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Margin segmentation and volcano-tectonic architecture along the volcanic margin off Argentina/Uruguay, South Atlantic

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Abstract

Some 25,000 kilometers of regional multichannel seismic data, acquired by BGR along the continental margins off Argentina and Uruguay document that the Early Cretaceous South Atlantic continental breakup and initial sea-floor spreading were accompanied by large-scale, transient volcanism emplacing voluminous extrusives, manifested in the seismic data by huge wedges of seaward dipping reflectors (SDRs). The emplacement of the deeply buried, 60–120 km wide SDRs was probably episodic as documented by at least three superimposed SDRs units. Distinct along-margin variations in architecture, volume, and width of the SDRs wedges are probably related to margin segmentation. It is suggested that the margin can be divided, at least, in four compartments bounded by the Falkland Fracture Zone/Falkland transfer, the Colorado transfer, the Ventana transfer and the Salado transfer. The individual margin segments reflect in the distribution and thickness of the post-rift sediments. The individual transfer zones may have acted as rift propagation barriers, selectively directing rift segments in left stepping patterns along the western South Atlantic margin. Although we found extensive variations in the architecture, style, and extent of the seaward dipping reflector sequences, a general trend is that the largest volumes are emplaced close to the proposed transfer zones and the width of the SDRs wedges decreases northward within the individual margin segments. We suggest that mainly adiabatic decompression and melt generation from shallow sources can explain distinct along-margin variations in the volcano-tectonic architecture and volumes of extruded magmas.

Keywords: volcanic passive margin; South Atlantic; breakup; rifting; reflection seismology; Argentina; sedimentary basin; margin segmentation

1. Introduction and geological setting

Volcanic rifted margins are characterised by massive occurrences of extrusive volcanism and intrusive magmatism formed during the rupture of the continental lithosphere and breakup (Hinz, 1981; Mutter et al., 1982; Roberts et al., 1984; White and McKenzie, 1989; Holbrook and Kelemen, 1993; Eldholm et al., 1995). Recent reviews illustrate the wide distribution of such margins that may represent 75–90% of the global continental passive margins (Eldholm et al., 2000; Menzies et al., 2002). Hinz et al. (1999) showed that the relatively sparsely investigated Argentine margin is of the volcanic type. Adjacent to the wide shelf the steep slope is underlain by extensive volcanics, manifested by thick wedges of seaward dipping reflectors (SDRs) (Hinz et al., 1999). These seaward dipping reflectors are distinct wedge-shaped units underlying the present slope. The convex-upward curvature and seaward dip of the lavas probably result from differential subsidence during the initial rifting phase (Hinz, 1981; Mutter et al., 1982).

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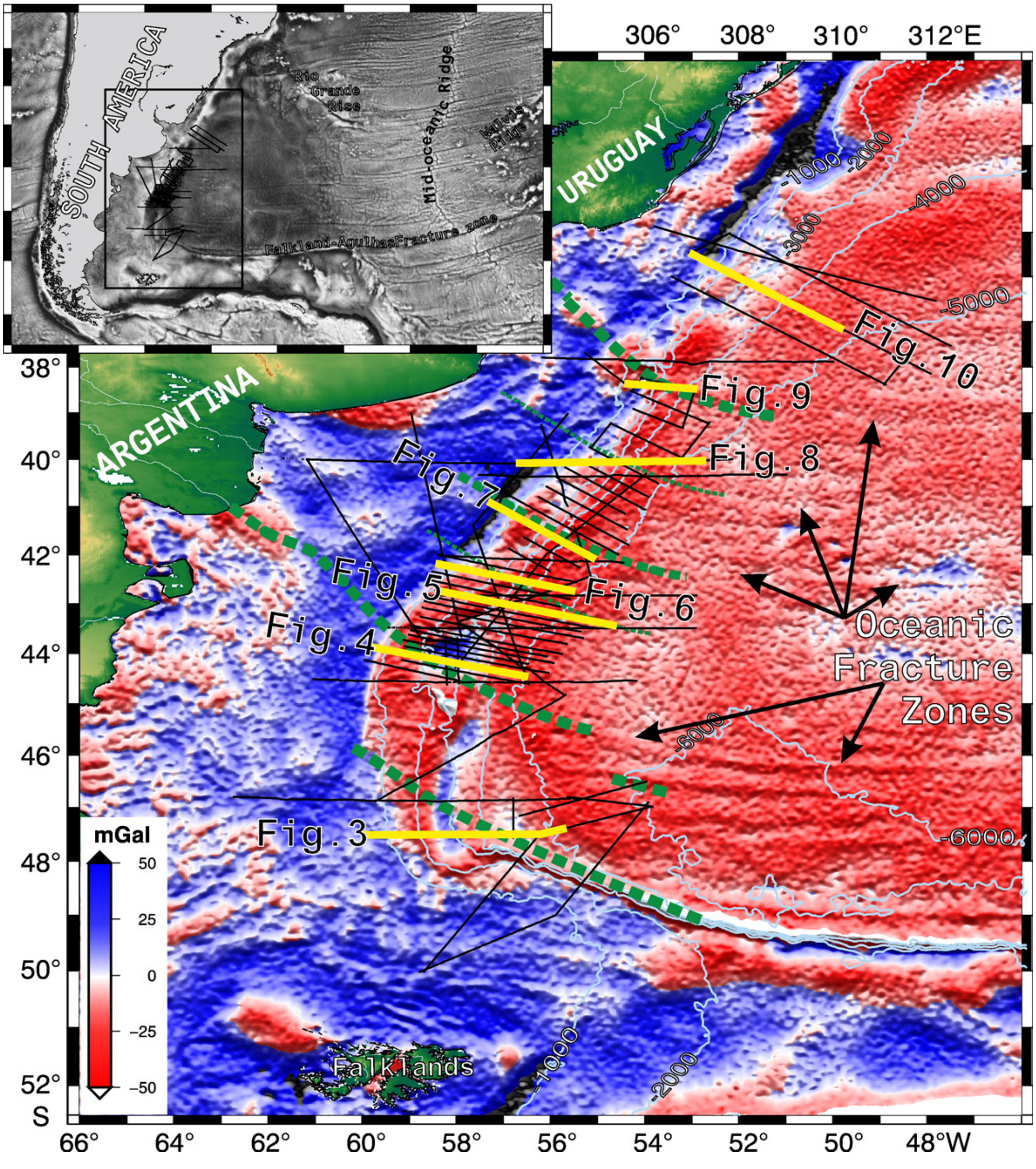

Fig. 1. Study area in the western South Atlantic and location of multichannel seismic reflection (MCS) lines of BGR cruise 1987, R/V SONNE cruise SO-85 1993, BGR cruise 1998 and BGR cruise 2004. The locations of the example seismic lines shown in Figs. 3–10 are indicated as yellow solid lines. Satellite-derived gravity field (Sandwell and Smith, 1997) is shown for the offshore area. Proposed transfer zones as interpreted in Fig. 2 are indicated as dashed green lines. Oceanic fracture zones in the deep Argentine Basin may correlate with the suggested transfer zones (see text).

The formation of the South Atlantic margins resulted from the breakup of the Gondwana supercontinent. The final opening of the South Atlantic took place in Lower Cretaceous with inferred opening ages between Argentina/Uruguay and South Africa/Namibia ranging from 126 to 137 Ma (Rabinowitz and Labrecque, 1979; Unternehr et al., 1988; Nürnberg and Müller, 1991; Peate, 1997; Gladczenko et al., 1997; Lawver et al., 1998; Jokat et al., 2003). Unternehr et al. (1988), Nürnberg and Müller (1991), Uchupi and Emery (1991), Lawver et al. (1992), and Müller et al. (1993) assumed a combination of complex rift and strike-slip faults, active before and during the breakup, to achieve a fit without gaps/overlaps for the southern South Atlantic. The

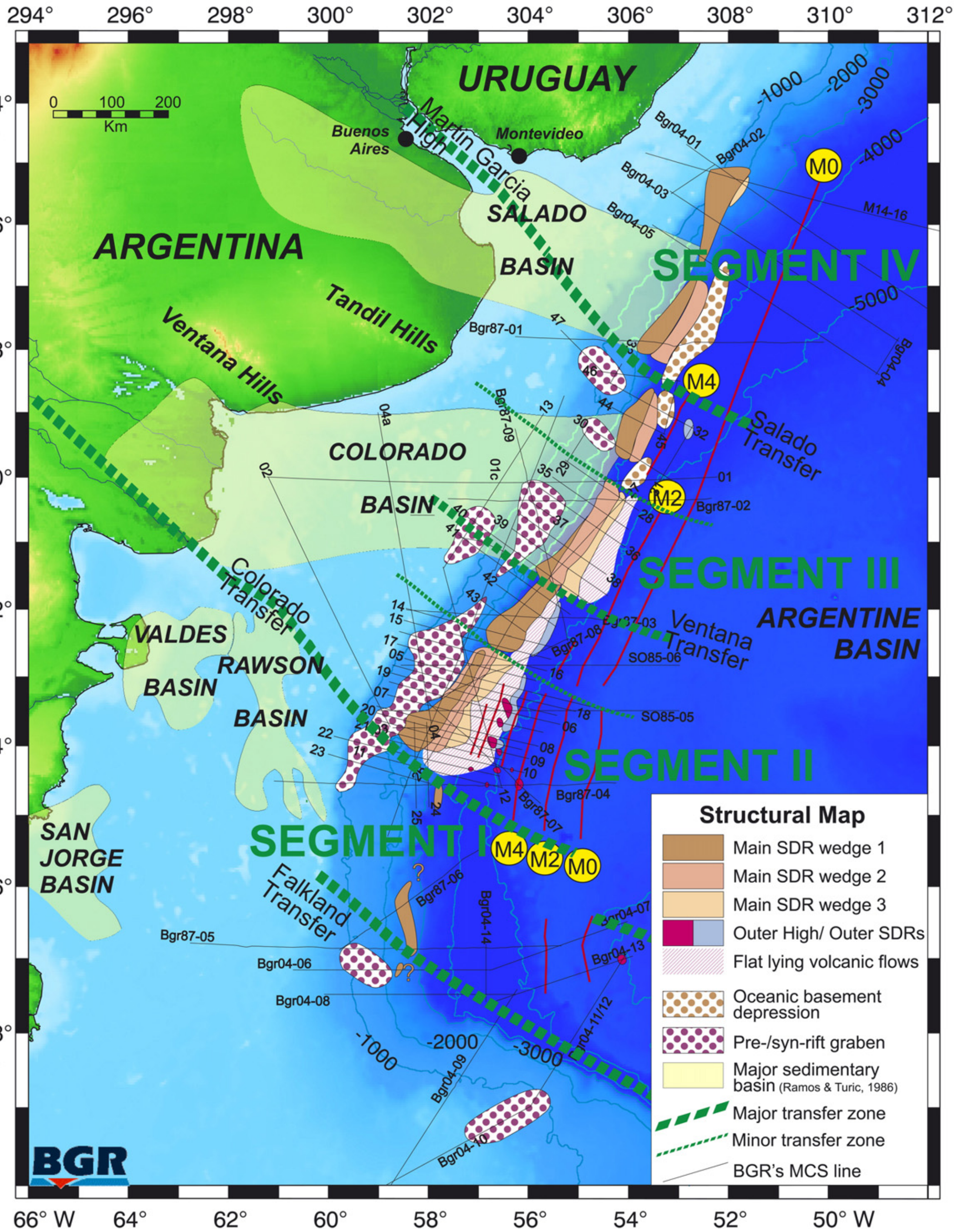

Fig. 2. Structural map showing the distribution of extensive volcanics manifested by thick wedges of seaward dipping reflector sequences (SDRs), additional volcanic/magmatic features, oceanic basement depressions and pre-/syn-rift grabens. Major sedimentary basis on the shelf were adopted from Ramos and Turic (1996). Transfer zones and margin segmentation as interpreted from variations in the margins volcano-tectonic character, post-rift sediment distribution, potential field data and earlier studies is indicated.

