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Key Points:
- We observe different inclination angles and structure of the SDRs in two conjugate sections across the South Atlantic margin
- Modeling suggests a detachment fault bounds the SDRs on the South American side
- We suggest a simple shear mechanism to explain the initial break-up of the South Atlantic

Supporting Information:
- Supporting Information S1

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Fault-controlled lithospheric detachment of the volcanic southern South Atlantic rift

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Abstract We present structural models of two exemplary conjugate seismic lines of the southernmost South Atlantic margins to examine their initial evolution, especially the seaward-dipping reflectors (SDRs). Modeling illustrates the different structure and inclination angles of the SDRs, which therefore require different subsidence histories. Since typical symmetrical subsidence models are not applicable, we suggest a model with a westward-dipping detachment fault that offsets the SDRs on the South American margin and we speculate on passively subsided SDRs on the South African margin. We propose a simple-shear rifting mechanism to explain the initial break-up of the South Atlantic.

1. Introduction

Both active and passive rifting models have been invoked to explain the formation of volcanic passive margins [*Sengör and Burke*, 1978]. Extension associated with rifting can be kinematically described in terms of as either pure or simple shear, or a combination of both [*McKenzie*, 1978; *Wernicke*, 1985; *Lister et al.*, 1986; *Kusznir et al.*, 1991; *Reston et al.*, 1996]. The widespread arcuate, concave-down geometry of seaward-dipping reflectors in cross section (SDRs) has been previously explained by symmetrical subsidence models [*Hinz*, 1981; *Mutter*, 1985], or more recently, by fault-related models [*Geoffroy*, 2005; *Mjelde et al.*, 2007; *Stica et al.*, 2013]. *Eldholm et al.* [1995] questioned purely symmetric break-up models and suggested from magmatic asymmetries, as observed from the extrusives distribution and volumes in the North Atlantic, that simple shear extension should be considered. Also, the role of faulting in the formation of the shape of SDRs is a highly controversial topic [*Hinz*, 1981; *Mutter*, 1985; *Roberts et al.*, 1984; *Eldholm et al.*, 1995; *Planke et al.*, 2000; *Geoffroy*, 2005; *Stica et al.*, 2013; *Clerc et al.*, 2015]. Here we provide evidence for a westward-dipping asymmetric lithospheric detachment that controlled the break-up of the southernmost Atlantic Ocean (or: the final stage of rifting).

2. Geological Setting

The break-up of the South Atlantic began in the Early Cretaceous. Reconstructions of seafloor magnetic anomalies and the transient age propagation of the break-up unconformities along the margins confirm the proposition that the South Atlantic opening began in the south and then propagated northward [*Franke*, 2013; *Heine et al.*, 2013; *Jackson et al.*, 2000; *Koopmann et al.*, 2014b; *Moulin et al.*, 2010]. Prior to and during the early phase of the formation of the ocean basin, voluminous volcanism affected both Mesozoic intracratonic basins onshore (Paraná-Etendeka large igneous province) and the rifted crust offshore [*Blaich et al.*, 2009; *Franke et al.*, 2010; *Gladczenko et al.*, 1997; *Hinz et al.*, 1999; *Koopmann et al.*, 2014a; *Peate*, 1997]. The southernmost segment, close to the Falkland-Agulhas Fracture Zone (FAFZ), however lacks extrusive magmatism [*Becker et al.*, 2012; *Franke et al.*, 2007; *Koopmann et al.*, 2014a] (Figure 1).

We carefully chose representative seismic profiles of the margins of the South Atlantic, perpendicular to the spreading ridge, which we consider to be type crustal sections for the margin segment under consideration (Figures 1 and 2). Because these sections are located at the southern limit of the SDRs, this area is an ideal location to study the initial stages of the opening of the South Atlantic. Volcanic rifting and thus the emplacement of SDRs initiates to the north of the Colorado-Cape Transfer Zone [*Franke et al.*, 2007; *Koopmann et al.*, 2014a], and extend northward until the Walvis Ridge/Rio Grande Rise. In general the SDRs form

