

## The continental margin of Uruguay: Crustal architecture and segmentation

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### ABSTRACT

The Uruguayan continental margin comprises three sedimentary basins: the Punta del Este, Pelotas and Oriental del Plata basins, the genesis of which is related to the break-up of Gondwana and the opening of the Atlantic Ocean. Herein the continental margin of Uruguay is studied on the basis of 2D multichannel reflection seismic data, as well as gravity and magnetic surveys. As is typical of South Atlantic margins, the Uruguayan continental margin is of the volcanic rifted type. Large wedges of seaward-dipping reflectors (SDRs) are clearly recognizable in seismic sections. SDRs, flat-lying basalt flows, and a high-velocity lower crust (HVLC) form part of the transitional crust. The SDR sequence (subdivided into two wedges) has a maximum width of 85 km and is not continuous parallel to the margin, but is interrupted at the central portion of the Uruguayan margin. The oceanic crust is highly dissected by faults, which affect post-rift sediments. A depocenter over oceanic crust is reported (deepwater Pelotas Basin), and volcanic cones are observed in a few sections. The structure of continental crust-SDRs-flat flows-oceanic crust is reflected in the magnetic anomaly map. The positive free-air gravity anomaly is related to the shelf-break, while the most prominent positive magnetic anomaly is undoubtedly correlated to the landward edge of the SDR sequence. Given the attenuation, interruption and/or sinistral displacement of several features (most notably SDR sequence, magnetic anomalies and depocenters), we recognize a system of NW-SE trending transfer faults, here named Río de la Plata Transfer System (RPTS). Two tectono-structural segments separated by the RPTS can therefore be recognized in the Uruguayan continental margin: Segment I to the south and Segment II to the north.

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## 1. Introduction

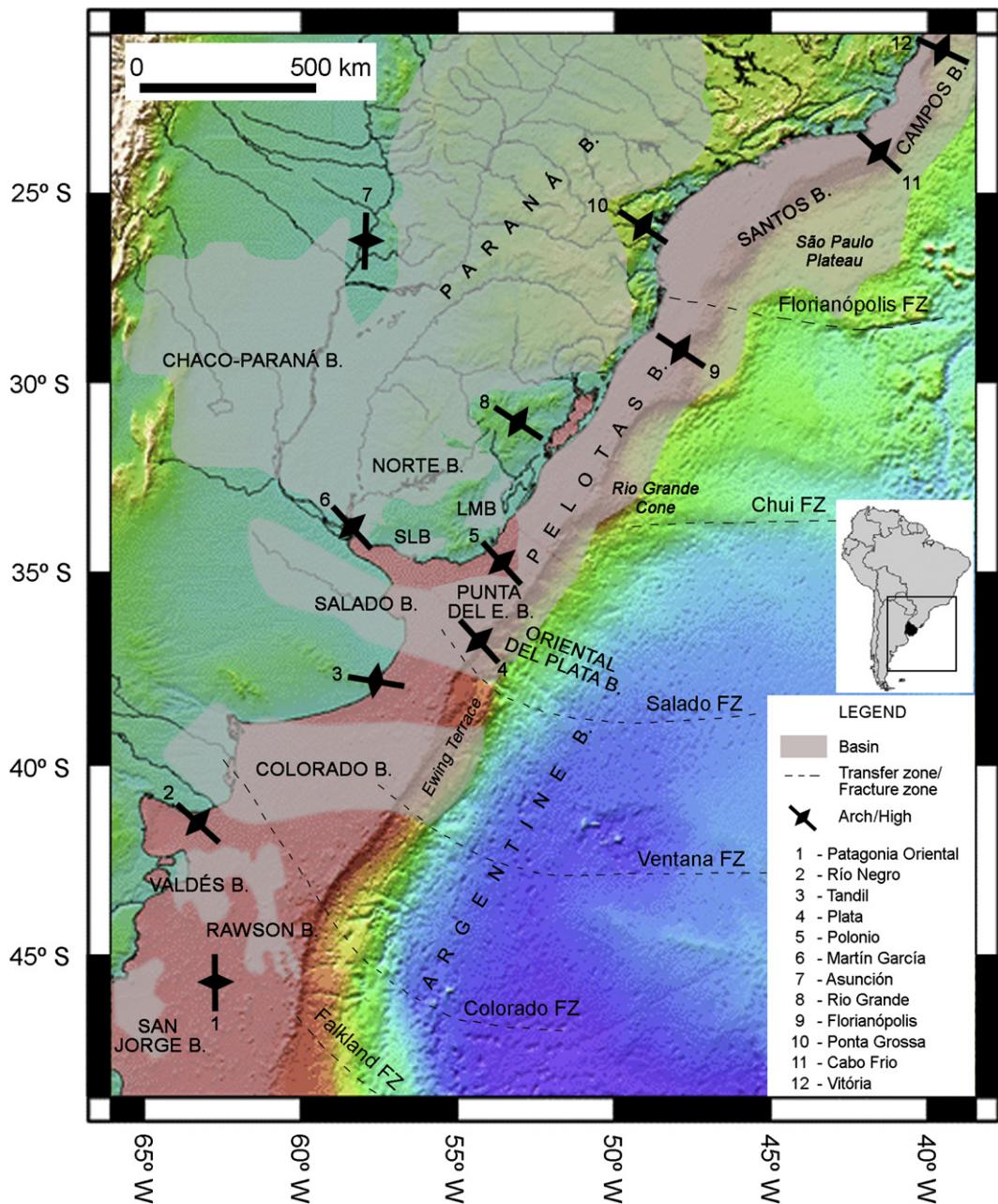
The South Atlantic margin of South America has received wide attention in recent times, due to its bearing on such diverse topics as margin structure and development (e.g., Jackson et al., 2000; Mohriak et al., 2002; Franke et al., 2007, 2010; Schnabel et al., 2008; Blaich et al., 2009), erosional and depositional products of contour currents (e.g., Hernández-Molina et al., 2009, 2010), sediment dynamics and slope stability (e.g., Krastel et al., 2011), source rock maturity (Grassman et al., 2011), subsidence analysis (e.g., Contreras et al., 2010), and petroleum potential (e.g., Urien, 2001). Although some of these studies made indirect references to the offshore basins of Uruguay, there are no recent studies dealing specifically with them.

As it is typical for most South Atlantic margins, the Uruguayan continental margin is of the volcanic rifted type (e.g. Hinz et al., 1999; Franke et al., 2007, 2010). Large wedges of seaward-dipping reflectors (SDRs), interpreted as volcanosedimentary sequences formed during the break-up of Western Gondwana (e.g. Gladzenko et al., 1997; Eldholm et al., 2000; Jackson et al., 2000; Talwani and Abreu, 2000; Menzies et al., 2002; Franke et al., 2007, 2010), are clearly recognizable in seismic sections. It has been recently proposed by Franke et al. (2007) that the Argentinean and Uruguayan continental margin is segmented by several NW-trending transfer zones (Fig. 1), which delimit four main ca. 400 km long segments. This scheme received recent support from potential field data (Blaich et al., 2009).

In this contribution we describe the internal architecture of the SDR wedges, as well as other volcanic features interpreted from seismic sections, notably horizontal reflections seaward of the SDRs interpreted as flat-lying basalt flows. Moreover, we recognize two distinct tectono-structural segments in the Uruguayan continental margin, divided by a transfer zone.