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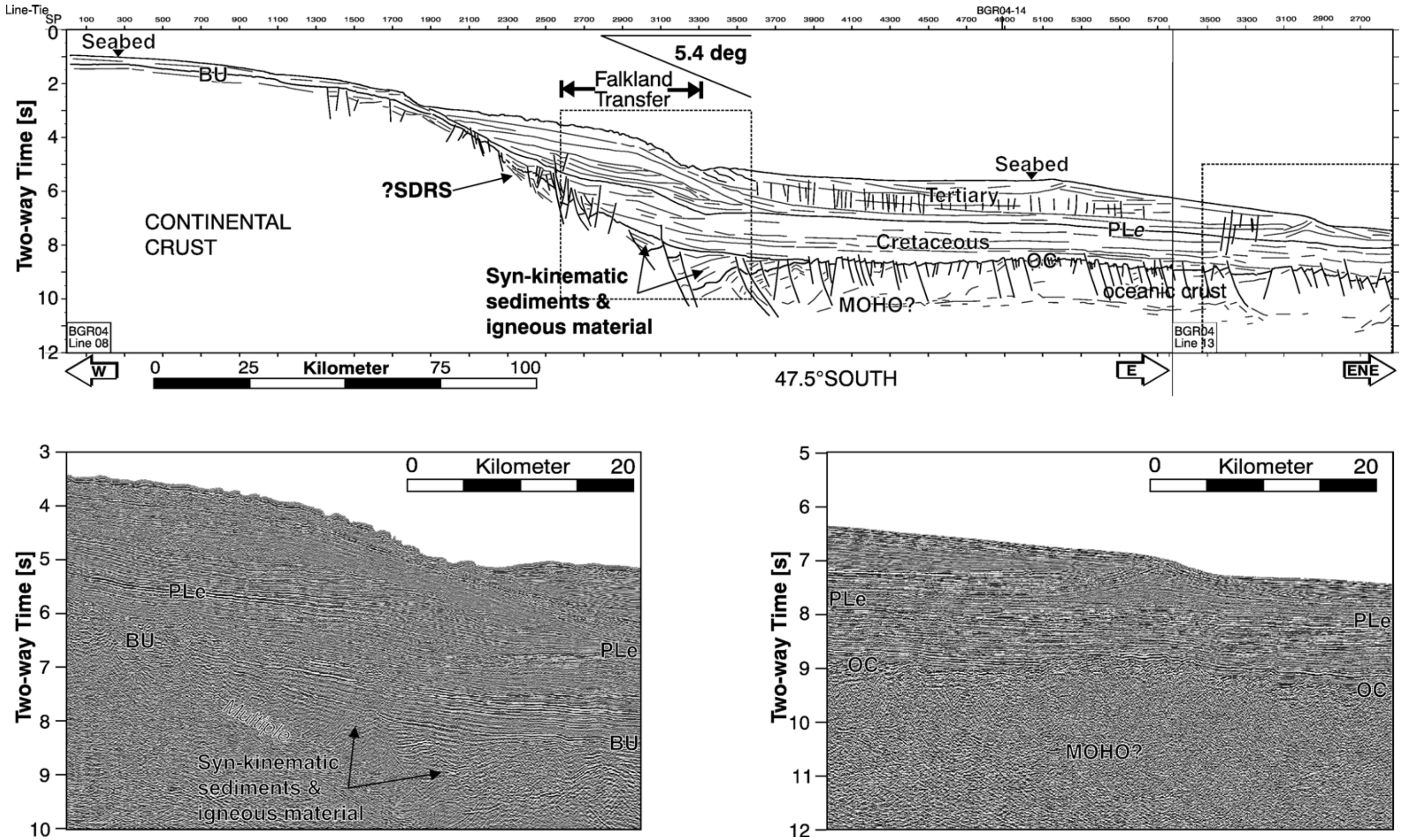

Fig. 3. Profile BGR04-08/BGR04-13, situated north of the Falkland/Malvinas Fracture zone in margin segment I. Vertical exaggeration is about 3:1 for the sedimentary successions and about 1.5:1 for the crustal sections (at interval velocities of 2.5 km/s and 4.5 km/s, respectively). The proposed transfer zone is interpreted where the steep basement, dipping at about 5.4 degree (calculated with an average sediment interval velocity of 2.5 km/s) is dissected by deep penetrating faults. The oceanic crust is also dissected by numerous faults. OC: top of the oceanic crust, BU: breakup unconformity, PLe: Pedro Luro Equivalent, SDRs: Seaward dipping reflector sequences. For location see Fig. 1.

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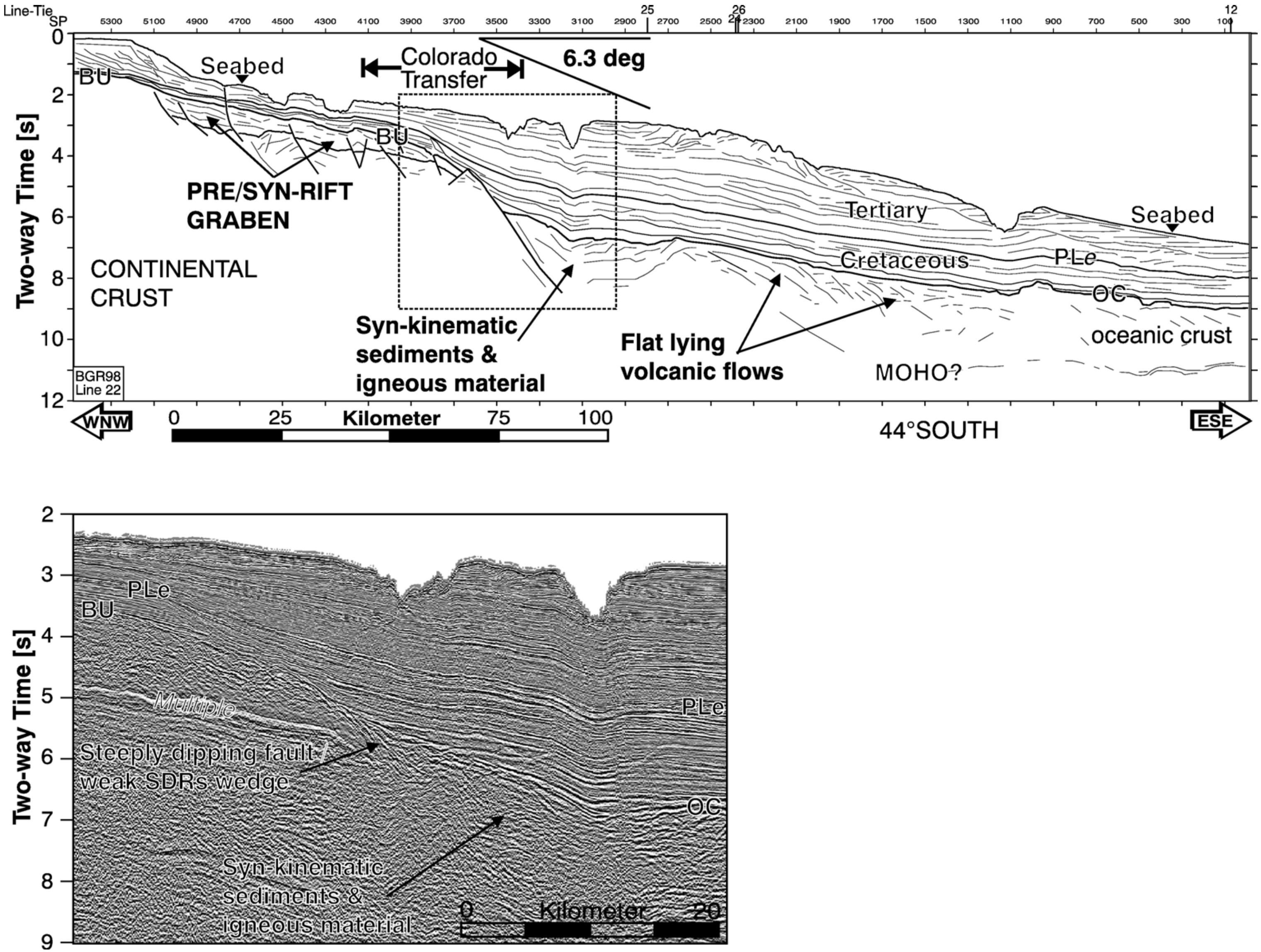

Fig. 4. Profile BGR98-22, running across the proposed Colorado transfer zone between margin segments I and II. The transfer zone is interpreted where the steep basement, dipping at 6.3° is dissected by a high angle fault that coincides with a weak SDRs wedge. Legend as in Fig. 3; location see Fig. 1.

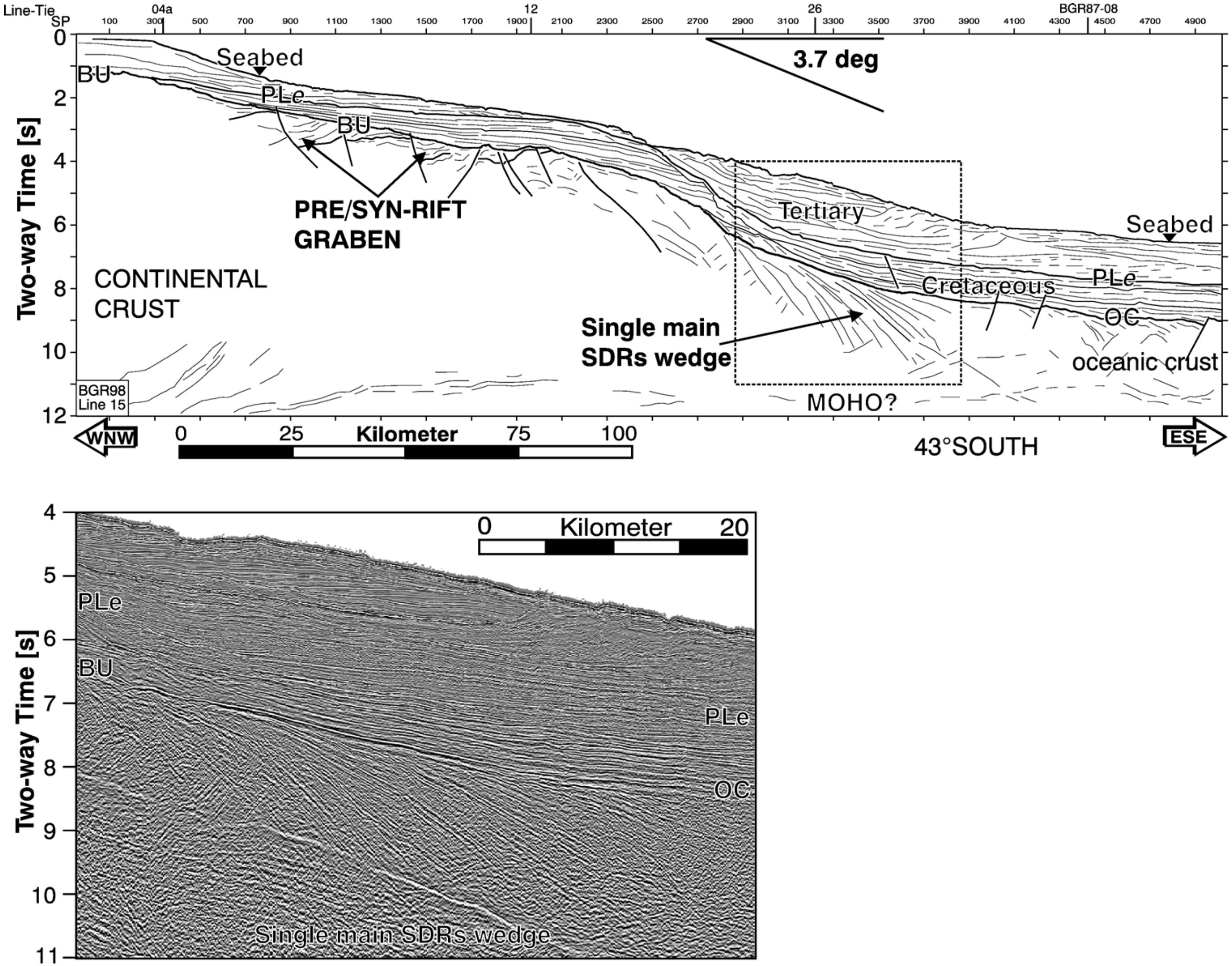

Fig. 5. Profile BGR98-15 running across the minor transfer zone in margin segment II. The transfer is interpreted between a high angle fault penetrating deep into the crust and the steeply dipping basement. The SDRs sequence is defined by high frequency arcuate internal reflections and shows a significant different internal pattern in comparison to the southern margin segment II. Legend as in Fig. 3; location see Fig. 1.