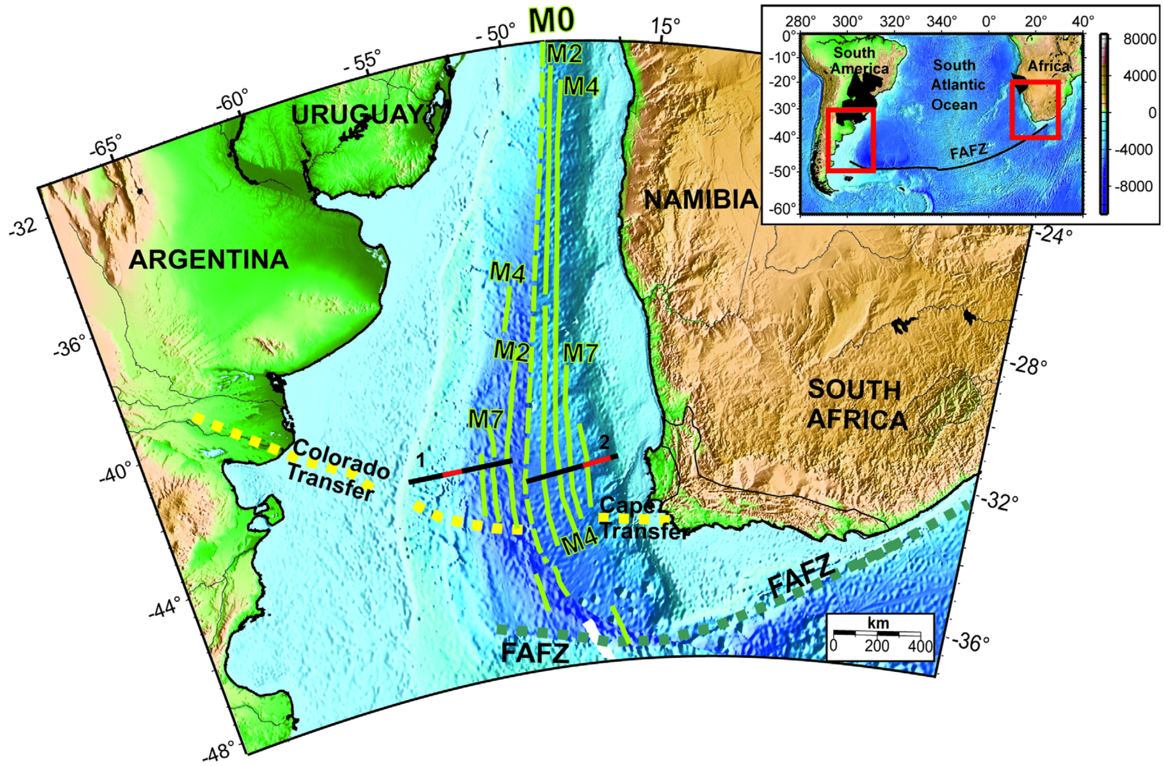

Figure 1. The southern South Atlantic reconstructed along sea floor spreading anomaly M0 (dashed green line, ca. 125 Ma). The black lines show the cross sections discussed in the text: line 1 (BGR98-18) and line 2 (BGR03-16a). The red lines are the parts of the seismic displayed in Figures 2a and 2b. Magnetic anomalies are shown as green lines. Colorado-Cape Fault Zone (dashed yellow line), FAFZ - Falkland Agulhas Fracture Zone (dashed green line). The inlay shows the present-day South Atlantic with the Parana-Etendeka flood basalts (black area).

distinct wedges that show internally a distinct arcuate reflection pattern in cross section. On the contrary, the tops of the SDR wedges are typically subhorizontal over tens of kilometers on along-strike profiles. *Franke et al*. [2007] explained the observed strong discontinuities on the tops of individual SDRs as being caused by erosion, followed by episodic emplacement in the seaward direction. After the most-landward SDR wedge was emplaced, a hiatus occurred, which possibly included weathering and subsidence before the next wedge was emplaced [*Franke et al*., 2007; *Koopmann et al*., 2014a].

Indication of regional simple-shear extension is not only provided by the irregular distribution and volumes of the magmatic extrusives [*Koopmann et al*., 2014b] but also by the major asymmetry in the across-margin volumes of the HVLC [*Becker et al*., 2014]. In addition, the wide and deeply subsided rift grabens on the African margin, e.g., the Orange Basin, are in sharp contrast to the narrow and scattered syn-rift grabens on the conjugate margin [*Franke et al*., 2007] and may be explained by simple-shear extension.