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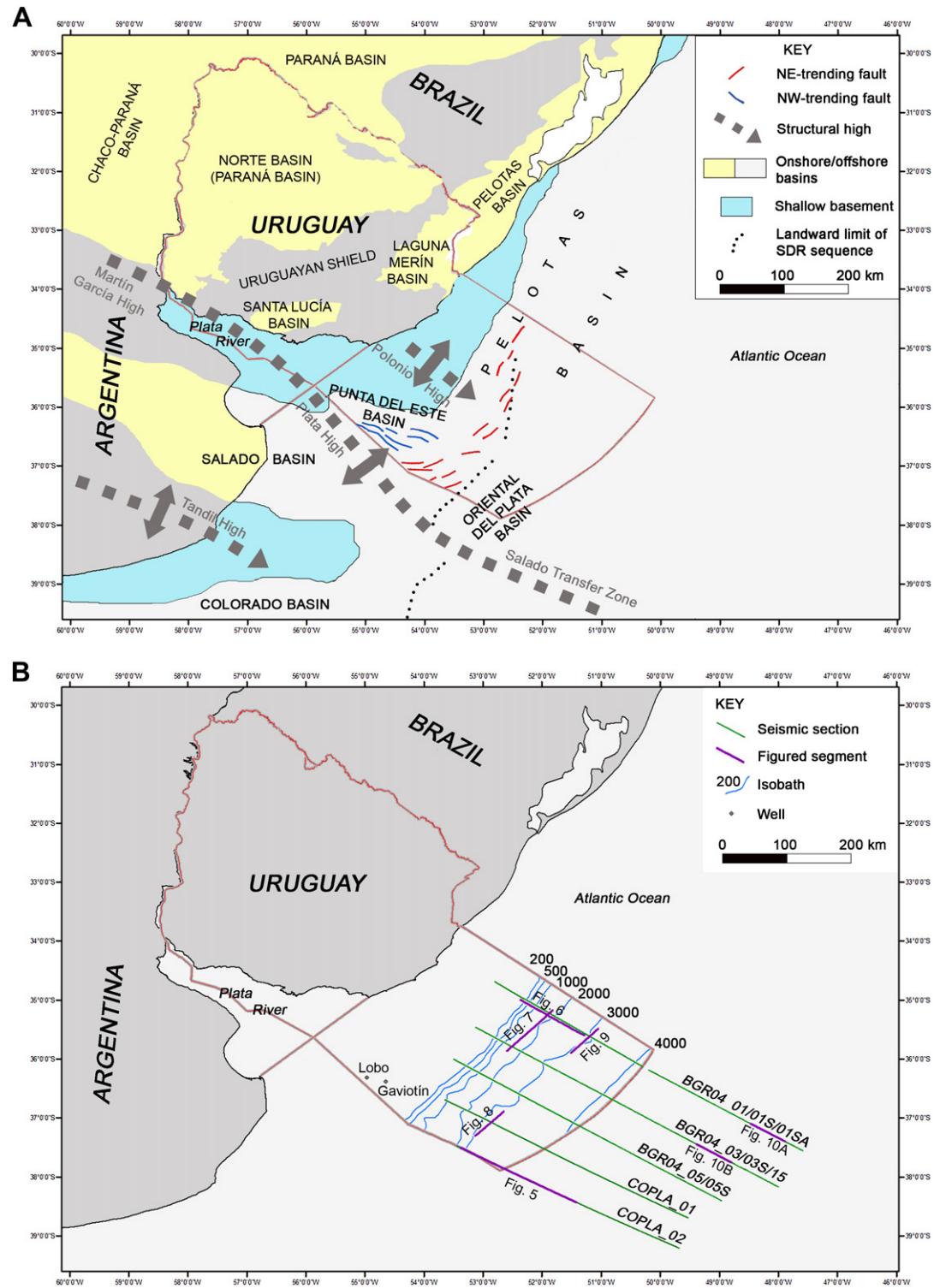
**Figure 1.** Topographic-bathymetric map of southern South America overlain by selected offshore and onshore basins and structural highs. Inset shows the location of the figure within South America, with Uruguay coloured in black. Abbreviations: LMB, Laguna Merín Basin. SLB, Santa Lucía Basin. For more detail see [Figure 2](#). After Mohriak (2003), Franke et al. (2007), Milani et al. (2007) and Blaich et al. (2009). Seafloor topography after Becker et al. (2009).

## 2. Geological framework

Six sedimentary basins are recognized in Uruguay: three of them are offshore ([Figs. 1 and 2A](#)), and are called Punta del Este, Pelotas and Oriental del Plata basins (Ucha et al., 2004; de Santa Ana et al., 2009), while the remaining three are onshore basins, and are known as Norte (which is the southern portion of the Paraná Basin, and is present in the pre-rift sequence of the continental margin; see below), Laguna Merín (the onshore equivalent of the Pelotas Basin) and Santa Lucía basins ([Figs. 1 and 2A](#)). The genesis of the offshore sedimentary basins is related to the break-up of Gondwana and the opening of the South Atlantic Ocean in the Late Jurassic-Early Cretaceous (e.g., Almeida, 1967; Rabinowitz and LaBrecque, 1979; Gladczenko et al., 1997; Jackson et al., 2000). The

three basins have a total extent, in the Uruguayan territorial waters, of more than 85,000 sq km (the Pelotas and Oriental del Plata basins are the only ones which reach the 200-nautical mile limit). Although the maximum drilled thickness is of 3631 m (Gavotín well; [Fig. 1B](#)), it must be taken into account that the well was drilled in very shallow waters in a proximal position and over a structural high. Indeed, based on seismic data the maximum thickness exceeds 8000 m.

The Punta del Este Basin, which developed on continental crust, is a funnel-shaped aulacogen (Stoakes et al., 1991; Ucha et al., 2004), indeed the northernmost 'aulacogenic embayment' (Urien, 2001) recorded in the South Atlantic margin of South America. According to those authors, it is separated from the Salado Basin to the WSW by the Martín García/Plata High, and



**Figure 2.** A, tectono-structural map of Uruguay depicting onshore and offshore basins and structural highs. The landward limit of the SDR sequence is based on Franke et al. (2007). For a more accurate see Figures 11–13. B, location of the main seismic lines interpreted and of Figs. 4–8 and 10. Selected isobaths are shown (values in meters). The location of the Gaviotín and Lobo wells is also indicated.

from the Pelotas Basin to the WSW by the Polonio High (Figs. 1 and 2). The Pelotas Basin, which corresponds to the flexural border of a precursor rift structure and develops on continental, transitional and oceanic crust, extends from the Polonio High up to the Florianópolis Fracture Zone (Fontana, 1996), where the Santos Basin starts (Fig. 1).

Two main structural trends can be recognized in the Uruguayan offshore basins (Fig. 2A). On one hand, the NW trend of the proximal Punta del Este Basin (Fig. 2A) indicates an extensional stress normal to the continental margin, as in several Argentinean South Atlantic basins (e.g. Salado, Colorado, and Golfo de San Jorge basins; Figs. 1 and 2A), attributed to the initial rifting stage which started in

the Jurassic and subsequently aborted. On the other hand, the NE trend of the distal Punta del Este Basin and Pelotas Basin (Fig. 2A) is in accordance with the general trend of most Brazilian South Atlantic basins (Fig. 1), reflecting a second rifting stage of Early Cretaceous age. It is interesting to note that NE-trending faults are also recorded in the distal parts of Punta del Este Basin, with no evidence so far that older faults are significantly overprinted by younger ones (Fig. 2A). This spatial differentiation was also observed in the Colorado Basin (Autin et al., 2011), but differs from what is observed in other basins around the world with several rifting events, such as the Bonaparte Basin in the northern Australian shelf (e.g. Cadman and Temple, 2004).

In response to different basin styles, subsidence histories, and sedimentary inputs, as well as the dynamics of the Polonio High (which probably was a positive area from the Jurassic at the end of the Cretaceous), the Punta del Este and Pelotas basins had a different evolution until the Late Maastrichtian. The stratigraphy of both basins is represented by large depositional sequences (see also Stoakes et al., 1991; Ucha et al., 2004; Morales et al., 2010), briefly described below.

### 2.1. Punta del Este Basin

The pre-rift sequence of the Punta del Este Basin is represented not only by Precambrian crystalline rocks of the Uruguayan Shield but also by Paleozoic sedimentary rocks drilled by the Gaviotín well (Fig. 2B), which can be correlated with some units of the Norte (Paraná) Basin (Veroslavsky et al., 2003; Fig. 2A).

The synrift sequence, of inferred Jurassic-Neocomian age, includes alluvial-fluvial and lacustrine deposits interbedded with volcanic and volcanioclastic rocks. Several conspicuous hemigrabens can be recognized in the Punta del Este Basin, with a lower, essentially volcanic fill and an upper siliciclastic fill (totalling up to 2500 m according to seismic data).

The early post-rift sequence shows a clear transgressive character, with the development of marine sequences for the first time since the Paleozoic. This presumably Barremian-Aptian sequence is equivalent to the transitional sequence of the Orange Basin and other productive South Atlantic basins (e.g. Bray and Lawrence, 1999; van der Spuy, 2003). The remainder of the Cretaceous post-rift sedimentation is characterized by several sequences of minor order, including the development of conspicuous clinoforms (Morales et al., 2010).

### 2.2. Pelotas Basin

In the Pelotas Basin (undrilled in the Uruguayan portion) the pre-rift sequence has not been characterized yet, although it has been drilled in the Brazilian portion of the basin, where it has been shown to correspond to Paleozoic and Mesozoic units of the Paraná Basin (Bueno et al., 2007). The synrift sequence shows a much more restricted hemigraben development. The Cretaceous post-rift sequence, although present, is less thick than in the Punta del Este Basin. It is interesting to note that these marine sequences (developed during the Cretaceous post-rift sedimentation in both the Punta del Este and Pelotas basins) are not recorded in the Salado and Colorado basins. This was due to the presence in the Argentinean basins of a conspicuous external high (see e.g. Urien and Zambrano, 1996), which precluded marine incursions until the Maastrichtian. This external high is only present with a subtle expression in the southernmost tip of the Punta del Este Basin, disappearing towards the NE.

### 2.3. Common evolution in the Cenozoic

Late Maastrichtian sedimentation (Gaviotín Formation; Ucha et al., 2004) surpassed, for the first time, the internal and external highs, and a single offshore sedimentary province was formed (also including the Salado Basin). It is represented by a series of events induced by eustatic oscillations, corresponding to regressive and transgressive deposits in the Paleocene, fluvio-deltaic regressive sediments in the Eocene-Oligocene, transgressive deposits in the Miocene, deltaic progradations in the Miocene and transgressive deposits in the Pleistocene. In the northern region of the margin the Cenozoic package reaches a thickness of 6000 m.