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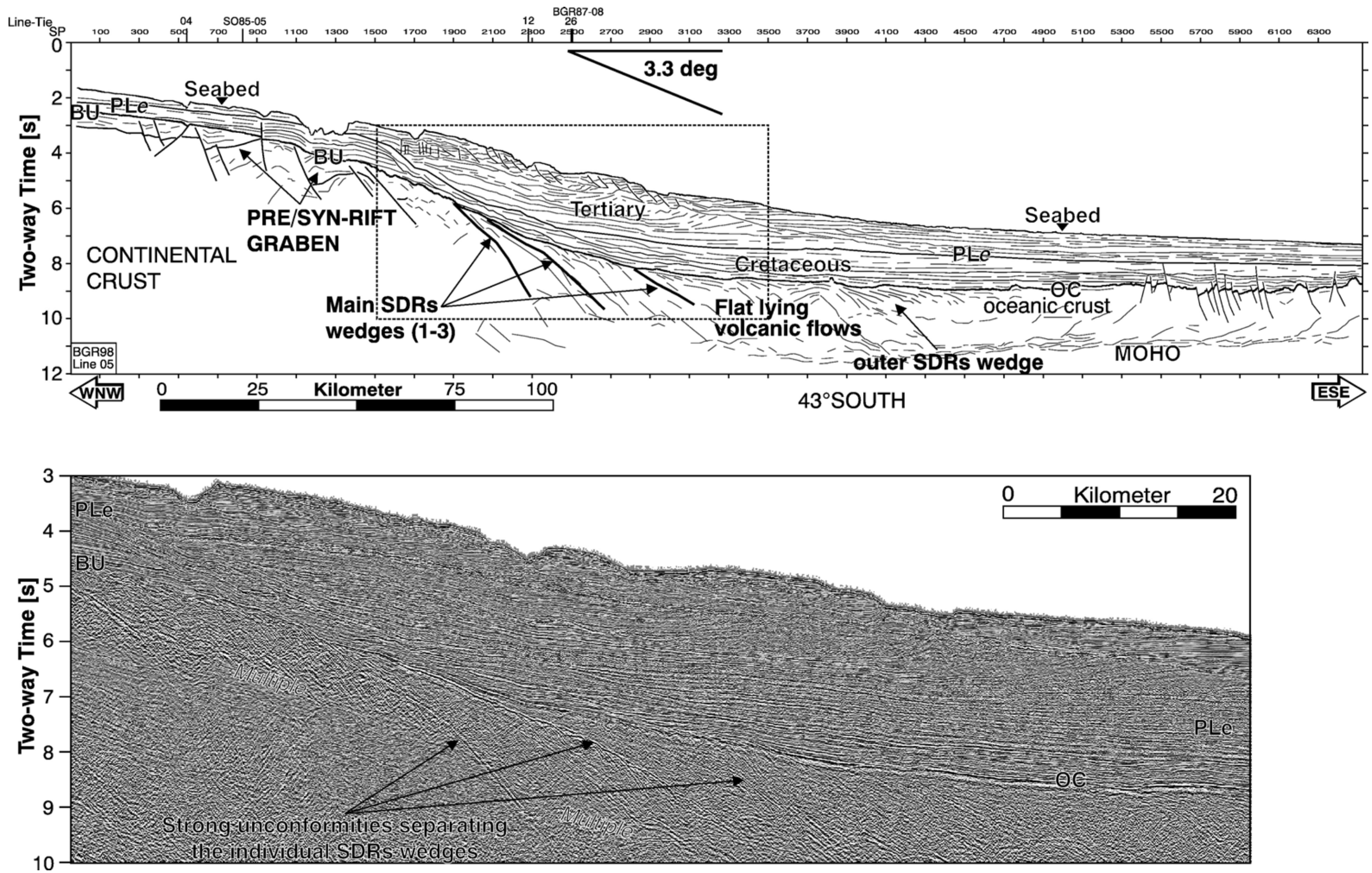

Fig. 6. Profile BGR98-05, situated in margin segment II. Multiple SDRs wedges are separated by strong unconformities. The top of the oceanic crust is well defined by a flat, low-frequency reflector band. Legend as in Fig. 3; location see Fig. 1.

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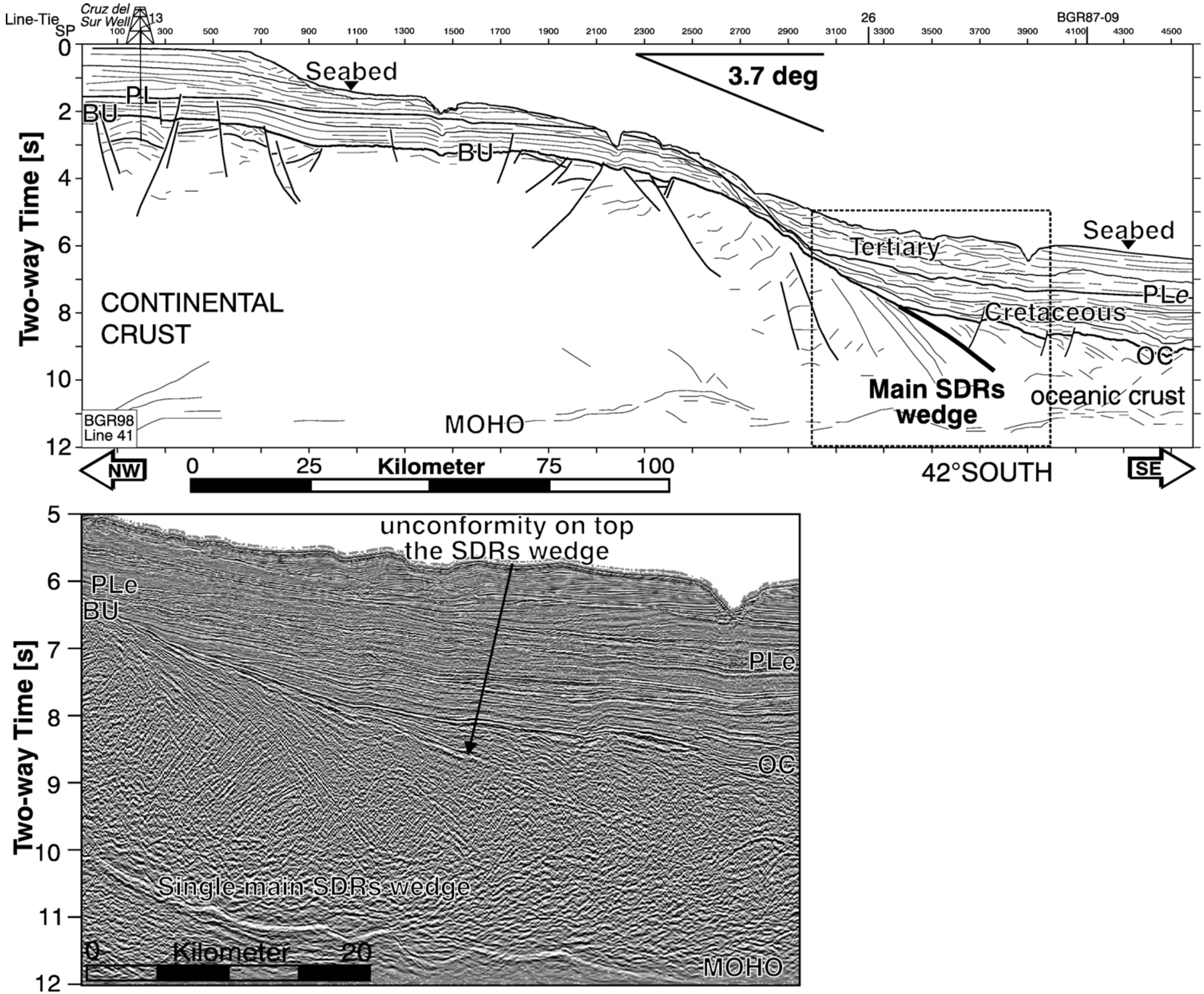

Fig. 7. Profile BGR98-41, situated in the northern margin segment II. One single main SDRs wedge developed that exhibits one strong unconformity on top. The SDRs sequence below shows high frequency arcuate internal reflections. We correlated the stratigraphy with the Cruz del Sur well, located at the NW end of the line (Bushnell et al., 2000). Legend as in Fig. 3; location see Fig. 1.

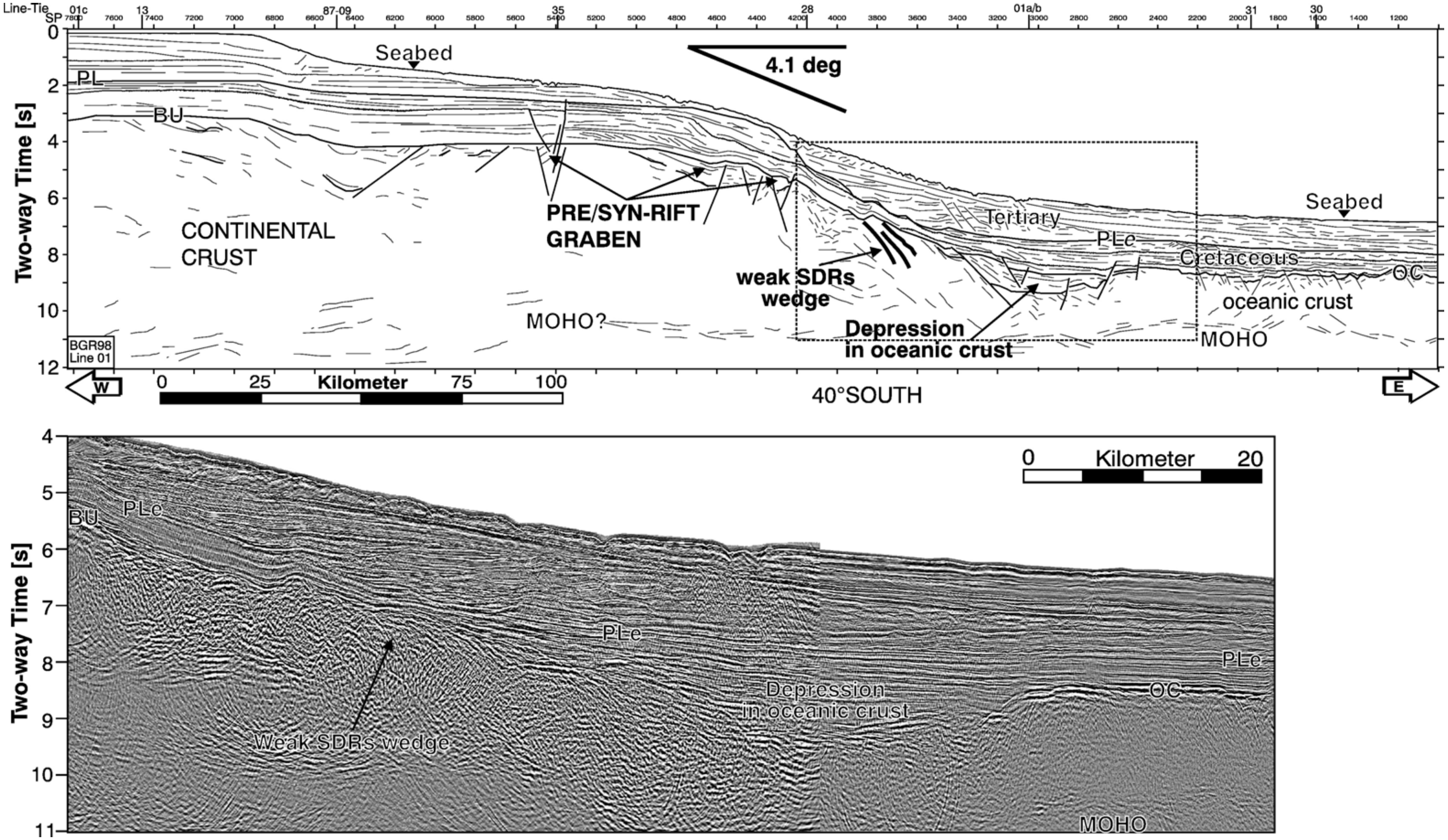

Fig. 8. Profile BGR98-01 illustrating the along-margin variations in the volcanic/magmatic activity. The SDRs wedge is very narrow and thin with respect to the southern part of margin segment III. Seaward of the SDRs sequence a depression in the oceanic crust is located that we interpret as expression of a seaward lava flow with a scarp forming the eastern boundary of the depression. Legend as in Fig. 3; location see Fig. 1.