3. Methods

The seismic data used in this study were acquired during two scientific cruises performed by the German Federal Institute of Geosciences and Natural Resources (BGR) in 1998 and 2003. The two sections, BGR98-18 (line 1) and BGR03-16a (line 2), are regarded as conjugate because they cross the margin close to the Colorado-Cape Segment Boundary (Figure 1). Previous interpretation of the time-migrated line 1 was presented by *Franke et al*. [2010]; line 2 was shown in *Koopmann et al*. [2014a] and *Franke* [2013]; line 1 was presented by *Franke et al*. [2010]. Poststack depth migration was applied to the South American seismic line (line 1). The African line was converted to depth using interval velocities (line 2; Figure 2a). The Mohorovičić boundary (Moho) and high-velocity lower crust (HVLC), which are beyond reflection seismic resolution, were projected onto the seismic lines from refraction seismic modeling of velocity sections published by

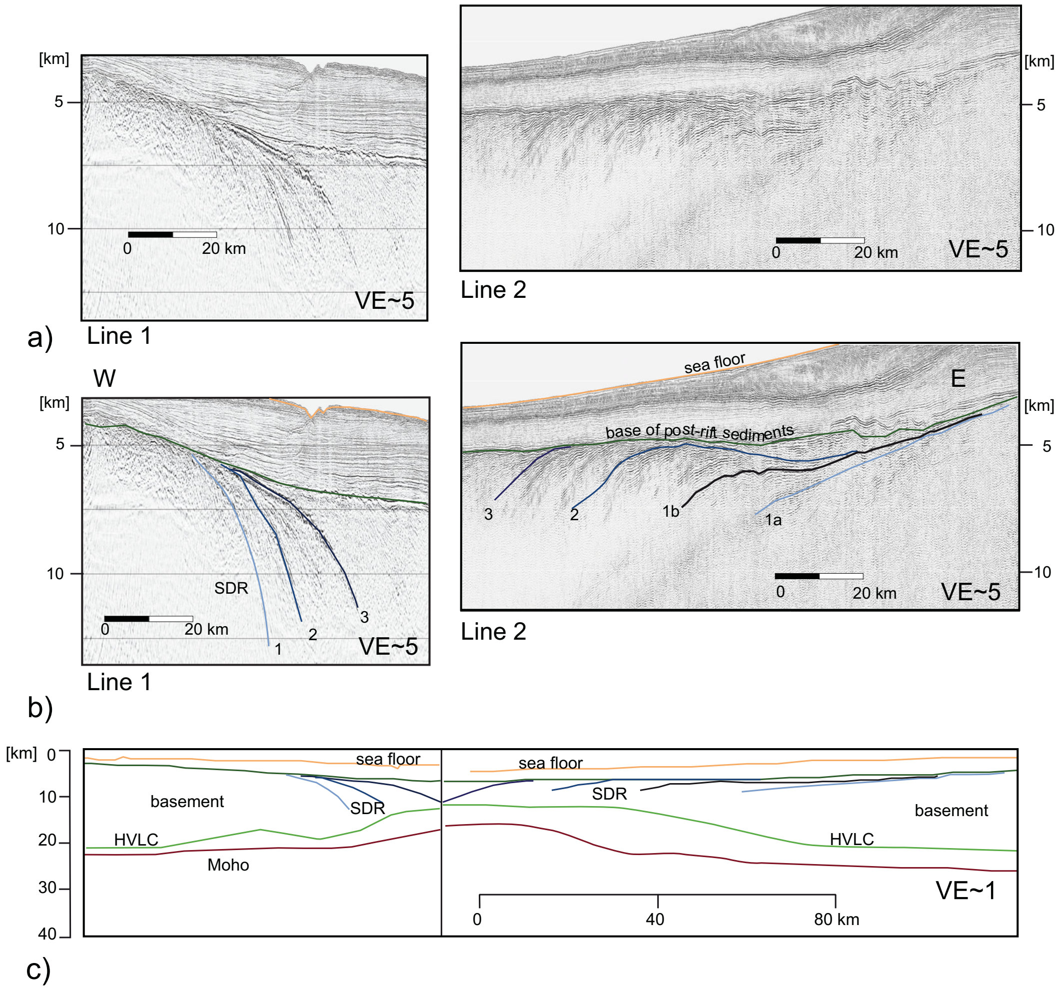

Figure 2. Depth-migrated seismic lines 1 and 2, showing the SDRs): (a) uninterpreted. (b) interpreted. (c) Structure model of the conjugated sections 1 and 2 showing the sea-floor (yellow), Moho (red), HVLC (high-velocity lower crustal bodies; light green), SDRs (dark, middle and light blue) and top basement (dark green).