### 2.4. Oriental del Plata Basin

The ultradeep water Oriental del Plata Basin (Figs. 1 and 2A), the boundaries of which are properly defined herein for the first time, is in part equivalent to the Argentine Basin of the Argentinean margin (which is also known as Patagonia Oriental Basin or Ameighino Basin; Urien and Zambrano, 1996; Urien, 2001; Barredo and Stinco, 2010). Its sedimentary fill reaches 5000 m and comprises Cretaceous and Cenozoic marine sequences. Its limit with the Punta del Este Basin is the landward limit of the SDR sequence (Fig. 2A). Consequently, the Oriental del Plata Basin develops over both transitional and oceanic crust (while the Punta del Este basin develops only over continental crust, as stated above). Thus, the Oriental del Plata Basin as defined herein is smaller in extent than conceived by other authors (e.g. see de Santa Ana et al., 2009).

## 3. Data and methodology

2D multichannel reflection seismic lines (Fig. 2) surveyed by COPLA (Comisión Nacional del Límite Exterior de la Plataforma Continental, Argentina) in the end of 2001-beginning of 2002 and by BGR (Federal Institute for Geosciences and Natural Resources, Germany) in 2004 were interpreted. The BGR cruise was part of an extensive program of deep seismic profiling along the Argentinean and Uruguayan margins, between 1987 and 2004, which produced a total data volume of 25,677 linear km (Hinz et al., 1999; Franke et al., 2007).

These lines, totalling 2412 linear km, almost reach the 350-nautical mile distance from the base line. Both time and depth-converted sections were available. Seismic data was acquired with a shot-point interval of 50 m in both the COPLA and BGR surveys, while streamer length was 6000 and 8000 m respectively (for more details see Neben et al., 2005; Franke et al., 2007; Hernández-Molina et al., 2010).

Data were locally complemented using near 10,000 km of 2D multichannel reflection seismic lines surveyed by CGGVeritas in 2007, which are part of a multiclient package property of ANCAP (Administración Nacional de Combustibles, Alcohol y Portland), the Uruguayan national oil company.

In all seismic sections key reflectors were interpreted, including top of SDR sequence (break-up unconformity, or AR1 of Hinz et al., 1999), top of oceanic crust, Cretaceous-Paleogene boundary (AR3 or Pedro Luro equivalent of Hinz et al., 1999 and Franke et al., 2007, respectively), sea bottom and, when it was possible, Mohorovicic discontinuity (Moho). Crustal features were then mapped, using the softwares The Kingdom Suite 8.5 and ArcGis 9.2. It must be noted that a detailed seismostratigraphic analysis of the Uruguayan offshore basins is in progress and falls beyond the scope of this contribution.

#### 4. Results and discussion

According to the employed methodology, it was possible to recognize three different crustal types in the offshore of Uruguay: continental, transitional and oceanic crust (Figs. 2 and 3).

##### 4.1. Continental crust

The continental crust is characterized by discontinuous reflectors of variable amplitude. It is affected by faulting, which is more intense in the Punta del Este Basin. Faulting is both synthetic and antithetic in the seaward half of the Punta del Este Basin (forming grabens, hemigrabens and horsts), and antithetic in the Pelotas Basin. Continental crust in the southern region of the continental margin extends over 300 km offshore, almost twice as far as in the northernmost region.

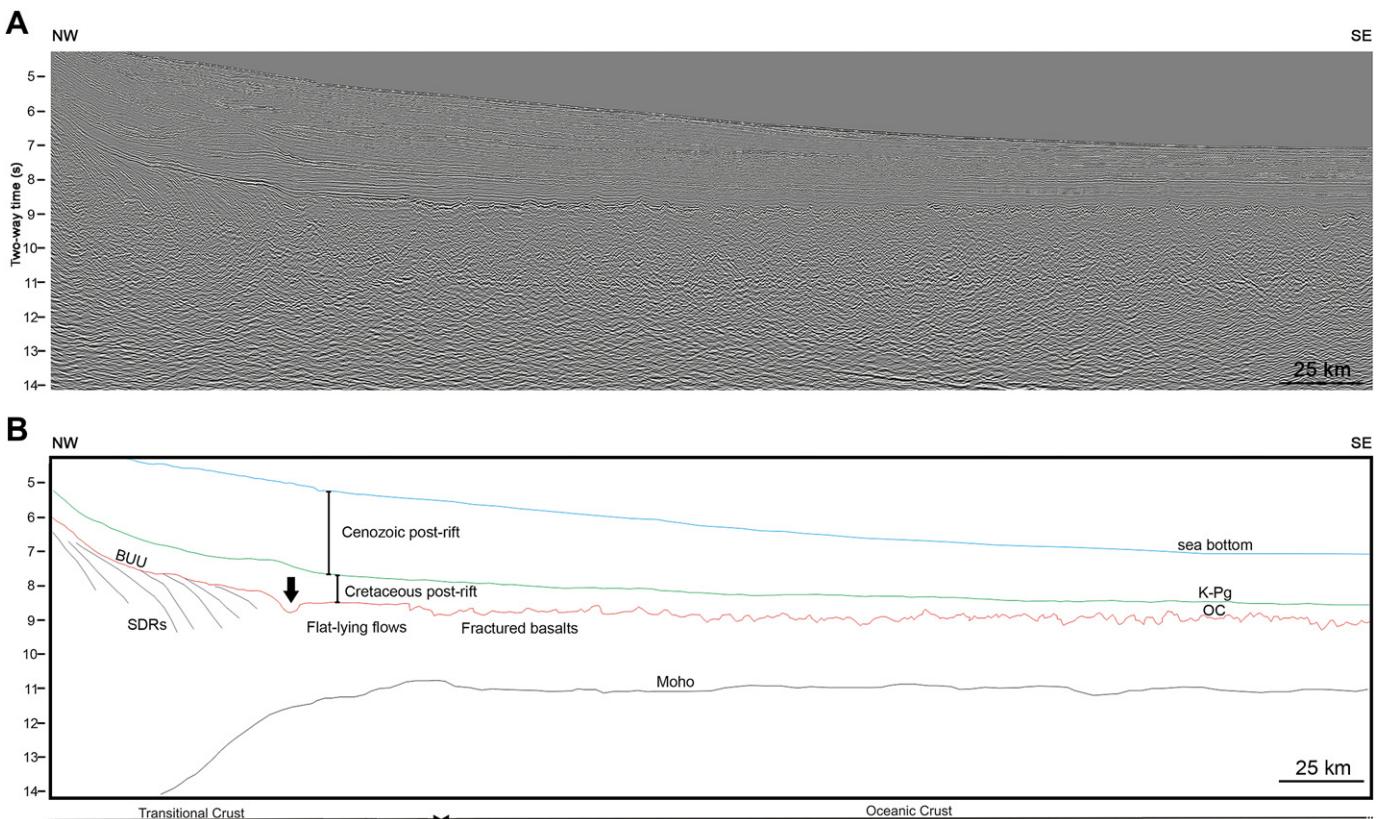
##### 4.2. Transitional crust

The transitional crust is characterized by significant Cretaceous magmatic activity (both extrusive and intrusive). In volcanic rifted margins the transitional crust usually includes, according to several authors (e.g. Bauer et al., 2000; Eldholm et al., 2000; Planke et al., 2000; Menzies et al., 2002; Geoffroy, 2005; Schnabel et al., 2008; Franke et al., 2007, 2010), seaward-dipping reflectors (SDRs), flat-lying basalt flows, dikes, and a high-velocity lower crust/lower crustal body (HVLC/LCB). These features are observed along the continental margin of Uruguay (Figs. 2–9), as already pointed out concerning SDRs by Hinz et al. (1999), Neben & Franke (in Neben et al., 2005), Franke et al. (2007: Figs. 2 and 10), and Blaich et al. (2009: Fig. 2).