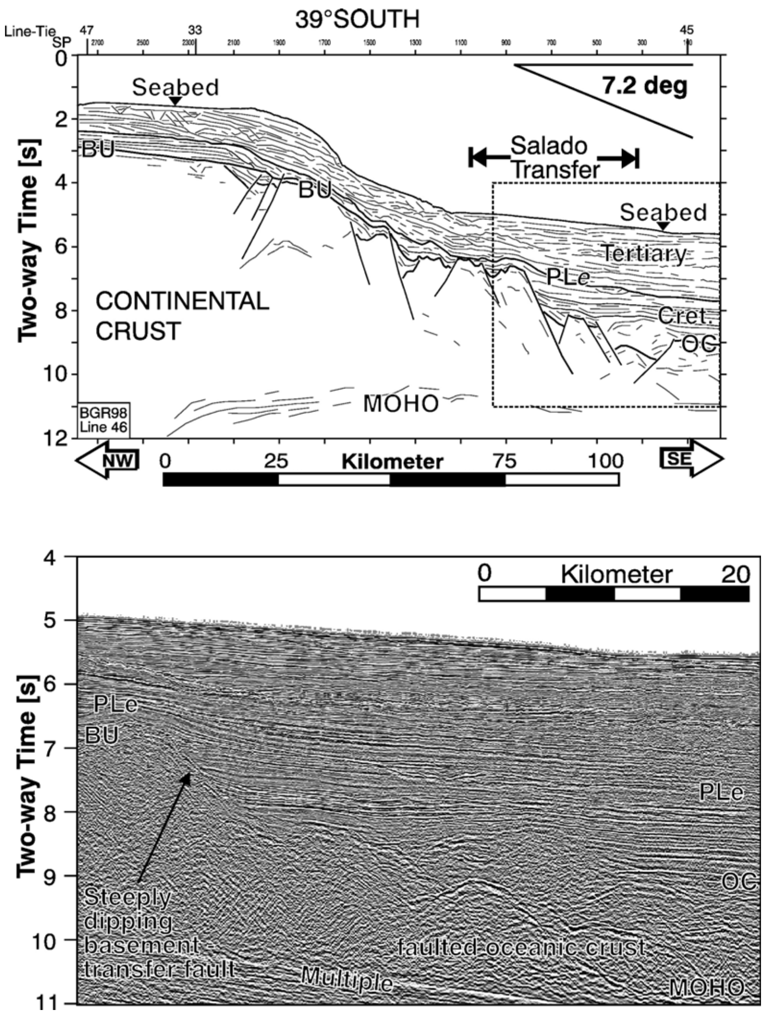

Fig. 9. Profile BGR98-46 running across the proposed Salado transfer zone between margin segment III and IV. We interpreted the transfer zone where the basement shows an extremely steep dip. The transitional/oceanic crust SE of the steeply dipping basement/fault is offset by faults up to 1.2 s (TWT) high resulting in a oceanic basement depression. Legend as in Fig. 3; location see Fig. 1.

opening of the South Atlantic occurred diachronously, rejuvenating from South to North (e.g. Rabinowitz, 1976; Rabinowitz and Labrecque, 1979; Austin and Uchupi, 1982; Sibuet et al., 1984; Uchupi, 1989) and may be described as a successive northward unzipping of rift zones (e.g. Jackson et al., 2000).

Here we report on a detailed investigation of the Argentine and Uruguay outer margin segments based on a set of about 25,000 line kilometres of 2D multichannel seismic (MCS) data that were acquired by BGR during the past 10 years (Fig. 1). The synthesis of these data show that the margin structure and especially the SDRs formations vary extensively in architecture, extent and thickness along strike of the margin. We propose that the emplacement of the deeply buried, 60–120 km wide SDRs was probably episodic and that the northward propagation of the South Atlantic rift took place in huge, but distinct along-margin segments that are bounded by transfer zones.

2. Data acquisition and processing

Between 1987 and 2004, the Federal Institute for Geosciences and Natural Resources (BGR) conducted an extensive program of deep seismic reflection profiling offshore Argentina and Uruguay (Fig. 1; BGR87: 3676 km, SO85: 4255 km, BGR98: 12,075 km, BGR04: 3785 km; Total data volume: 25,677 km). The studied area comprises the outermost shelf, slope and rise of the over 1800 km long eastern Argentina and Uruguayan continental margins, extending from the Falkland/Malvinas Plateau at about 50°S in

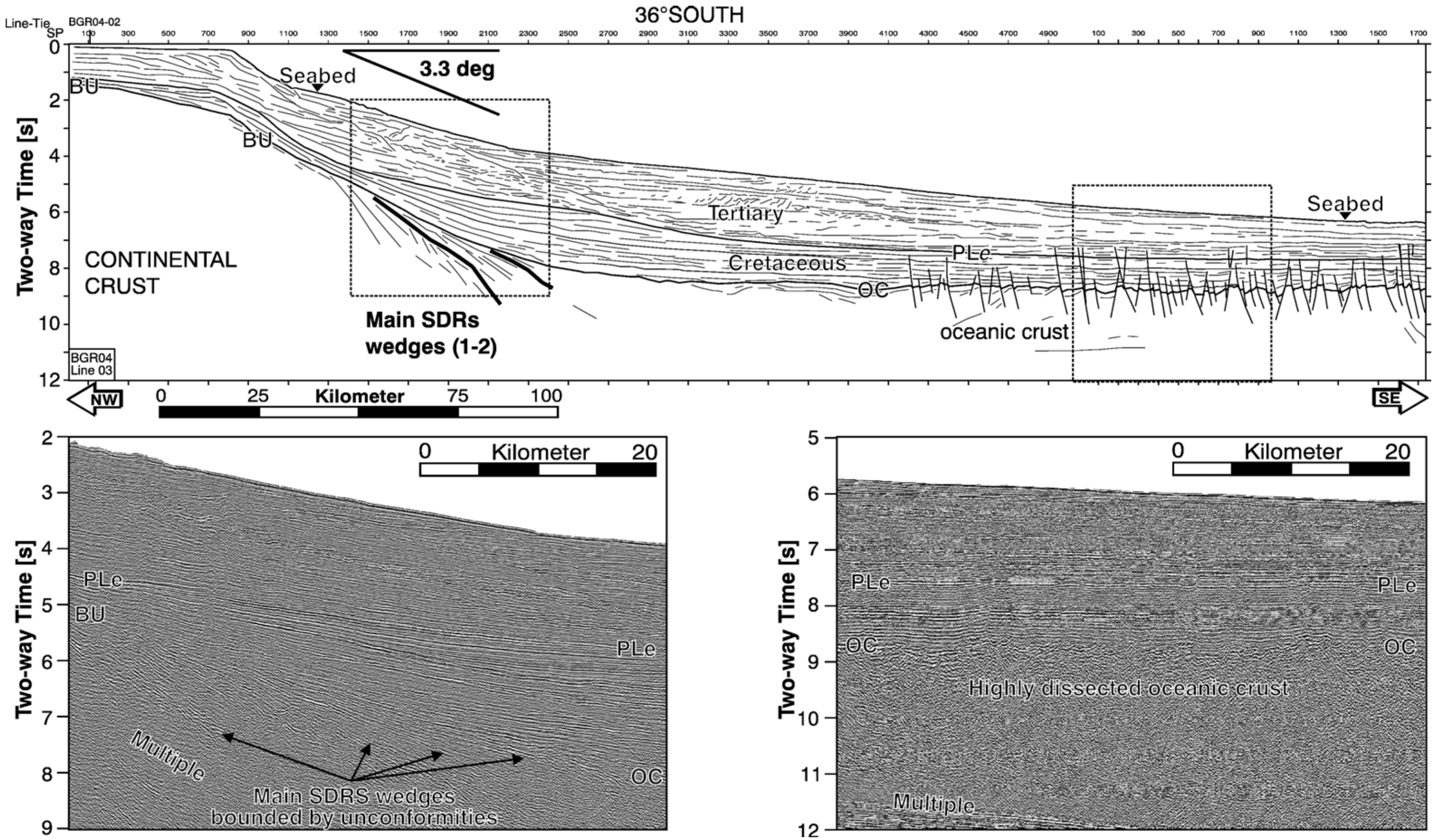

Fig. 10. BGR04-03/03S showing the tectono-magmatic architecture of margin segment IV. At least two SDRs wedges are separated by strong unconformities. The oceanic crust at some 100 km SE of the base of the slope is highly dissected by numerous faults that also penetrate the post-rift sediments. Legend as in Fig. 3; location see Fig. 1.

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the south to the Uruguayan margin at about 35°S in the north (Fig. 1). The area of investigation also encompasses the westernmost part of the deep-sea Argentine Basin.

All the seismic data were acquired with a shot point interval of 50 m and a sampling rate of 4 ms using multichannel streamer systems with varying configurations. Details of the acquisition and processing parameters during the earlier cruises along the South American margin are described in Hinz et al. (1999). The cable length during the BGR98 and BGR04 cruises varied from 3000 to 4500 m, with 150–180 channels, respectively. The source volume ranged from 3124 in^3 (51.2 l) to 4258 in^3 (69.8 l), with towed airgun arrays operating at a pressure of 2000 psi. Processing routines included pre-stack deconvolution, wave-number and frequency filtering and multiple attenuation, velocity analysis, stacking, deconvolution after stack, and FK or Kirchhoff time migration. Gravity and magnetic data were acquired concomitantly, allowing a combination of different geophysical methods to constrain the geological interpretation.

3. Results

All seismic data have been interpreted and compiled to a tectono-structural map of the Argentine/Uruguayan continental margin (Fig. 2). The varying volcano-tectonic architecture and margin segmentation are demonstrated by line drawings of selected MCS profiles and seismic sections in Figs. 3–10. The along-margin style and partly also the sediment distribution appear to be linked to cross-margin structural elements. We use the term transfer zone to describe crustal lineaments or discontinuities in the margin architecture.

3.1. Architecture and style of the emplaced volcanics

Although we identified up to five adjacent SDRs sequences we mapped for clarity a maximum of three wedges of SDRs that are bounded by strong unconformities (e.g. Fig. 6). The individual SDRs are convex up and show the characteristic internal divergent reflection pattern (Hinz, 1981; Mutter et al., 1982). The downsection is thickening and increases in dip. The individual main SDRs sequences may be traced down to almost Moho level if not masked by multiples. The “outer SDRs” wedges (Fig. 2; Fig. 6) in contrast are steeper and the individual internal reflections show in general an extent of only 0.5 s (two-way traveltime (TWT)). We infer that these wedges have been emplaced under subaquatic conditions due to progressive subsidence of the volcanic–magmatic crust.

Evidence for continentward-dipping normal faults, accommodating the space for SDRs flows is weak but locally some deep coherent, landward-dipping reflection elements might represent such faults or pre-rift substratum on which the wedge rests (Fig. 5). We found only locally topographic highs, separating the individual flows as e.g. suggested by Geoffroy (2005). In general the top of the SDRs wedges is flat (Figs. 5–7,10). However, the landward feather edge is in most cases distinct and represented by an elevation of some 200–500 ms (TWT) of the base of the post-rift sediments. On along-strike profiles, individual reflectors are typically subhorizontal. Seaward of these SDRs occasionally a volcanic outer high is present with in some cases an additional seaward dipping wedge, although poorly developed concerning thickness and breadth.

Individual SDR flows are on an average only 6 m thick (Barton and White, 1997), which is too thin to be resolved as individual reflectors with our acquisition systems. Thus the arcuate internal reflection pattern of the SDRs wedges may partly be caused by interference between stacks of thin basalt flows (Eldholm et al., 1995; Planke et al., 2000) with interbedded sediments, ashes and tuffs and weathered flow contacts providing further impedance contrasts (Roberts et al., 1984). Strong, arcuate reflectors, separating the sequences along the slope (Fig. 6), however, indicate variations in the continuity of the emplacement of the individual wedges. There are certainly several reasons that may explain the formation of discontinuities, as changes in (1) volume and rate of magmatic production, (2) the volcanic environment (vent geometry, relation to sea level, etc.), (3) any synvolcanic and postvolcanic deformation, and (4) rate and amount of subsidence (Eldholm et al., 1995). However, the SDRs wedges are generally not affected by deformation and the along-margin extent and architecture of the lava flows is in favour of an emplacement under similar conditions. We have not really a control on the subsidence but we assume it to be rather continuous within the individual margin segments. However, the spatial separation of the individual SDRs wedges indicates that subsidence can not sufficiently account for the generation of the strong unconformities. Therefore, we suggest that the different wedges, bounded by strong discontinuities are the expression of an episodic emplacement. According to our interpretation the most landward located SDRs wedge was emplaced first. After this wedge was emplaced, possibly weathered and subsided to a certain amount the next wedge was emplaced. Although this flow covers partly the first wedge, the main part of this wedge is located seaward of the first SDRs flow. The

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same procedure is proposed for the emplacement of the following SDRs wedges.

