see Figure 6A). This can be associated with an important regional subsidence and global third-order highstand interval in the middle Miocene (Kennett, 1982; Haq *et al.*, 1987).

Present-day circulation stage (UU, Figure 6B) began from the base of the UU, which marked the start of major changes in paleoceanography and depositional type at the basin scale. The base of the UU could be late-middle Miocene in age (Hinz *et al.*, 1999).

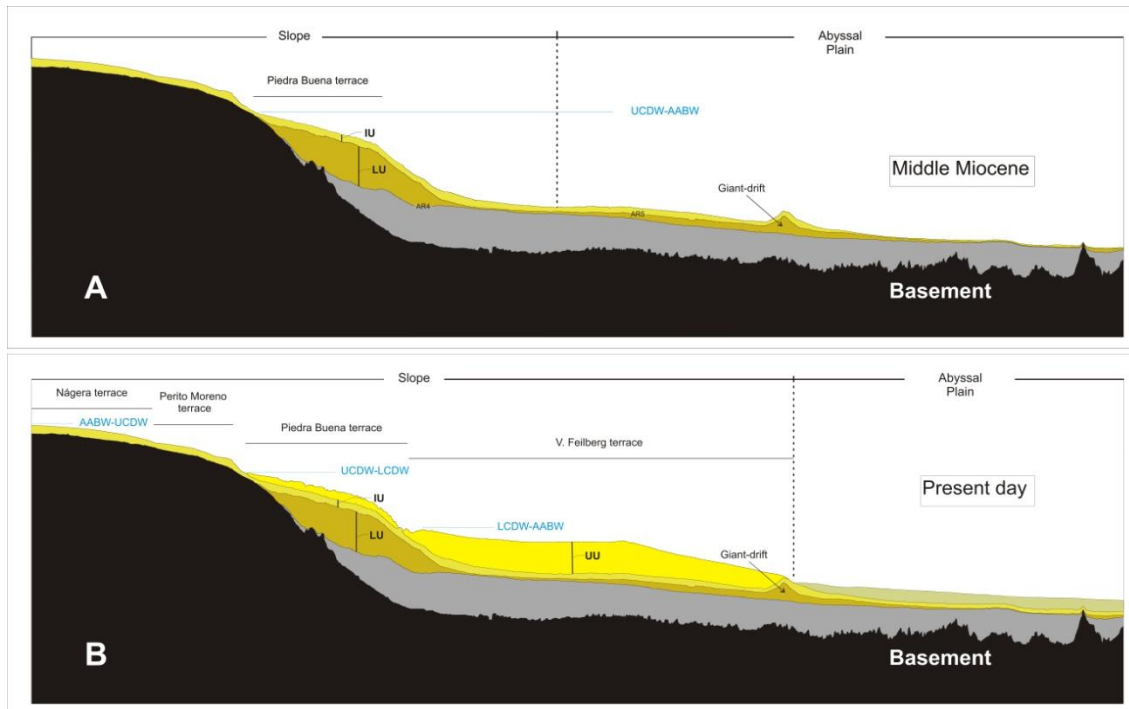


Figure 6: evolution sketch of the CDS in line ARG-30-31B (modified from Hernández-Molina *et al.*, 2009)

7- Determination of the Foot of the Slope by the General Rule in the Terraced Margin

To determine the foot of the slope by means of the general rule it is necessary to make reference to paragraph 5.1.3 of the Guidelines where this problem is formulated. The first step is to define the BOS region and after that the maximum change in the gradient within that base will be used to locate the FOS. As it is said in paragraph 5.4.5 of the Guidelines, in the BOS region the lower slope merges into the top of the continental rise or the deep ocean floor when the rise is not developed (ABLOS, 2006)

In this sector of the margin, the profiles have been analyzed using Savitzky-Golay filter grade 1 and 201 elements (10 km window) to identify the values that define the base of the slope and within that base, using wavelets Daubechies 2 (db2), the maximum change in the gradient is located to find the foot of the slope.

BOS and FOS could be determined using the accepted gradients which ranges between 1° and 6° for the lower slope, 0.8° to 0.2° for the continental rise (commonly 0.5°) and 0.15° for the deep ocean floor. Physiographic units identified in this sector are the continental slope and the deep ocean floor, as no rise has been identified according to the explanation given in section 4. Continental slope in this region is defined by the CDS and meets the abyssal plain at about 5,300-5,400 m water depth. The clearest example of this configuration is shown in the composite profile ARG-30-31B (Figure 7) where the terraced morphology of the slope can be imaged.