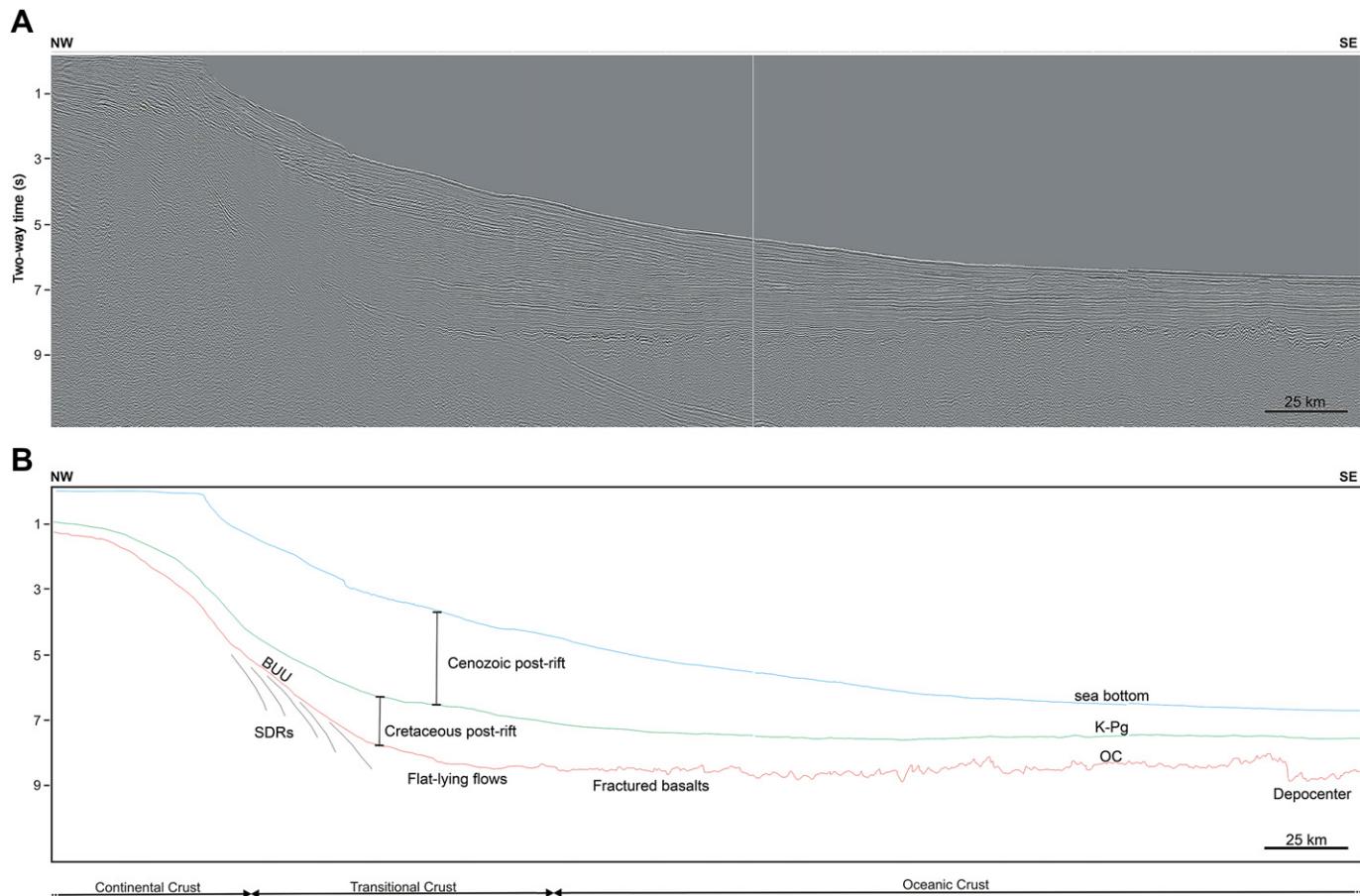
SDRs are visualized in seismic sections (Figs. 2–5) as wedges of arcuate, divergent reflectors with convexity to the top, which dip in seaward direction (being steeper with increasing depth). They are usually interpreted as basaltic flows, extruded sub-aerially in a few million years (during the last stage of rifting and immediately before the formation of oceanic crust), which are interbedded with volcanoclastic and clastic sediments (Mutter et al., 1982; Eldholm et al., 2000; Jackson et al., 2000; Planke et al., 2000; Talwani and Abreu, 2000). There is controversy concerning the nature of the transitional crust below the SDRs, being interpreted alternatively as extended continental crust (Austin and Uchupi, 1982; Gladchenko et al., 1997) or as an essentially igneous, proto-oceanic crust (e.g. Bauer et al., 2000).

Prominent reflections allow us to recognize two different wedges of SDRs along the Uruguayan continental margin (Fig. 5), the seaward wedge (SDR2) being younger, less steeply dipping and wider than the landward wedge (SDR1). Both wedges correspond to 'inner' SDRs. In fact, 'outer' or 'oceanic' SDRs have not been yet recognized, differing from other volcanic rifted margins (see Planke et al., 2000; Bauer et al., 2000; Geoffroy, 2005; Franke et al., 2007, 2010). The seaward termination of each wedge appears to be related to antithetic faults (this is evident at least in the northern segment; Fig. 5), which agrees with recent models of SDR emplacement (e.g. see Geoffroy, 2005).

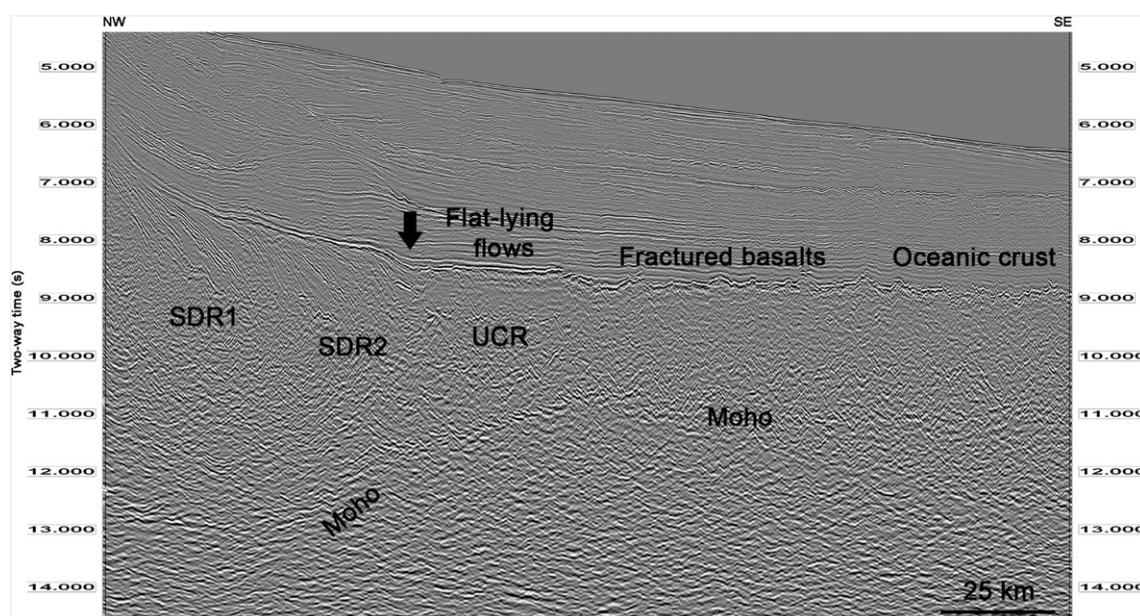
In dip seismic sections, SDRs of the southern region seem to have a more convex top and subvertically ending reflections (compare Figs. 4 and 5). It can be observed in strike seismic sections that the SDR sequence of the southern region dips and thickens to the north (Fig. 6), as in the Brazilian Pelotas Basin, which is accordance with the northward propagation of rifting (Talwani and Abreu, 2000). In strike seismic sections of the southern region, the SDR sequence is heavily affected by faulting (Fig. 7).



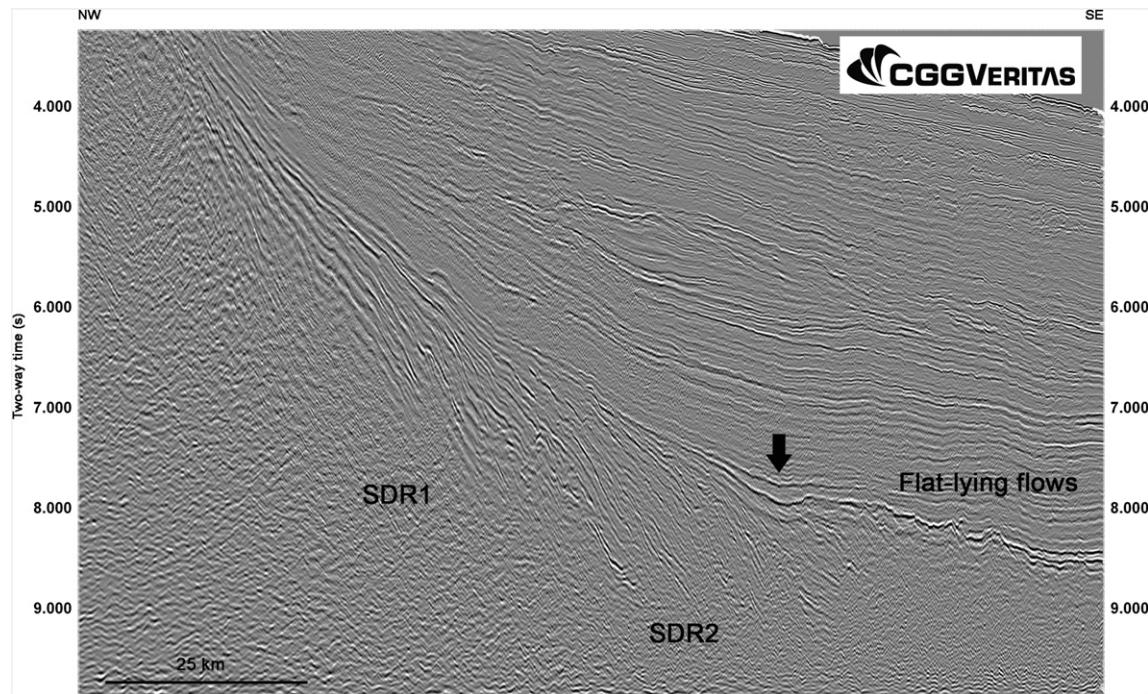
**Figure 3.** A, dip seismic section (COPLA-02) representative of the southern region (Oriental del Plata Basin), showing transitional and oceanic crusts. B, schematic interpretation. The arrow indicates a depression between the SDR sequence and flat-lying basalt flows. Abbreviations: BUU, break-up unconformity; OC, top of oceanic crust; K-Pg, Cretaceous-Paleogene boundary. See location in Figure 2B, with details of transitional crust portion shown in Figure 5.