3.2. Post-rift sediment distribution

Two main unconformities are identified throughout the study area (Figs. 3–10). The most prominent and extensive horizon is the breakup unconformity (BU). This horizon is equivalent to horizon AR1 of Hinz et al. (1999) and appears as an erosional surface along the entire Argentine and Uruguayan outer shelf. This horizon forms the base of the post-rift sediments at the slope. In the deep-sea Argentine Basin the base of these sediments is the top of the oceanic crust that is marked as OC in the line drawing examples shown in Figs. 3–10. By comparing our MCS data with previous seismic interpretations (e.g. Urien and Zambrano, 1996; Hinz et al., 1999), well data from the shelf (Bushnell et al., 2000), and with the conjugate southwestern African continental margin (Austin and Uchupi, 1982; Gerrard and Smith, 1983; Brown et al., 1995), we can distinguish another seismic marker horizon, the Pedro Luro equivalent (PLe). This horizon marks the Cretaceous/Tertiary boundary in the sedimentary successions and corresponds to horizon AR II of Urien and Zambrano (1996) and AR3 of Hinz et al. (1999). Several industrial wells drilled the Pedro Luro Formation (Paleocene) on the shelf and encountered predominantly pelagic shales (Bushnell et al., 2000). The thickness of the post-rift sediments (Fig. 11) ranges from 2 to more than 4.5 s (TWT).

In the south there are two sediment accumulations at the base of the slope region with more than 4 s (TWT) thick post-rift sediments. One elongated depocenter, extending from 45.5°S to 47.5°S and a circular depocenter centred at 44°S. Both correlate with distinct gravity highs (Fig. 1). This is surprising, as depocenters filled with sediments are expected to form gravity lows. However, we interpret a portion of the post-rift sediments to represent turbidites, and the gravity highs may reflect the combined effect of elevations of the seabottom produced and shaped primarily by deep-sea currents, and a decreased oceanic crustal thickness (Fig. 3).

Systematic variations of the sediment thickness along the continental slope will be discussed in Chapter 3.3.

3.3. Margin segmentation

Four major transfer zones on the volcanic Argentine/Uruguayan margin, South Atlantic, have been identified. It is suggested that the margin can be divided, at least, in four compartments (Segment I to IV) bounded by the Falkland Fracture Zone/Falkland transfer, the Colorado transfer, the Ventana transfer and the Salado transfer. Criteria for mapping and extending transfer zones across the margin were:

(1) a major lateral offset in the distribution of the SDRs wedges is observed,
(2) the basement shows a steeper than average slope with, in most cases, steep, deep penetrating faults offsetting the base of the post-rift sediments,
(3) either the architecture and style of the SDRs wedges changes dramatically, or indications for SDRs are weak or absent.

According to our interpretation the transfer zones probably represent old zones of weakness controlling the onset of the Upper Cretaceous seafloor spreading and may be linked and extending to recent oceanic fracture zones (Fig. 1).

3.3.1. The Falklands–Malvinas Fracture Zone and Margin Segment I

The Falklands–Malvinas Fracture Zone passes along the base of the steep bathymetric gradient along the northern Falklands–Malvinas platform. It is probably the western continuation of the Agulhas FZ of the eastern South Atlantic. The western continuation of the fracture zone, which previously was interpreted on the basis of magnetic data to turn to E–W and passing into the Jan Jorge Basin (Max et al., 1999) could not be confirmed. In the southern E–W running lines a steeply dipping basement is present, which is dissected by steep, deep reaching faults that cut through the entire crust (Fig. 3). As transform faults are expected to have steep to vertical dips (e.g. Bowen and White, 1986; Wilson et al., 2003) we interpret the structure as elongation of the Falklands–Malvinas Fracture Zone. The transfer zone thus extents in NW direction, in strike with the trend of the steep bathymetric gradient along the northern Falklands–Malvinas platform.

Margin Segment I represents a transition zone from a sheared margin to a typical volcanic margin. The EW-trending profiles across the Argentine shelf into the Argentine Basin show weak indications for SDRs (Fig. 3). These SDRs occur at a steeply dipping acoustic basement, where the margin is dissected by deep reaching shear faults. SDRs wedges could be occasionally identified and show a width of about 20 km in the northern part of this segment (Hinz et al., 1999) and less than 5 km in the South. Sediment infilled graben structures are developed along the shear faults. The graben fill probably consists of syn-rift sediments associated with igneous volcanoclastics (Fig. 3). One

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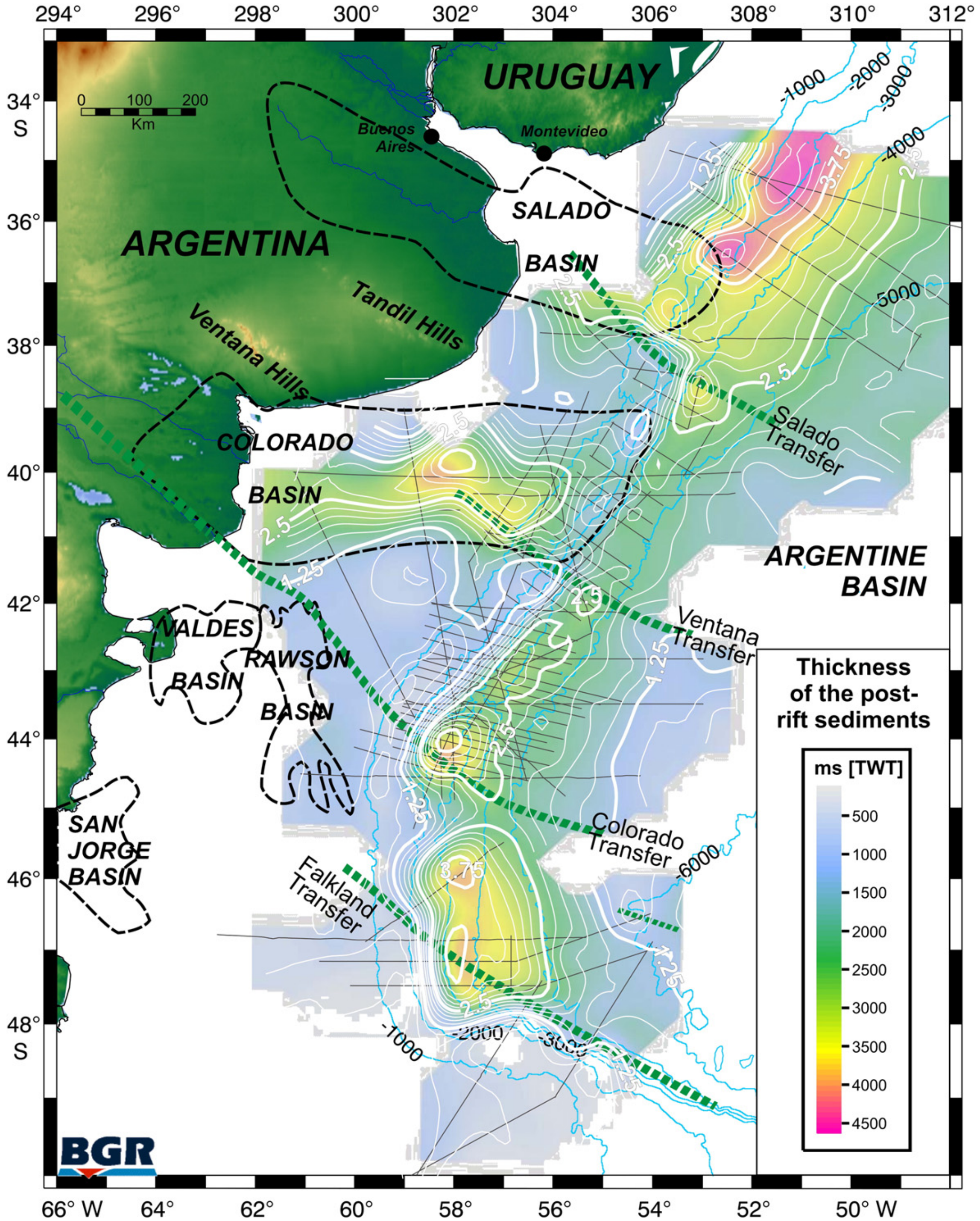

Fig. 11. Thickness of the post-rift sediments. The values in seconds (TWT) were calculated by subtracting the depth to the breakup unconformity/top of the oceanic crust from the depth to the seabottom. Contours are shown every 0.25 s (thin) and 1.25 s (thick). Major sediment accumulations at the slope occur in margin zone I and IV. The sediment thickness in margin zone II may correlate with the width and thickness of the SDRs sequences, i.e. both show maximum values close to the Colorado transfer and decrease northward. In margin segment III only a thin sedimentary cover is present at the slope.

basaltic outer high, 1.5 s (TWT) high, was found on the easternmost seismic lines we acquired (Fig. 2). The oceanic crust is well imaged, with a strong reflector at its surface that is intensively dissected by numerous ?normal faults that often extent down to Moho level (Fig. 3). This faulting is observed on all seismic lines in margin segment I, except north of 46°S where a continuous oceanic crust reflection was found. A discontinuous reflector at the base, corresponding to the reflection Moho indicates that the oceanic crust has a thickness of 1.5 to 2.0 s (TWT) or 4.5 to 6 km. This thickness is slightly decreased with respect to published values for Atlantic Ocean 'normal oceanic crust' (White, 1984; White et al., 1992; Rosendahl and Groschel-Becker, 1999). The decreased oceanic crustal thickness may be related to the nearby fracture zone.

3.3.2. The Colorado transfer and Margin Segment II

The Colorado transfer was first identified on magnetic data and described as Colorado Discontinuity (Ghidella et al., 1995). Max et al. (1999) interpreted it as the boundary between the La Plata craton and Patagonia Platform terranes. The Colorado transfer previously was better defined on the shallow shelf in the NW rather than in the SE or on the outer shelf (Max et al., 1999). We found a major change in the style of the slope as well as changes in the sedimentary cover at the foot of the slope where the seaward end of the Colorado transfer is expected to be located. This transfer zone is situated where the steep basement is dissected by a seaward dipping high angle fault accompanied by a weak SDRs wedge (Fig. 4). The proposed position of the Colorado transfer coincides with a major gravity low at the foot of the slope (Fig. 1). In general we can confirm the course of this transfer zone. However, we slightly adjusted the eastern portion of the Colorado transfer (Fig. 2). By extrapolating the SDRs wedges along-strike the margin, the offset along the Colorado transfer can be estimated. This results in a left-lateral offset of some 50 to 100 km at the transition from Segment I to Segment II. Another transfer zone, which is less prominent compared to the Colorado transfer, is identified at ~43°S (Fig. 2). At this transfer zone there is only a small offset in the SDRs distribution. The amount of extruded volcanics decreases slightly and there is a steeply dipping basement at this position (Fig. 6). Most striking is a distinct change in the reflection pattern of the SDRs wedges. While the wedges in the south show strong, arcuate reflectors, separating the sequences to the north of this transfer zone we observe a homogenous internal pattern of the SDRs wedges. In addition, we identified a step in the parallel layered SDRs wedges on the margin-parallel line BGR98-26. Steep faults cut the oceanic crust and create landward facing vertical offsets in the range of 0.5 to 0.75 s (TWT) in the vicinity of this transfer zone at the base of the slope (Fig. 5; SP 2200–3000) and also on the oceanic crust, situated east of an undisturbed oceanic crust.

Margin segment II is a volcanic margin with superimposed multiple SDRs wedges, which in some places extend over 100 km across the continental slope (Fig. 6). Distinct unconformities separate these wedges and up to five individual extrusive SDRs units are imaged in the seismic records. While SDRs wedge 2 is rather continuous parallel to the margin, the width of wedge 1 decreases northwards and the dip of the flows is steeping indicating initial flows deposited in the south. This trend is paralleled by an increasing higher frequency content of the seismic reflection pattern of the main discontinuity on top of SDRs wedge 1. SDRs wedge 3 is discontinuous and shows a decreasing width towards the centre of crustal segment II and again increasing width towards the northern end of the southern part of this segment. This wedge is significantly less thick with respect to main wedges 1 and 2, i.e. the arcuate reflections terminate some 1 s (TWT) beneath the top. Between main SDR wedge 3 and occasionally occurring volcanic outer highs the base of the post-rift sediments is formed by high amplitude reflections that show a pattern consisting of small-scale seaward dipping reflections along, in general, subhorizontal reflections. We interpret the base of the sediments as flat lying volcanic flows or sills resting on inferred oceanic crust. However, distinguishing between SDRs wedge 3 and the flat lying flows is not always straight forward and there may be to some extent a gradual transition of these features. Basaltic outer highs, up to 1 s (TWT) high and occasionally associated with another set of SDRs are widespread in Segment II. The outer highs show both, circular and elongated shape with an extent of some 10 to 20 km. According to our interpretation these features indicate the last phase of volcanic activity before the onset of continuous normal seafloor spreading in this segment. We believe that the outer SDRs wedges have been emplaced under subaquatic conditions as the seismic character is different and these flows are thin in comparison to the main wedges. North of the minor transfer zone within margin segment II the main SDRs wedge 1 is broad and defined by high frequency arcuate internal reflections. Here, the prominent discontinuities as found in the broad SDRs wedge of the southern part of margin segment II are less distinct or absent (Fig. 7). The width of main SDRs wedge 1 decreases from the minor transfer zone towards the northern edge of margin segment II.