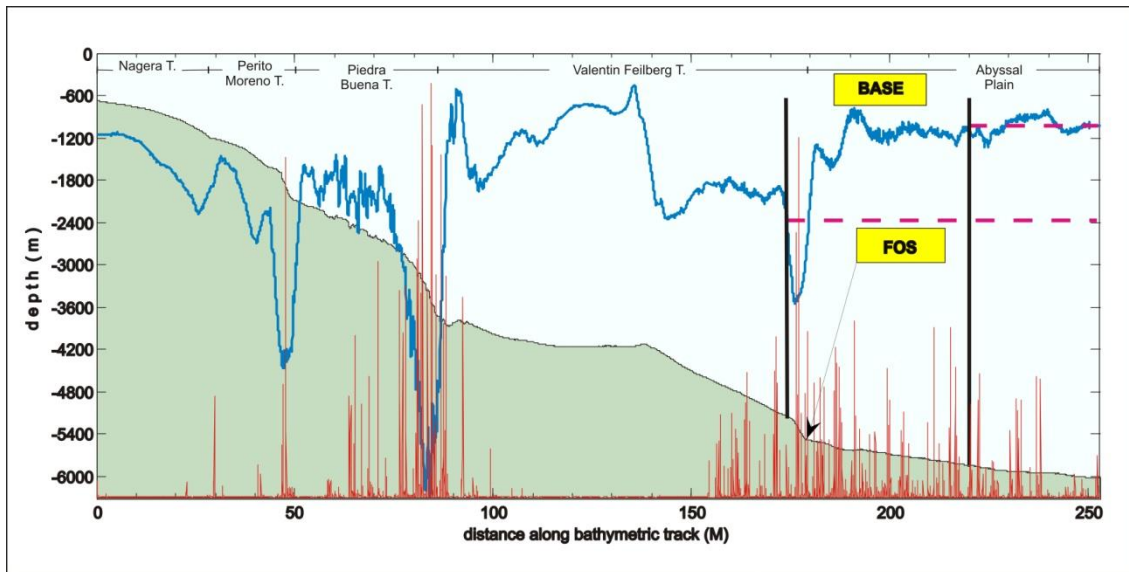


Figure 7: Identification of BOS and FOS along bathymetric profile ARG-30-31B. First derivative (blue line) and second positive derivative (red line).

8- Discussion and Conclusion

As it is seen in Figure 7, there is a maximum change in gradient associated with base of each terrace of the CDS. This fact causes some uncertainty about which of all those points should be considered the FOS. In the context of the CDS, the correct FOS point must be located at the base of the deepest terrace which coincides with the partial outcrop of the buried giant-drift.

In the Southern Passive Volcanic Argentine Margin the configuration of the continental slope is different in comparison with the classic morphological profile as it is defined by the CDS. Four well developed contouritic terraces, two contouritic channels and a buried giant-drift are the outstanding features of the CDS which extends from the shelf down to the abyssal plain without any rise. This configuration is due to the very active contouritic processes that have controlled the Southern passive volcanic Argentine Margin sedimentation and morphology along time to reach the present-day configuration.

The term continental rise refers to a physiographic domain located between the continental slope and oceanic basins, and its seaward limit is found where the regional gradient decreases until it becomes horizontal, at which points the abyssal plain domain begin. The continental rise is caused by the sedimentary build-up several kilometers thick, transported from the continents and deposited at the base of the continental slope by across-slope processes (Kennett, 1982). Erosional feature, such as submarine canyons and deep submarine channels, may go through continental rises, acting as the main pathways for the sedimentary transfer from shallow to deep submarine environments. Thus, the continental rise is a depositional feature closely related to the presence of deep submarine fans (Kennett, 1982; Einsele, G., 2000). With this contribution we conclude, based on the Argentine margin results, that when across-slope are no dominate in comparison with along-slope processes, a contourite depositional is developed. In this context the continental rise cannot be generated, especially if contourite terrace are formed by the action of different water masses. This kind of margins profile are different from those considered by the Scientific and Technical Guidelines of the CLCS (ABLOS, 2006).

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