**Figure 4.** A, dip seismic section (BGR04-01/01S/01SA) representative of the northern region (Pelotas Basin), showing continental, transitional and oceanic crusts. B, schematic interpretation. Abbreviations: BUU, break-up unconformity; K-Pg, Cretaceous-Paleogene boundary; OC, top of oceanic crust. See location in Figure 2B, and detailed portions shown in Figures 6 and 10A.



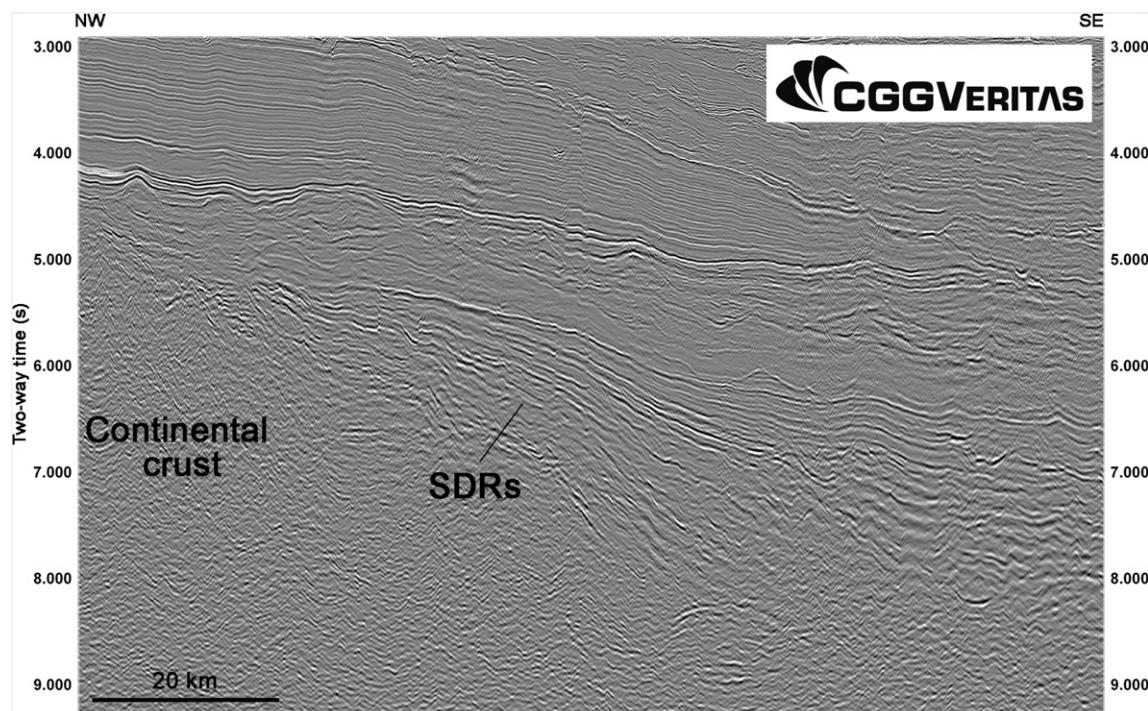
**Figure 5.** Detail of dip seismic section (COPLA-02) showing SDR wedges, flat-lying flows, fractured basalts and oceanic crust of the southern region. Abbreviations: SDR, seaward-dipping reflectors; UCR, upper crustal reflections. The arrow indicates a depression. See location in Figure 2B.



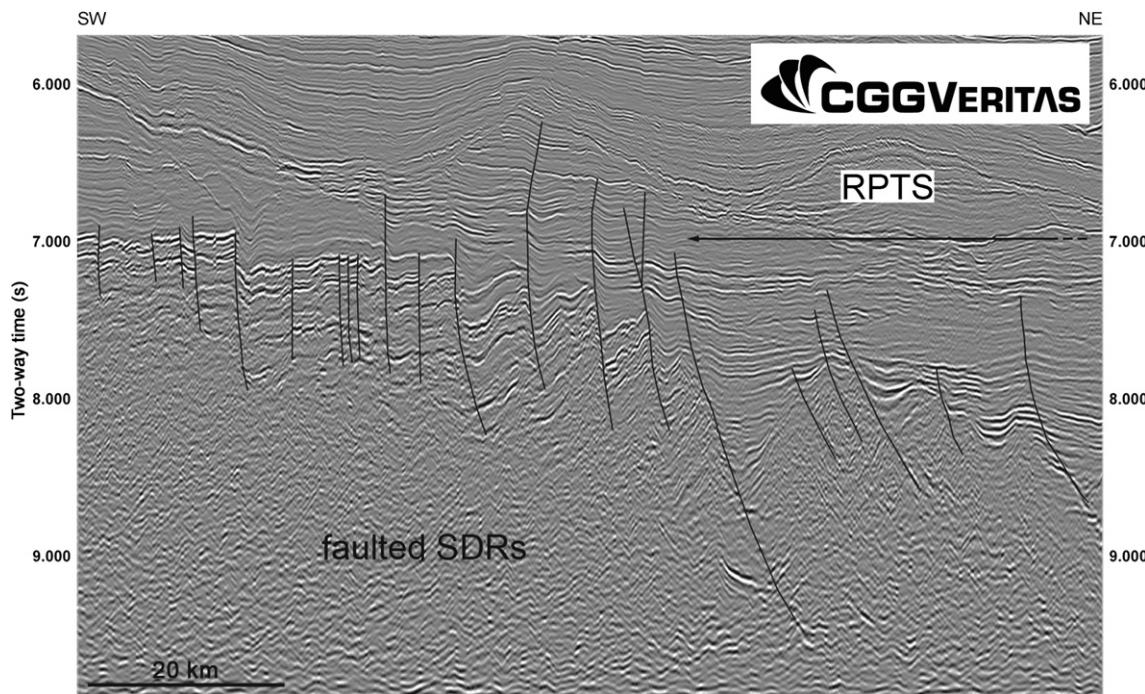
**Figure 6.** Detail of dip seismic section showing SDR wedges and flat-lying flows in the northern region. Abbreviations: SDR, seaward-dipping reflectors; UCR, upper crustal reflections. The arrow indicates a depression. See location in Figure 2B. Published with permission of CGGVeritas.

The SDR sequence has a maximum total width of 80–85 km (Figs. 2–5) and a thickness of more than 3 km, thus exceeding the maximum drilled thickness (1 km) of onshore flood basalts of the Arapey Formation (related to the Serra Geral magmatism) in the Uruguayan portion of the Paraná Basin (de Santa Ana and Veroslavsky, 2003; Fig. 2A). The SDR sequence becomes narrower towards, and is interrupted at, the central portion of the Uruguayan margin (Figs. 11–13).

Two South Atlantic SDR provinces have been recognized by Talwani and Abreu (2000), Santos-San Jorge (although SDRs masked by salt may be present in the Campos Basin; Jackson et al., 2000) and Walvis-Orange. From an exploratory point of view, the SDR sequences (analogue to the intertraps associated with basaltic flows in onshore Uruguay) have been interpreted by some authors to host hydrocarbon accumulations, as in the case of the Kudu gas field (offshore Namibia; Bray and Lawrence, 1999). Even source rock



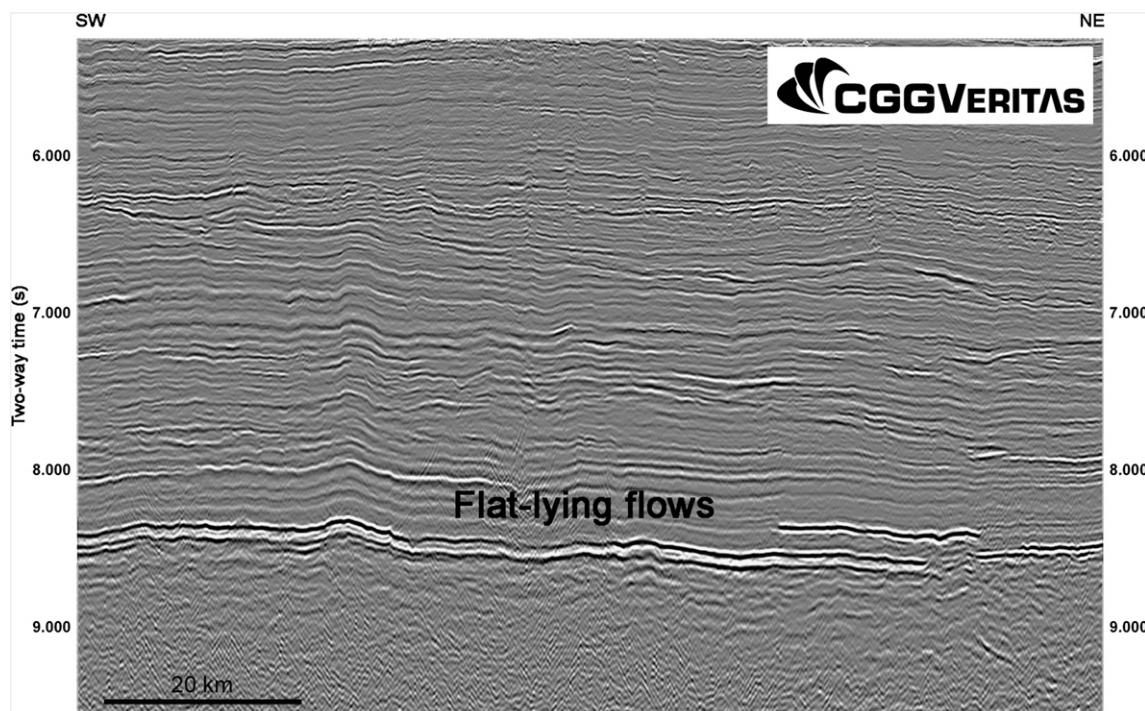
**Figure 7.** Detail of strike seismic section showing SDR sequence in the northern region. See location in Figure 2B. Published with permission of CGGVeritas.