The oceanic crust is well defined, with a strong continuous reflector at its surface. Its thickness is about 2 to 2.2 s (TWT) or 6 to 6.5 km in this segment. Whenever the seismic lines extend to more than about 100 kilometres from the base of the slope the oceanic crust is highly dissected by faulting.

3.3.3. The Ventana transfer and Margin Segment III

At ~41.5°S the Ventana transfer marks another major change in the volcano-tectonic architecture of the continental margin. Coinciding with a left-lateral offset of some 20 to 30 km of the SDRs wedges three main SDRs sequences, bounded by strong unconformities are developed (Fig. 2). At ~40°S an additional transfer zone may be present because there is another left-lateral offset in the distribution of the SDRs sequences. The breadth and thickness of the SDRs wedges show a minimum at this location (Fig. 8), but on the margin-parallel lines running across the wedge and onto oceanic crust there is no indication for a shear fault. This transfer thus remains doubtful and is shown as thin dashed line in Fig. 2.

Margin segment III is another volcanic margin with multiple SDRs wedges, which in some places extend over 80 km across the continental slope. In segment III the basement is generally steeper in the vicinity of the SDRs sequences compared to the southern segments. North of the Ventana transfer, at ~41.5°S three main SDRs wedges are developed, separated by prominent reflection horizons. Further northward main SDRs wedge 1 becomes increasingly buried beneath SDRS wedge 2 and a general decrease in width and thickness of the volcanic units is observed (Fig. 8). In contrast to margin segment II in this segment the steeply dipping individual reflectors of SDRs wedge 3 are often dissected by faults that also affect Cretaceous post-rift sediments further upsection. There are no indications for outer highs or outer SDRs sequences in this segment but this may be due to the limited seaward extent of the seismic lines. Moho reflections are widespread, about 2 s (TWT) beneath the basement surface but increasing in depth beneath the SDRs wedges. In this segment the oceanic crust is not affected by faulting and shows an average thickness of 2 s (TWT) or approximately 6 km.

North of about 40°S, SDR wedge 3 is absent and the flat laying flows terminate. Occasionally north of 40°S a depocenter in the oceanic crust is mapped just east of relative small wedges of SDRs (Fig. 2). Along line BGR98-01 (Fig. 8) this depocenter, that is about 1 s (TWT) deep terminates at an inferred scarp. In addition this depocenter is affected by some faulting. To the north this feature changes its character and is replaced by deep reaching, landward-dipping faults. Well expressed is another depocenter in oceanic crust at the northernmost tip of Segment III adjacent to two well defined SDRs wedges (Fig. 2).

3.3.4. The Salado transfer and Margin Segment IV

Another very prominent lineament is the Salado transfer. The distribution of the SDRs sequences shows a clearly imaged left-lateral offset of more than 50 km along this transfer. Additionally a steeply dipping basement is present (Fig. 9) that shows distinct similarities to the sheared margin segment at the Falkland transfer (Fig. 3). In western direction this transfer may follow the Martin Garcia high that was mapped at the northern edge of the Salado Basin (e.g. Urien and Zambrano, 1996).

Data coverage in this segment is much lower with respect to the southern parts. However, some general observations are worth mentioning: At 38°S there are three wedges of SDRs present that have a total width of ~80 km (Hinz et al., 1999). Offshore Uruguay, between 35°S and 37°S the width of the SDRs wedges increases (Fig. 10). It is narrow along line BGR04-05 but along the northernmost MCS lines again 2 to 3 wedges with a total width of ~70 km were identified. The dip of the basement at the slope is not as steep with respect to the southern segments. The post-rift sedimentary cover at the slope is at 4 to 5 s (TWT) thick in this margin segment and may be related to sediment discharge from the Rio del la Plata river. A prominent depression in the oceanic crust is present at this margin segment (Fig. 2). All over Segment IV the surveyed oceanic crust is highly dissected by faults with the intensity of faulting increasing seawards and northwards.

3.3.5. Segmentation and sediment thickness

Margin segment II possesses with 3 to 4 s (TWT) a relatively thick sedimentary cover while the thickness of the sediments in segment III is mainly less than 3 s (TWT) (Fig. 11). In margin segment IV at more than 4.5 s (TWT) thickness the thickest sedimentary cover evolved. Talwani and Abreu (2000) found a positive correlation of the sediment thickness with the breadth of the volcanic SDRs wedge for the central South Atlantic. In the western part of the southern South Atlantic this finding can be confirmed to a large extent. The southward increasing volume of the sediments in margin segment II correlates with the downdip broadening of the volcanics. The same holds true along the Uruguayan margin where the width of the SDRs wedges and the thickness of the sediments correlate to some extent. The fact that the broad SDRs wedges in margin segment III (Fig. 2) do not correlate to the total thickness of the sediments is likely caused by the wide Colorado Basin in

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which sediments are trapped. In addition strong erosion affected the continental slope along this margin segment.

An elongated depocenter with more than 2.5 s (TWT) thick post-rift sediments is also present in front of the shelf of margin segment I between 45.5°S and 47.5°S. However, a major portion of the post-rift sediments is contained in a "delta-like" unit of predominantly Neogene age, which shows overlapping sedimentary drift structures formed by deep-water contour currents.

In summary we observe a link between sediment thickness and the breadth of the SDRs wedges. Most striking is the observation that the sediment thickness along the volcanic Argentine/Uruguayan margin north of 45°S apparently correlates with the segmentation suggesting that the sediment distribution reflects differences in the margin's structural setting and subsidence.

3.3.6. Segmentation and magmatism

Our data confirm other studies that found considerable variations in the seismic character of SDRs (e.g. Eldholm et al., 1995; Jackson et al., 2000). Distinct unconformities with a low-frequency seismic pattern, separating the SDRs wedges are concentrated in margin segments II and III (Fig. 2). The individual flows are spatially separated in the south while main SDRs wedge 1 becomes increasingly buried beneath main SDRs wedge 2 in the northern part of these segments. In the northern part of margin segment II one broad wedge is present with an arcuate, high frequency internal pattern. This is replaced by again three spatially separated wedges of SDRs where the main wedge is offset in a sinistral sense by 20 to 30 km at the Ventana transfer. In margin segment IV we observe again spatially separated individual flows bounded by strong unconformities. These variations are the expression of an apparently general trend in the breadth and thickness of the SDRs sequences: The largest volumes of volcanics are systematically emplaced along the southern edges of the margin segments, just north of the transfer zones. The breadth and thickness of the SDRs decreases towards the north from there on before another wide and thick wedge was emplaced at the southern edge of the segment adjacent to the north.

4. Discussion

4.1. Transfer zones, magmatism and structural inheritance

The transfer zones are constrained by (1) the location, architecture and breadth of the SDRs sequences, (2) structures in the basement, and (3) the distribution of the post-rift sediments. We limited the interpretation to the continental slope areas and occasionally extended it to shelfal/onshore structures. However, there may also be a relationship of the transfer zones and younger oceanic fracture zones that was found to be typical for the well studied North Atlantic margins (e.g. Tsikalas et al., 2001; Eldholm et al., 2002; Mjelde et al., 2003). Strongly faulted oceanic crust in the vicinity of the proposed transfer zones may indicate that the transfer systems deformed both, continental crust and the new adjacent oceanic crust (Figs. 3,6,7). In Fig. 1 oceanic fracture zones as derived from satellite altimeter data that may correlate with the proposed transfer zones are indicated.

Among other factors the pre-rift lithosphere configuration influences rift duration, melt production and width and symmetry of the continental margin pair (Van Wijk et al., 2001; Corti et al., 2003; Van Wijk et al., 2004). The most significant along-margin change in breakup magmatism and volcanism marks the transition between margin segments I and II along the Colorado transfer. The location of this transfer at the transition from the Patagonia Platform terranes to the La Plata craton also points towards the importance of the pre-rift lithosphere configuration and composition. Another zone of weakness is proposed along the Permian-Early Triassic Tandil and Ventana Hills (Fig. 2; Urien et al., 1981; Uliana and Biddle, 1987). The latter probably represent the western continuation of the Cape Fold Belt in South Africa (e.g. Dingle et al., 1983; Uliana and Biddle, 1987; Andreis et al., 1989; Kelley and Light, 1993). Assuming that the Ventana Hills (Figs. 1 and 2) represent the western continuation of the Cape Fold Belt in South Africa this structure must extend across the continental margin. An offshore continuation of the inferred onshore Claromecó Basin situated between the Ventana and the Tandil Hills would strike in the same direction (Kelley and Light; 1993; Franke et al., 2006). The NW–SE orientation of the deep depocenter within the Colorado Basin (Fig. 11; 302°–304°E) fits with the projected continuation of the Claromecó Basin and indicates such a link. In the southeastern prolongation of these structural discontinuities we recognize the Ventana transfer and possible additional transfer zones within margin segments II and III. Strike-slip faulting along the Martin Garcia high with a horizontal displacement of blocks was identified at the northern edge of the Salado Basin (Urien and Zambrano, 1996). This discontinuity that extends along the Rio del la Plata mouth is the likely landward extension of the proposed Salado transfer. Based on these finding we propose that the locations of the transfer zones are inherited from ancient basement

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structures with zones of weakness present on the flanking landmass.

Along the southernmost segment I the transition from a volcanic margin to a sheared margin occurs. This margin segment mainly formed along strike-slip or transform faults as manifested by the steeply dipping basement at the slope and the highly dissected oceanic crust. On the gravity data several, parallel transform faults running towards margin segment I are observable (Fig. 1). The limited along-margin extent of the individual sheared parts of this margin may have prevented the excess of partial melting processes necessary for the generation of large amounts of melts. The SDRs wedges thus are absent or weak in this segment.

4.2. Shallow and deep magma sources

The production of the large volumes of basaltic volcanism as manifested by the SDRs sequences in volcanic rifted margins is certainly spatially and temporally related to continental breakup. However, the mechanism responsible for the emplacement of the basaltic flows is considerably controversial (e.g. Menzies et al., 2002). Melts are produced by variations in pressure and temperature, and these can be achieved by either lithospheric thinning or plumes, or, more generally spoken, thermal anomalies. Plume models generally require that the mantle temperature be elevated above that of the normal asthenosphere before breakup (e.g., White and McKenzie, 1989; Griffiths and Campbell, 1991; Ernst and Buchan, 1997). In that case melt is generated from a deep-seated thermal anomaly in upwelling mantle and spread along the margin after rupturing the continental lithosphere.

Alternatively, plate driven lithospheric thinning and subsequent rupturing may cause passive upwelling of normal asthenosphere and subsequent melt generation by adiabatic decompression (e.g. Mutter et al., 1988). This occurs without a thermal anomaly and/or plume and may have led to considerable melt production on rifted margins (e.g., Holbrook and Kelemen, 1993; Boutilier and Keen, 1999; Korenaga et al., 2000). The Paraná–Etendeka continental flood-basalt provinces in Brazil and Namibia respectively were emplaced mainly between 129 and 133 Ma (e.g. Renne et al., 1992; Stewart et al., 1996; Peate, 1997; Menzies et al., 2002). Newer studies from the western margin of the Paraná province reveal that melt generation occurred in two major phases; at 145 Ma and 127.5 Ma, i.e. before and at the end of the 139–127.5 Ma Paraná–Etendeka flood-basalt eruptions (Gibson et al., 2006). These authors conclude that the Paraná–Etendeka large igneous province, associated with the impact of the Tristan plume was long lived and immediately predate continental breakup.

Although these findings may point towards an anomalous mantle temperature influencing the evolution of the volcanic margin the magmatic architecture of the margin and the structures identified in the data can hardly be explained by a simple plume model originating from the deep mantle. Why did the rift start in the south at about 48°S when the plume was centered at about 30°S? If the South Atlantic opened like a zipper how does this fit with the plume model? Most striking is the question of the spatial distribution of melts manifested by the SDRs sequences. Within the plume hypothesis a continuous decrease (or, at least, a continuous amount) of volcanism and magmatism with increasing distance from the plume is expected.

The seismic data demonstrate that the offshore SDRs, which are in excess 10 km thick, are much thicker than the average flood-basalt thickness (only 0.7 km) in the onshore Paraná province (Leinz et al., 1968; Peate, 1997). More important, however, is the observation that the rate of volcanic rock production decreases from south to north within the individual volcanic margin segments II and III, bounded by the Colorado, Ventana and Salado transfer zones (Fig. 12). The major part of volcanic extrusives more or less terminates to the South at the Colorado transfer. Some 150 km south of this location there is another SDRs wedge located beneath the slope (Lines BGR87-05 and-06; Hinz et al., 1999). From these findings we suggest a link between margin segmentation and volume, architecture and breadth of the volcanics for the western South Atlantic margin. The, at least, four transfer zones offset the Lower Cretaceous rift and are associated with changes in distribution and volume of emplaced volcanic material, mark changes in structural pattern and margin subsidence. We propose that the South Atlantic rift evolved more likely by instantaneous breakup of longer sections of about 400 km rather than by continuous propagating rifting (Fig. 12). The proposed transfer zones may have acted as rift propagation barriers. If this is right the rift opened in distinct segments with an episodic emplacement of the huge amount of volcanic material within short time periods in each segment. The emplacement of the SDRs wedges would be mainly controlled in terms of excess melting by decompression. This in our view better explains the observed discontinuities and the systematically decreasing breadth of the SDRs wedges from south to north within the individual margin segments rather than mantle-plume influences. Deep

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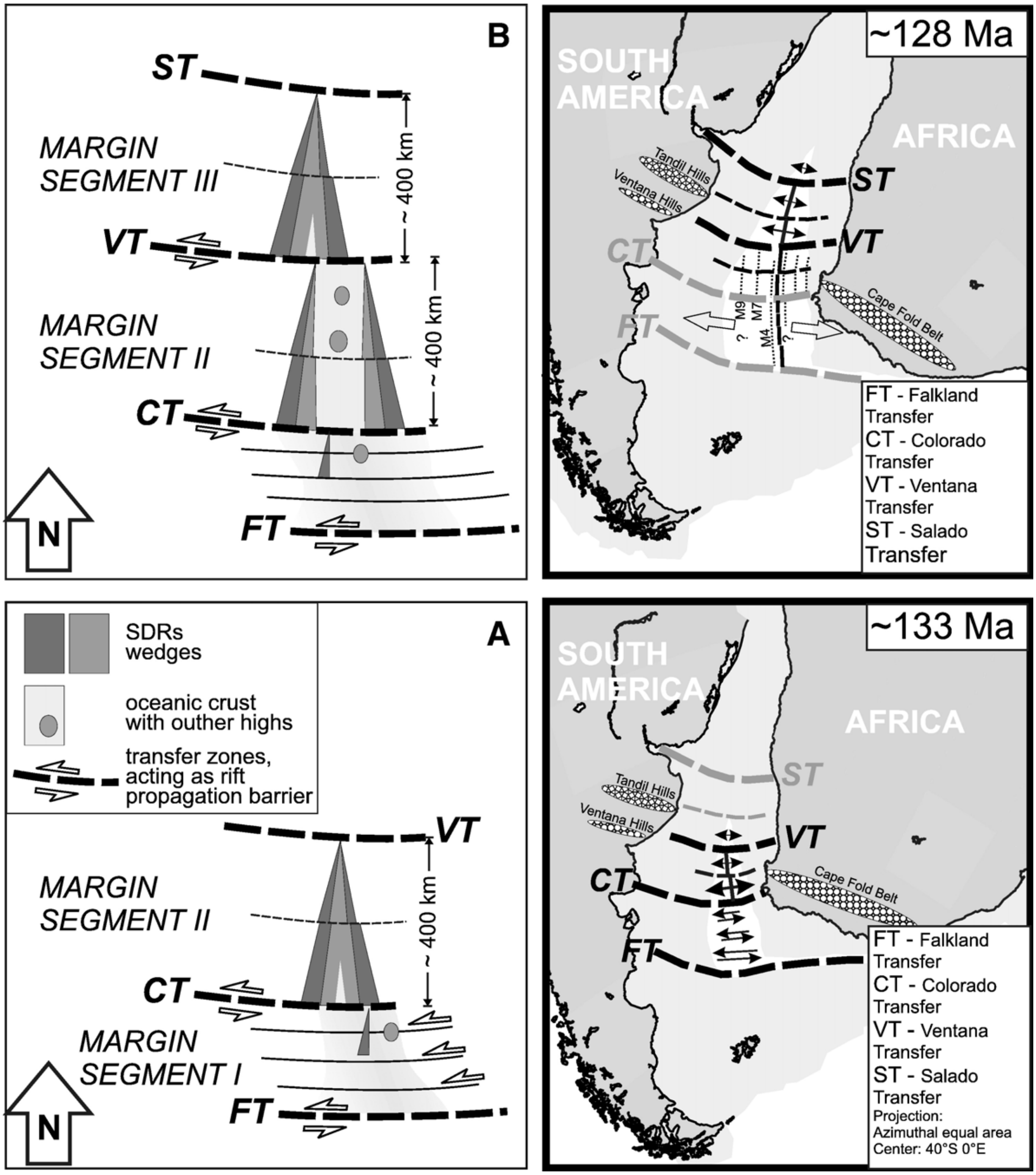

Fig. 12. Sketches illustrating the evolution of the southern South Atlantic rift (A, B) and plate reconstructions for 133 Ma and 128 Ma (modified from Jokat et al., 2003 and Macdonald et al., 2003). Time scale according to Gradstein et al. (2004). A. Margin segment I between the Falkland transfer (FT) and the Colorado transfer (CT) is dominated by strike-slip movements, which probably prevent the generation of large volumes of melt. North of the Colorado transfer (CT) a longer section (margin segment II) opens with initially a narrow SDRs wedge. At the future transfer zone about 400 km to the north (Ventana transfer, VT), rifting is interrupted resulting in heat accumulation in the upper mantle. This enhances convection in the asthenosphere and the subsequent emplacement of multiple SDRs wedges. The breadth of the SDRs wedges decreases northwards. B. When the next segment opened (margin segment III) north of the Ventana transfer (VT) initially a narrow SDRs wedge was emplaced with an offset in a sinistral sense. Another major transfer (ST— Salado transfer), again about 400 km to the north, interrupts the rifting process. The same heat accumulation and enhanced mantle convection is proposed as for margin segment II, resulting in the emplacement of the multiple SDRs wedges in this margin segment. At this stage we suggest an overprint of the southern segment resulting in the formation of volcanic outer highs and seaward SDRs sequences.

and relatively sharp lithosphere rupturing in form of fast propagating rift zones have been inferred as mechanism for transient excess melting by decompression for the diachronous emplacement of the SDRs along the Argentina margin (e.g. Hinz et al., 1999). The new data suggests that the observed transfer zones are important features for the emplacement of the SDRs. If the assumption of interrupted rifting is correct heat accumulation is likely to occur, resulting in enhanced convection in the asthenosphere (e.g. Mutter et al., 1988; Saunders et al., 1997). This may explain the formation of the large volumes of emplaced volcanic material. When the next segment was disrupted far field stresses may have affected the adjacent segment to the south resulting in the emplacement of the flat lying flows and the outer high, outer SDRs wedges (Fig. 12). The mantle temperature may or may not have been elevated above that of normal asthenosphere before breakup but local melt generation by adiabatic decompression in our view better explains the distinct variations in the architecture of the volcanic margin.

5. Summary and conclusions

Some 25,000 line kilometres of regional MCS data acquired on the Argentine and Uruguayan margin, South Atlantic, have been investigated with regard to the trend of crustal scale transfer zones, and the volume, architecture and width of SDRs wedges. The main findings are as follows:

- We have identified 4 transfer zones along the Argentine/Uruguayan continental margin, namely the Falkland, Colorado, Ventana and Salado transfers. Two less prominent transfer zones exist in addition. We propose that these transfer zones inhibit rift propagation, selectively directing rift segments in mainly left stepping patterns. The transfer zones may represent the initial formation of oceanic transform faults.
- The architecture, style and extent of the seaward dipping reflector sequences vary extensively and systematically. A general trend is that the largest volumes are emplaced close to the mapped transfer zones and the breadth of the SDRs wedges decreases northward within the individual margin segments.
- The margin segments correlate with differences in the volcano-tectonic architecture and the distribution of the post-rift sediments.
- The different volcano-tectonic architectures of the margin segments and the different volumes of extruded magmas may indicate that the emplacement of the volcanic material was controlled by the tectonic setting and the pre-rift lithosphere configuration within individual margin segments. We suggest that mainly adiabatic decompression and melt generation from shallow sources can explain distinct along-margin variations.

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References

Andreis, R.R., Iniguez, L.L., Lluch, L.L., Rodriguez, R., 1989. Cuenca Paleozoica de Ventania, Sierras Australes, Provincia de buenos Aires. In: Chebli, G., Spalletti, L. (Eds.), Cuencas sedimentarias Argentinas (Serie Correlacion 6). Universidad Nacional de Tucumen, Argentina, pp. 265–298.

Austin, J.A., Uchupi, E., 1982. Continental–Oceanic crustal transition of southwest Africa. AAPG Bull. 66 (9), 1328–1347.

Barton, A.J., White, R.S., 1997. Volcanism on the Rockall continental margin. J. Geol. Soc. Lond. 154, 531–536.

Boutilier, R., Keen, C., 1999. Small-scale convection and divergent plate boundaries. J. Geophys. Res. 104, 7389–7403.

Bowen, A.N., White, R.S., 1986. Deep-tow seismic profiles from the Vema transform and ridge- transform intersection. J. Geophys. Res. 143, 807–817.

Brown, L.F., Benson, J.M., Brink, G.J., Doherty, S., Jollands, A., Jungslager, E.H.A., Keenan, J.H.G., Muntingh, A., Wyk, N.S.J.V., 1995. Sequence stratigraphy in offshore South African divergent basins. AAPG Stud. Geol. 41, 1–184.

Bushnell, D.C., Baldi, J.E., Bettini, F.H., Franzin, H., Kovas, E., Marinelli, R., Wartenburg, G.J., 2000. Petroleum system analysis of the Eastern Colorado Basin, offshore Northern Argentina. In: Mello, M.R. (Ed.), Petroleum systems of South Atlantic margins. Am. Assoc. Petrol. Geol. Mem., vol. 29, pp. 403–415.

Corti, G., Van Wijk, J., Bonini, M., Sokoutis, D., Cloetingh, S., Innocenti, F., Manetti, P., 2003. Transition from continental break-up to punctiform seafloor spreading: how fast, symmetric and magmatic. Geophys. Res. Lett. 30 (12), 1604. doi:10.1029/ 2003GL017374, 1–4.

Dingle, R.V., Siesser, W.G., Newton, A.R., 1983. Mesozoic and Tertiary geology of Southern Africa. A.A. Balkema, Rotterdam (375 pp).

Eldholm, O., Skogseid, J., Planke, S., Gladczenko, T.P., 1995. Volcanic margin concepts. In: Banda, E., Torné, M., Talwani, M. (Eds.), Rifted ocean–continent boundaries. Kluwer, Dordrecht, pp. 1–16.

Eldholm, O., Gladczenko, T.P., Skogseid, J., Planke, S., 2000. Atlantic volcanic margins: a comparative study. In: Nøttvedt, A., Larsen, B.T., Olaussen, S., Tørudbakken, B., Skogseid, J., Gabnelson, R.H., Brekke, H., Birkeland, O. (Eds.), Dynamics of the Norwegian Margin. Geological Society of London Special Publication, vol. 167. The Geological Society, London, pp. 411–428.

Eldholm, O., Tsikalas, F., Faleide, J.I., 2002. Continental margin off Norway 62–75 °N: Paleogene tectono–magmatic segmentation and sedimentation. In: Jolley, D.W., Bell, B.R. (Eds.), The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and

Magmatic Processes. Geological Society of London Special Publication, vol. 197. Geological Society, London, pp. 39–68.