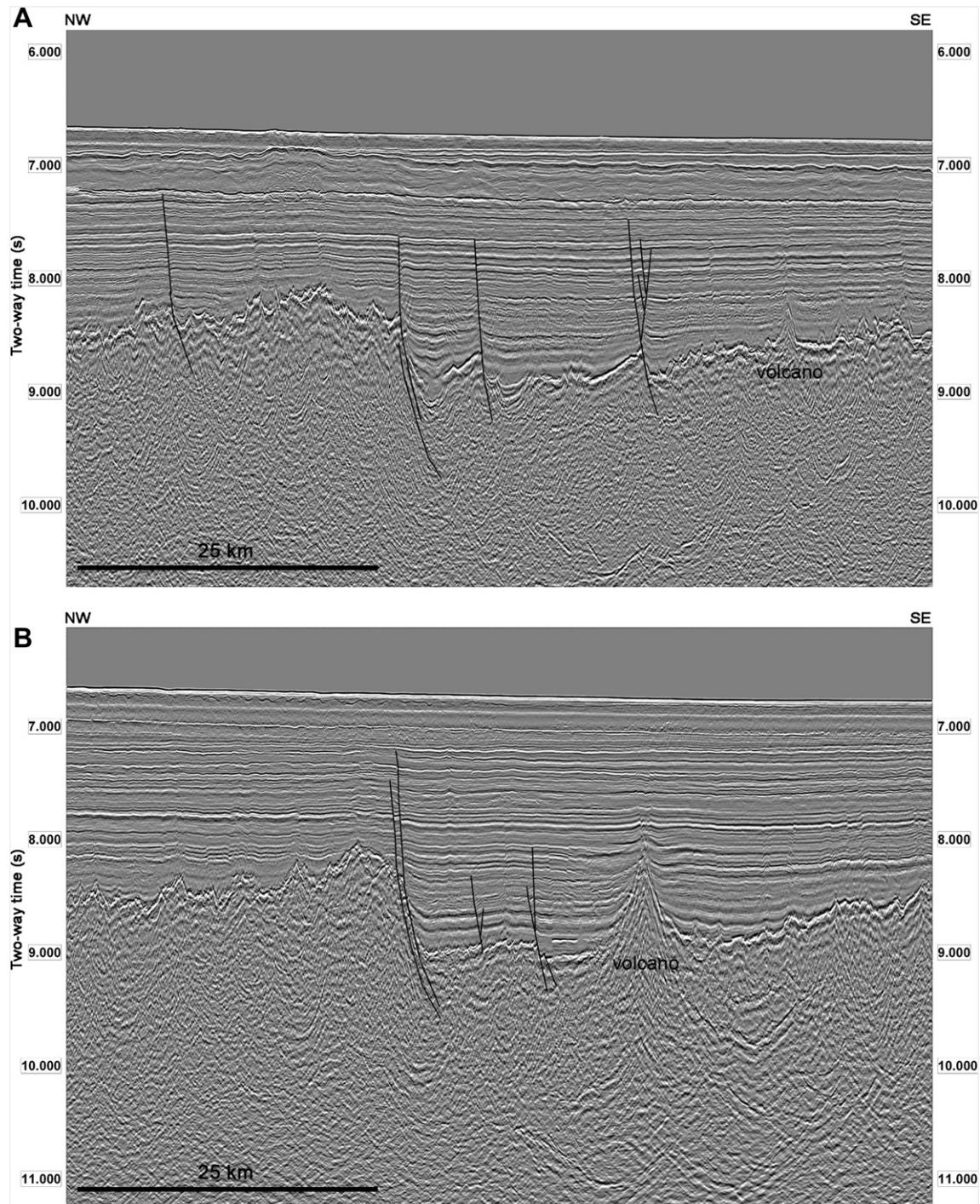
**Figure 8.** Detail of strike seismic section showing faulted SDR sequence in the southern region. Note that towards the northeast (towards the right in the figure) SDRs are interrupted, and a group of faults related to the Rio de la Plata Transfer System are recognized. The RPTS influences SDR faulting. These faults are probably subparallel to both the RPTS and the Salado Transfer Zone. See location in [Figure 2B](#). Published with permission of CGGVeritas.

potential has been proposed in certain basins (e.g. offshore Mozambique; [Matthews et al., 2001](#)). Several controversial or incompletely known topics still exist concerning the SDRs (e.g. [Planke and Alvestad, 1999](#); [Mohriak et al., 2002](#)), which are beyond the scope of this paper.

Seaward of the SDR sequence, but landward of the oceanic crust, horizontal and subparallel reflectors with high acoustic impedance contrast are recognized ([Figs. 2–5 and 8](#)). They probably represent flat-lying basalt flows (e.g. [Bauer et al., 2000](#); [Planke et al., 2000](#); [Franke et al., 2007, 2010](#)), with variable width (40–80 km).



**Figure 9.** Strike seismic section showing at 8.5 s flat-lying flows of the northern region. See location in [Figure 2B](#). Published with permission of CGGVeritas.



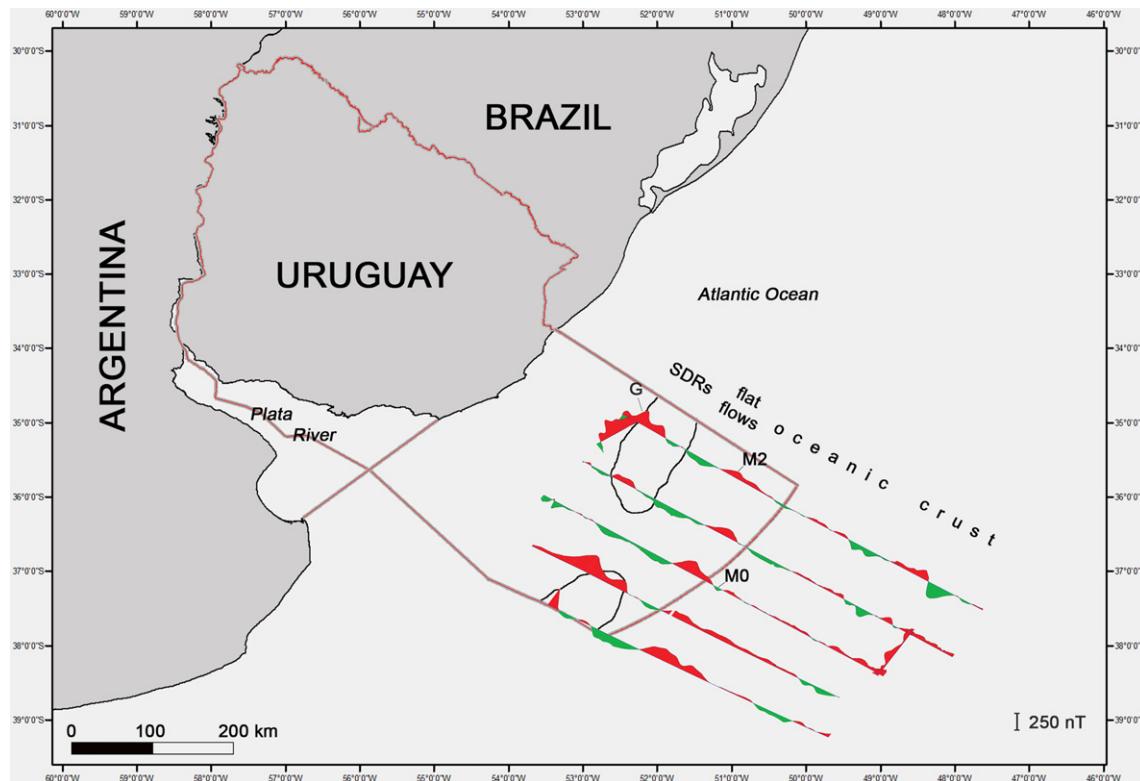
**Figure 10.** Dip seismic sections BGR04-01SA (A) and BGR04-03S (B) showing a deepwater depocenter in the northern region. Note the large volcanic cone in B. See location in Figure 2B.

Underlying flat-lying flows are stacks of irregular and hummocky reflections (Fig. 4), called Upper Crustal Reflections (UCR) by Franke et al. (2010), which are believed to mark the transition from subaerial to submarine eruptions (see also Planke et al., 2000).

A depression between the SDRs and the flat-lying basalts (Figs. 4 and 5) can be interpreted as the scarp of a basalt pile (as suggested independently by Franke et al., 2007; Fig. 8). The depression could have been enhanced due to fault-related subsidence of the distal SDRs. Bassetto et al. (2000) mentioned a similar feature in the continental margin of Brazil, noting the concavity of the superimposed horizons. The depression is filled either by volcanics or

hard sedimentary rocks (given the high seismic velocities). The width of the depression is variable, appearing to be larger at the central portion of the margin (where SDRs are not recognized). Clear outer volcanic highs have not been recognized, differing from other margins (Bauer et al., 2000; Planke et al., 2000; Franke et al., 2007, 2010).