Ernst, R.E., Buchan, K.L., 1997. Giant radiating dike swarms: their use in identifying pre-Mesozoic large igneous provinces and mantle plumes. In: Mahoney, J., Coffin, M.F. (Eds.), Large igneous provinces: Continental oceanic and planetary flood volcanism. American Geophysical Union Geophysical Monograph, vol. 100, pp. 297–334.

Franke, D., Neben, S., Schreckenberger, B., Schulze, A., Stiller, M., Kravczyk, C., 2006. Crustal structure across the Colorado Basin, offshore Argentina. Geophysical Journal International 165 (3), 850–864. doi:10.1111/j.1365-246X.2006.02907.x.

Geoffroy, L., 2005. Volcanic passive margins. C. R. Geosci. 337, 1395–1408.

Gerrard, I., Smith, G.C., 1983. Post-Paleozoic succession and structure of the southwestern African continental margin. In: Watkins, J.S., Drake, C.L. (Eds.), Studies in continental margin geology. AAPG Mem., vol. 34, pp. 49–74.

Ghidella, M.E., Paterlini, M., Kovacs, L.C., Rodriguez, G., 1995. Magnetic anomalies on the Argentina Continental Shelf. 4th International Congress of the Brazilian Geophysical Society and 1st Latin American Geophysical Conference, Expanded abstracts, pp. 269–272.

Gibson, S.A., Thompson, R.N., Day, J.A., 2006. Timescales and mechanisms of plume–lithosphere interactions: 40Ar/39Ar geochronology and geochemistry of alkaline igneous rocks from the Paraná–Etendeka large igneous province. Earth Planet. Sci. Lett. 251 (1–2), 1–17.

Gladczenko, T.P., Hinz, K., Eldholm, O., Meyer, H., Neben, S., Skogseid, J., 1997. South Atlantic volcanic margins. J. Geophys. Res. 154, 465–470.

Gradstein, F.M., Ogg, J.G., Smith, A.G., et al., 2004. A Geologic Time scale 2004. Cambridge University Press, Cambridge (589 pp).

Griffiths, R.W., Campbell, I.H., 1991. Interaction of mantle plume heads with the earth's surface and onset of small-scale convection. J. Geophys. Res. 96, 18295–18310.

Hinz, K., 1981. A hypothesis on terrestrial catastrophes: wedges of very thick oceanward dipping layers beneath passive continental margins—their origin and paleoenvironmental significance. Geol. Jahrb., Reihe E, Geophys. 22, 3–28.

Hinz, K., Neben, S., Schreckenberger, B., Roeser, H.A., Block, M., Gonzalvez de Souza, K., Meyer, H., 1999. The Argentine continental margin north of 48°S: sedimentary successions, volcanic activity during breakup. Mar. Pet. Geol. 16, 1–25.

Holbrook, W.S., Kelemen, P.B., 1993. Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. Nature 364, 433–436.

Jackson, M.P.A., Cramez, C., Fonck, J.-M., 2000. Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks. Mar. Pet. Geol. 17 (4), 477–498.

Jokat, W., Boebel, T., König, M., Meyer, U., 2003. Timing and geometry of early Gondwana breakup. J. Geophys. Res. 108 (B9), 1–19. doi:10.1029/2002JB001802.

Kelley, M.L., Light, M.P.R., 1993. Basin evolution and prospectiveity of the Argentine continental margin. J. Pet. Geol. 16 (4), 451–464.

Korenaga, J., Holbrook, S., Kent, G., Kelemen, P., Detrick, R., Larsen, H.-C., Hopper, J., Dahl-Jensen, T., 2000. Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography. J. Geophys. Res. 105, 21591–21614.

Lawver, L., Gahagan, L., Coffin, M., 1992. The development of paleoseaways around Antarctica. In: Kennett, J.P., Warnke, D.A. (Eds.), The Antarctic paleoenvironment: A perspective on global change, vol. 56. American Geophysical Union, pp. 7–30.

Lawver, L.A., Gahagan, L.M., Dalziel, I.W.D., 1998. A tight fit-Early Mesozoic Gondwana, a plate reconstruction perspective. Mem. Natl. Inst. Polar Res., Spec. Issue 53, 214–229.

Leinz, V., Bartorelli, A., Isotta, C.A., 1968. Contibuiçao ao estudo do magmatism basáltico Mesozóic da bacia do Paraná. Ann. Acad. Bras. Ciênc. 40, 167–181.

Macdonald, D., Gomez-Pereza, I., Franzese, J., Spalletti, L., Lawver, L., Gahagan, L., Dalziel, I., Thomas, C., Trewind, N., Hole, M., Paton, D., 2003. Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic. Mar. Pet. Geol. 20, 287–308.

Max, M.D., Ghidella, M., Kovacs, L., Paterlini, M., Valladares, J.A., 1999. Geology of the Argentine continental shelf and margin from aeromagnetic survey. Mar. Pet. Geol. 16 (1), 41–64.

Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J., 2002. Characteristics of volcanic rifted margins. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J. (Eds.), Volcanic Rifted Margins. Special Paper, vol. 362. Geological Society of America, Boulder, Colorado, pp. 1–14.

Mjelde, R., Shimamura, H., Kanazawa, T., Kodaira, S., Raum, T., Shiobara, H., 2003. Crustal lineaments, distribution of lower crustal intrusives and structural evolution of the Vøring Margin, NE Atlantic; new insight from wide-angle seismic models. Tectonophysics 369 (3), 199–218.

Mutter, J.C., Talwani, M., Stoffa, P.L., 1982. Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by "subaerial sea-floor spreading". Geology 10, 353–357.

Mutter, J.C., Buck, W.R., Zehnder, C.M., 1988. Convective partial melting — a model for the formation of thick basaltic sequences during the initiation of spreading. J. Geophys. Res. 93 (B2), 1031–1048.

Müller, R., Royer, J.-Y., Lawver, L., 1993. Revised plate motions relative to hotspots from combined Atlantic and Indian hotspot tracks. Geology 21, 275–278.

Nürnberg, D., Müller, R.D., 1991. The tectonic evolution of the South Atlantic from Late Jurassic to present. Tectonophysics 191, 27–53.

Peate, D.W., 1997. The Paraná–Etendeka Province. In: Mahoney, J.J., Coffin, M.F. (Eds.), Continental, Oceanic, and Planetary Flood Volcanism. Geophysical Monograph, vol. 100, pp. 217–245.

Planke, S., Symonds, P.A., Alvestad, E., Skogseid, J., 2000. Seismic volcano-stratigraphy of large-volume basaltic extrusive complexes on rifted margins. J. Geophys. Res. 105 (B8), 19335–19351.

Rabinowitz, P.D., 1976. Geophysical study of the continental margin of southern Africa. Geol. Soc. Amer. Bull. 87, 1643–1653.

Rabinowitz, P.D., Labrecque, J.L., 1979. The Mesozoic South Atlantic Ocean and evolution of its continental margins. J. Geophys. Res. 84 (B11), 5973–6002.

Ramos, V.A., Turic, M.A., 1996. Geologia y Recursos Naturales de la Plataforma Continental Argentina. Asociacion Geol. Arg. e Inst. Arg. Petr. (452 pp).

Renne, P., Ernesto, M., Pacca, I., Coe, R., Glen, J., Prevot, M., Perrin, M., 1992. The age of the Parana flood volcanism, rifting of Gondwanaland, and the Jurassic–Cretaceous boundary. Science 258, 975–979.

Roberts, D.G., Backman, J., Morton, A.C., Murray, J.W., Keene, J.B., 1984. In: Blackman, J. (Ed.), Evolution of volcanic rifted margins: Synthesis of Leg 81 results on the west margin of Rockall Plateau. Init. Rep. DSDP, vol. 81, pp. 883–911.

Rosendahl, B.R., Groschel-Becker, H., 1999. Deep seismic structure of the continental margin in the Gulf of Guinea: a summary report.

In: Cameron, N.R., Bate, R.H., Clure, V.S. (Eds.), Oil and Gas Habitats of the South Atlantic. Geological Society Special Publications, London, pp. 75–83.

Sandwell, D.T., Smith, W.H.F., 1997. Marine Gravity from Geosat and ERS-1 Altimetry. J. Geophys. Res. 102, 10039–10054.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., Kent, R.W., 1997. The North Atlantic igneous province. In: Mahoney, J., Coffin, M.F. (Eds.), Large igneous provinces: Continental oceanic and planetary flood volcanism. American Geophysical Union Geophysical Monograph, vol. 100, pp. 45–94.

Sibuet, J.-C., Hay, W.W., Prunier, A., Montadert, L., Hinz, K., Fritsch, J., 1984. In: Hay, W.W., Sibuet, J.-C., Al, E. (Eds.), Early evolution of the South Atlantic Ocean: Role of the rifting episode. Initial Reports of the Deep Sea Drilling Project, vol. 75, pp. 469–481.

Stewart, K., Turner, S., Kelley, S., Hawkesworth, C., Kirstein, L., Mantowani, M., 1996. 3-D $^{40}Ar/^{39}Ar$ geochronology in the Parana flood basalt province. Earth Planet. Sci. Lett. 143, 95–110.

Talwani, M., Abreu, V., 2000. Inferences regarding initiation of oceanic crust formation from the U.S. east coast margin and conjugate South Atlantic margins. In: Mohriac, W., Talwani, M. (Eds.), Atlantic Rifts and Continental Margins. Geophysical Monograph, vol. 115. American Geophysical Union, Washington, DC, pp. 211–234.

Tsikalas, F., Faleide, J.I., Eldholm, O., 2001. Lateral variations in tectono-magmatic style along the Lofoten–Vesterålen volcanic margin off Norway. Mar. Pet. Geol. 18 (7), 807–832.

Uchupi, E., 1989. The tectonic style of the Atlantic Mesozoic rift system. J. Afr. Earth Sci. 8 (no. 2/3/4), 143–164.

Uchupi, E., Emery, K., 1991. Pangaean divergent margins: historical perspective. Mar. Geol. 102, 1–28.

Uliana, M.A., Biddle, K.T., 1987. Permian to Late Cenozoic evolution of Patagonia, main tectonic events, magmatic activity, and depositional trends. In: McKenzie, G.D. (Ed.), Gondwana six: structure, tectonics, and geophysics. Am. Geophys. Monograph, vol. 40. AGU, Washington, D.C., pp. 271–286.

Unternehr, P., Curie, D., Olivet, J., Goslin, J., Beuzart, P., 1988. South Atlantic fits and intraplate boundaries in Africa and South America. Tectonophysics 155, 169–179.

Urien, C.M., Zambrano, J.J., 1996. Estructura del margen continental. In: Ramos, V., Turic, M. (Eds.), Geologia y recursos naturales de la plataforma continental Argentina. Asociacion Geologica Argentina, Buenos Aires, Argentina, pp. 29–65.

Urien, C.M., Zambrano, J.J., Martins, L.R., 1981. The basins of southeastern South America (southern Brazil, Uruguay, and eastern Argentina), including the Malvinas Plateau and southern South Atlantic paleogeographic evolution. In: Volkheimer, W., Musacchio, E.A. (Eds.), Cuencas sedimentarias del Jurasico y Cretacico en America del Sur. Comite Sudamericano del Jurasico y Cretacico, vol. 1, pp. 45–126.

Van Wijk, J.W., Huismans, R.S., Ter Voorde, M., Cloetingh, S.A.P.L., 2001. Melt generation at volcanic continental margins: no need for a mantle plume? Geophys. Res. Lett. 28, 3995–3998.

Van Wijk, J.W., Van der Meer, R., Cloetingh, S.A.P.L., 2004. Crustal thickening in an extensional regime: application to the mid-Norwegian Voring margin. Tectonophysics 387, 217–228.

White, R.S., 1984. Atlantic oceanic crust: seismic structure of a slow spreading ridge. In: Gass, I.G., Lippard, S.J., Shelton, A.W. (Eds.), Ophiolites and Oceanic Lithosphere. Geol. Soc. London Spec. Publ., vol. 13, pp. 101–111.

White, R., McKenzie, D., 1989. Magmatism at rift zones: the generation of continental margins and flood basalts. J. Geophys. Res. 94, 7685–7729.

White, R.S., McKenzie, D., O'Nions, R.K., 1992. Oceanic crustal thickness from seismic measurements and rare earth element inversions. J. Geophys. Res. 97, 19683–19715.

Wilson, P.G., Turner, J.P., Westbrook, G.K., 2003. Structural architecture of the ocean–continent boundary at an oblique transform margin through deep-imaging seismic interpretation and gravity modelling: Equatorial Guinea, West Africa. Tectonophysics 374, 19–40.

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