Differing from the continental crust, transitional crust appears to be wider in the northern segment, with a maximum width of near 150 km, compared to a maximum width of 125 km in the southern segment. The thickness of the transitional crust is variable, given the shallowing of the Moho discontinuity (Figs. 2 and 4).



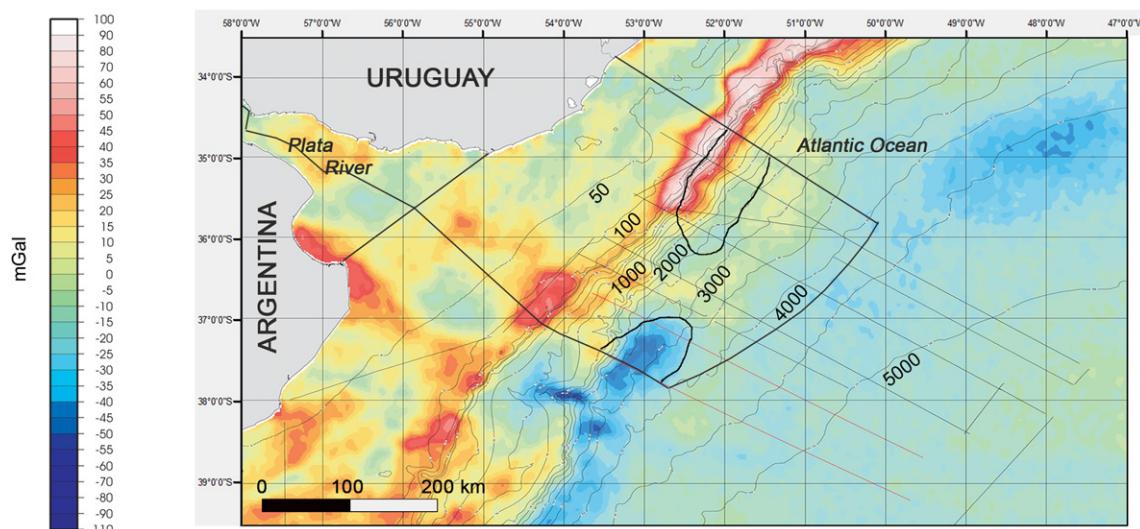
**Figure 11.** Magnetic anomaly map of the offshore of Uruguay, based on COPLA and BGR data. Black lines delimit the extent of SDR sequences. Note close correspondence between the main positive anomaly (G anomaly) and the landward edge of the SDR sequence. Seafloor spreading anomalies after Schrenkenberger and Paterlini (2005). Scale in miligals.

Thickness values typical of oceanic crust are reached seaward of the flat-lying basalt flows. Preliminary density modelling (Neben et al., 2005; Schnabel et al., 2010; and unpublished seismic refraction data, ANCAP) suggests the presence of high-velocity lower crust (HVLC) in the transitional crust below the region of the SDRs. In general, HVLC has been interpreted as underplated material, being typical of most rifted volcanic margins (e.g. Kelemen and Holbrook, 1995; Menzies et al., 2002; Geoffroy, 2005; Gernigon et al., 2005), including those of Argentina and the conjugate margin (Bauer et al.,

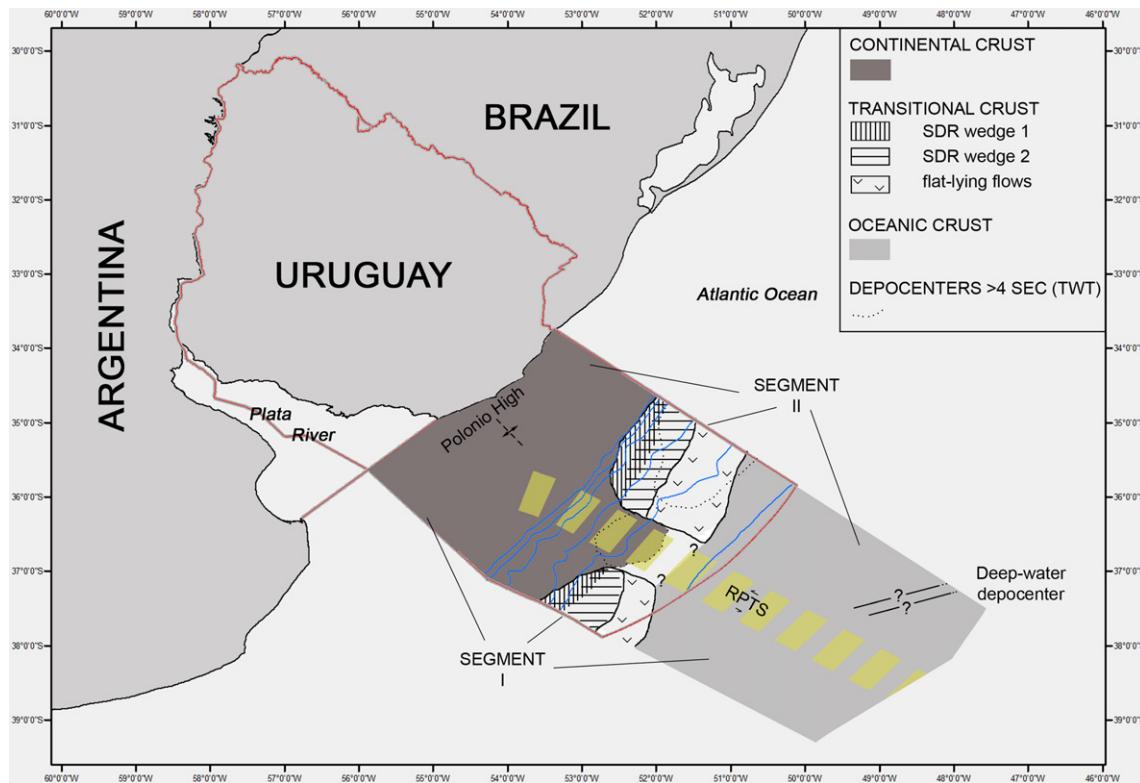
2000; Schnabel et al., 2008; Hirsch et al., 2009). It must be taken into account that Heyde in Neben et al. (2005) used a 25-km wide SDR sequence, when the real width is three times larger.

#### 4.3. Oceanic crust

The transition between flat-lying flows and oceanic crust is not sharply demarcated, spanning several kilometres of fractured basalts (Figs. 2–5). The oceanic crust is readily recognized due to its



**Figure 12.** Free-air anomaly and bathymetric map of the offshore of Uruguay, based on COPLA and BGR data, as well as Sandwell and Smith (2005). Black lines delimit SDR sequences within the study area. Note close correspondence of the main positive anomaly with the shelf-break.



**Figure 13.** Map of crustal types and major tectonic features in the continental margin of Uruguay. Continental and oceanic crusts are indicated. Within the transitional crust, SDR wedges and flat-lying flows are mapped. There is a certain amount of overlap between SDR 1 (the more landwardly placed wedge) and SDR 2 (the more seawardly placed wedge). The RPTS interrupts SDR sequences and the flat-lying flows, and strongly controls slope depocenter development and probably also the deepwater depocenter. The question marks in the central portion of the margin reflect uncertainty of the underlying crust type due to poor data coverage. Isobaths indicate 200 m intervals, as in Figure 2B.

irregular, hummocky (i.e. mounded) pattern, affected by diffractions (Figs. 2, 3 and 10). The sedimentary cover is continuous along the Uruguayan continental margin up to the 350-nautical mile limit (Figs. 2 and 3). The average thickness of post-rift sediments over oceanic crust is 2000 m (Figs. 2, 3 and 10). The oceanic crust is highly dissected by faults, which affect post-rift sediments (Fig. 10). A few hundred metres to 2 km high volcanic cones (Fig. 10) are observed in some seismic sections, even in depth-converted ones, allowing us to discard the possibility that they represent seismic ‘pull-ups’. The average thickness of the oceanic crust in depth-converted seismic sections is 7 km.

#### 4.4. Potential field data

The structuration of continental crust-SDRs-flat flows-oceanic crust is reflected in the magnetic anomaly map, where NE lineaments are observed (Fig. 11). According to Bauer et al. (2000), ‘inner’ SDRs show high remanent magnetization values, while flat-lying flows show low or none values. Schreckenberger & Paterlini (in Neben et al., 2005) tentatively identified in the offshore of Uruguay the M3, M2 and M0 seafloor spreading magnetic anomalies, while Hinz et al. (1999:Figs. 1 and 9) and Ghidella et al. (2006) mapped the M3 and M0 anomalies, and Franke et al. (2007:Fig. 2) and Blaich et al. (2009:Fig. 2) the M0 anomaly. Hinz et al. (1999) noted that the seaward edge of the SDR sequence is close to M3 at 35.5° S, while at 44° S it lies 100 km landward of it, implying a diachronous emplacement of the SDR sequence.

The most prominent positive magnetic anomaly, here interpreted as the G magnetic anomaly (in agreement with Blaich et al., 2009) spatially coincides with the beginning of the SDR sequence (Fig. 11). Indeed, both the G magnetic anomaly and the SDR sequence are

interrupted in the central portion of the margin and deflect seaward in the southern segment. A second seaward positive magnetic anomaly may be related to the SDR2 wedge (i.e., the most seawardly placed wedge; Fig. 11). It must be noted that Moulin et al. (2010) interpreted the G anomaly of Rabinowitz and LaBrecque (1979) in the Pelotas Basin as the M4 anomaly, implying that in the northern segment of Uruguay the G anomaly (more or less equivalent to the “Large Marginal Anomaly” of Moulin et al., 2010) would be even closer to the coast, implying a more dramatic shift. The G anomaly is correlated with the beginning of the SDR sequence in both the Argentine and conjugated African margin (Gladczenko et al., 1997; Hinz et al., 1999; Bauer et al., 2000; Schreckenberger and Paterlini in Neben et al., 2005; Blaich et al., 2009), being absent south of the Colorado-Hope transfer zone (Ghidella et al., 2006; Blaich et al., 2009).

On the other hand, the prominent positive free-air gravity anomaly spatially coincides with the shelf-break. It corresponds to the “shelf-edge” anomaly typical of volcanic rifted margins (e.g., Bauer et al., 2000; Franke et al., 2010), and it is attenuated at the centre of the margin (Fig. 12). As can be appreciated in the southern segment, it is not related to the SDR sequence (Fig. 12). Bouguer anomaly map, in turn, shows a sharp increase in the region of the transitional crust (ANCAP, unpublished data), as also described in the South Atlantic (e.g. Blaich et al., 2009).

In summary, both gravity (free-air) and magnetic anomalies are less prominent at the central portion of the margin and the magnetic anomalies are displaced sinistrally (as SDR wedges are).

#### 4.5. Depocenters

Post-rift depocenters over continental and transitional crust contain a maximum sedimentary fill that exceeds 4.5 s (TWT) or

6500 m (Fig. 13). The thickest areas (in fact thicker than reported for the Argentinean margin; Franke et al., 2007:Fig. 11) are located in the region of the continental slope, with a large northern depocenter (roughly between the 1500 and 3500-m isobaths; Fig. 13) and a more compressed southern depocenter (roughly between the 2500 and 3500-m isobaths; Fig. 13). The southern depocenter is located in a heavily faulted zone that controlled its development (Fig. 13). Between both depocenters the thickness of the sedimentary fill decreases. Strikingly, there is an ultradeep water ENE-WSW trending depocenter over oceanic crust (associated with strong faulting and a 2 km high volcanic cone) in seismic sections BGR04-01SA and BGR04-03S, where sediment thickness almost doubles (Figs. 10 and 13). This depocenter seems to continue in Brazilian waters. A similar, though less developed feature is observed in the southern segment (Fig. 2).

#### 4.6. Segmentation

Segmentation of South Atlantic margins by transfer zones is well documented (e.g. Meisling et al., 2001; Franke et al., 2007, 2010; Blaich et al., 2009). Franke et al. (2007) recognized four main NW-trending transfer zones in the Argentinean continental margin, named from S to N Falkland/Malvinas, Colorado, Ventana and Salado. They separate four main ca. 400 km long segments, among which Segment IV comprises the continental margin of Uruguay (but see below). Each transfer zone (which represent an old zone of weakness) may have acted as rift propagation barriers, according to Franke et al. (2007), by selectively directing rift segments in a left stepping pattern along the western South Atlantic margin. This segmentation would explain along-margin variations concerning for example architecture, volume, and width of the SDRs wedges, as well as distribution and thickness of post-rift sediments (Franke et al., 2007). The transfer zones are probably linked seaward to recent E–W oceanic fracture zones, and landward to huge structural onshore lineaments, such as those recognized by Jacques (2003).

Concerning the continental margin of Uruguay, given the attenuation, interruption and/or sinistral displacement of several features (SDRs, depocenters and potential field anomalies; see above), we recognize a system of NW–SE trending transfer faults (rather than a single large fault), herein named Río de la Plata Transfer System (RPTS; Fig. 13). This structural corridor includes the southern limit of the Polonio High (Stoakes et al., 1991:Fig. 8). These faults are recognized in seismic sections (e.g., Fig. 7), where they dissect Early Cretaceous and even Late Cretaceous sediments. However, the RPTS still may represent a tectonically active region, given that seismic activity has been detected in recent times (e.g. in 1848 and 1988) at this location (Assumpção, 1998; Benavídez Sosa, 1998).

Thus, two tectono-structural segments can be recognized in the Uruguayan continental margin to each side of the RPTS (Fig. 13), Segment I to the south and Segment II to the north, or following the nomenclature of Franke et al. (2007), Segments IV (redefined) and V. According to the episodic rupture model proposed by Franke et al. (2007), rifting should have been stopped at the RPTS, subsequently resuming. Thus, Segment II is inferred to be younger than Segment I.

SDRs and flat-lying flows are narrower in the northern part of the Segment I, which agrees with the statement by Franke et al. (2007) that volcanism in each segment decreases northwards.

Bathymetric profiles and geomorphic features of the continental slope also differ in the northern and southern segments: in the northern segment there is a smooth curvature of constant gradient, with the slope transitioning directly to the abyssal plain (Fig. 3), while in the southern segment several submarine terraces (and

associated contouritic deposits) are present. Although in the southern segment the erosive and depositional features are related to contour currents product of the Antarctic water masses interacting with the sea-floor (e.g. see Hernández-Molina et al., 2009: Fig. 1C), we cannot discard some influence of the RPTS on the different geomorphic configurations. Locally the RPTS may have had a role in offshore petroleum systems, by providing hydrocarbon migration pathways and influencing the distribution and geometry of hydrocarbon reservoirs.

The nature and tectonic setting of the RPTS is analogous to that of the Salado Transfer Zone (STZ) to the south, although in the STZ the dislocation of the G anomaly is even more conspicuous, unless we accept the proposal of Moulin et al. (2010), which depicted a large shift of the G anomaly in the northern segment of Uruguay (see Moulin et al., 2010: Fig. 3). Franke et al. (2007) depicted the STZ continuing towards the NW–SE-trending Martín García-Plata High (see also Fig. 2A), a major basement arch that tectonically defines the northern boundary of the Salado Basin, separating it from the Santa Lucía and Punta del Este basins (Stoakes et al., 1991; Jacques, 2003). However, strong inflections are needed to make both structural elements a continuous feature (see Franke et al., 2007 and Fig. 2A). An alternative possibility suggested by potential field data is that the STZ continues through the Salado Basin and that the Martín García High continues in the RPTS, which would be in accordance with earlier proposals (Tankard et al., 1995; Jacques, 2003). The RPTS is probably related a zone of weakness into which the Plata River had eroded (Moulin et al., 2010).

Blaich et al. (2009) showed that the Colorado and Salado transfer zones have counterparts in the conjugate southwestern African margin. This appears to be also the case of the RPTS, given that the paleogeographical restoration at Chron M0 of Blaich et al. (2009:Fig. 10) depicts an interruption of the positive free-air gravity anomaly and of the G magnetic anomaly in the Namibian offshore, which allows to infer the presence of a NE-trending transfer zone (which if continued would intersect the Namibian coast at a latitude of approximately 25° S).

#### 4.7. Continent ocean transition

The COT zone can be located due to its association with a distinct shallowing of the Moho discontinuity, a strong negative-positive gradient on the Bouguer-corrected gravity field, and a prominent positive magnetic anomaly field, which includes the G anomaly (Blaich et al., 2009 and references therein). The prominent positive gravimetric anomaly related to the shelf-break (or “shelf-edge” anomaly) depicts the COT in the western South African margin, but this is not the case of the Argentinean/Uruguayan conjugate margin given that the COT is placed seawards of it (Blaich et al., 2009; see also Fig. 12).

In the case of Uruguay, the Moho discontinuity is evident in COPLA-01 and COPLA-02 seismic sections, reaching normal values for oceanic crust seaward of the flat-lying flows (Fig. 4). Indeed, the Moho deepens from 15 km to 19 km below the flat-lying flows zone. On the other hand, a strong negative–positive gradient in this region is evident in Bouguer anomaly maps (Heyde, 2005; Blaich et al., 2009). The G anomaly, as already mentioned, is also present in the Uruguayan continental margin (e.g. Stoakes et al., 1991; Blaich et al., 2009), approximately depicting the landward limit of the COT (Fig. 11).

#### 5. Conclusions

In the continental margin of Uruguay, the existence of a NW–SE trending transfer system (Río de la Plata Transfer System) is proposed on the basis of the interruption and/or sinistral

displacement of SDR wedges, potential field anomalies and depocenters. The recognition of the RPTS, which separates two segments with different tectonic and stratigraphic evolutionary histories, is a contribution to the well documented segmentation of the entire South Atlantic margin of South America.

As proposed by Jacques (2003), the RPTS may have functioned as an important transcrustal zone of lateral accommodation during Late Jurassic rifting and South Atlantic opening, possibly separating NW–SE graben/rift development in the south from “true” passive margin style (NE–SW or coast-parallel rifting) in the north.

Finally, the COT can be recognized from the landward edge of the SDR sequence to the seaward edge of flat-lying volcanic flows.

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