Schnabel et al. [2008] and *Hirsch et al.* [2009]. To construct a structural model, we incorporated the reflection seismic horizons in a 2D Move^{TM} model, including seafloor, SDRs, basement, top HVLC, and the Moho (Figure 2c).

Any disturbed horizon that can be considered to represent an originally flat surface and now forms the shape of the hanging-wall can be used to predict the geometry of the fault below it [*Davison*, 1986; *Groshong*, 1989]. Of the different methods available, the assumption of constant slip is most useful because it assumes that the slip, i.e., the displacement of the hanging-wall, is at all points along the fault constant [*Davison*, 1986]. If, instead, assumptions of constant heave or throw are used, and the fault changes dip, e.g., it is listric, then the hanging wall would undergo extreme deformation as the amount of slip would change as the dip changed. This we consider unrealistic.

In the constant-slip model, a fault is firstly drawn at an expected angle between the regional and tip of the first hanging-wall bed, in this case SDR 1. The straight line length of this fault segment represents the first increment of displacement (*d*). A rectangle is constructed so that the top edge connects the top of the hanging-wall with the regional, while the perpendicular is allowed to extend to the last contact of the hanging-wall with the fault (Figure 3). This is repeated at intervals of *d* until the fault is constructed [*Davison*, 1986]. Additional hanging-wall beds can be used to construct the fault trace independently and the resultant traces can be compared.

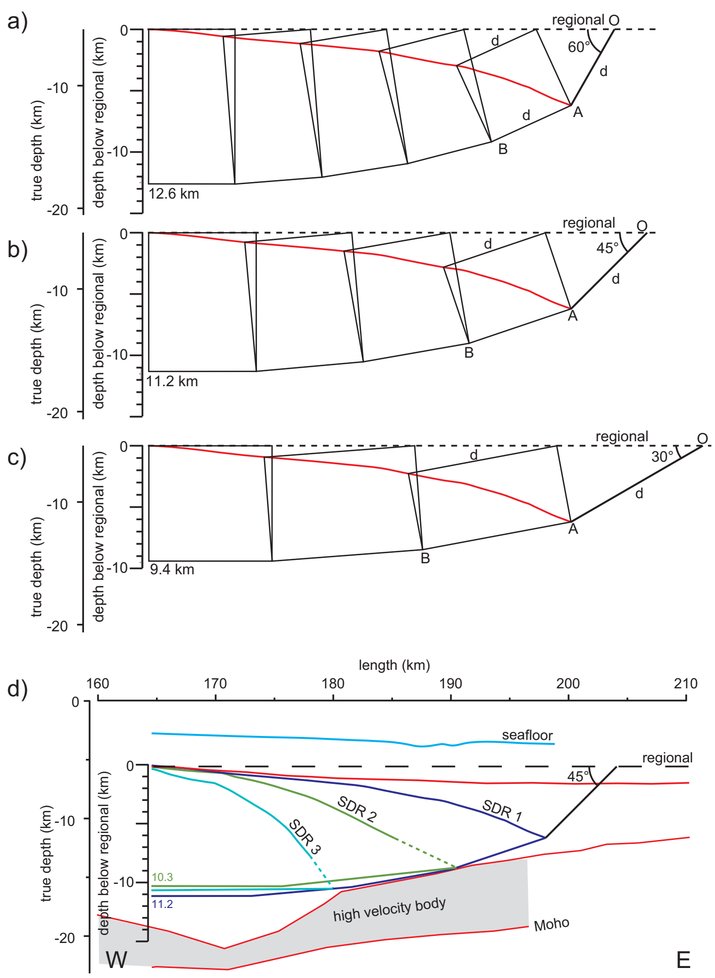

Figure 3. Prediction of fault geometry of the South American structure model by considering the SDRs to form the hanging-wall of a one listric fault. a-c) Fault traces constructed using constant slip for three different starting dips and SDR1: (a) 60° (b) 45° (c) 30°. (d) Structure model with SDRs (1–3) for a starting dip of 45°. Note the projection of the SDRs 2 and 3 to the major fault as indicated by dashed lines. The final detachment depth (relative to the regional at the top of the SDRs is between 10.3 and 11.2 km (ca. 15 km present-day depth).

4. Results

4.1. Seismic Interpretation

The structure model of the conjugate seismic lines shown in Figure 2c) (see supporting information for the entire reflections seismic sections) are displayed with no vertical exaggeration. For clarity we mapped three reflectors of the inner SDRs wedge (Figures 2b and 2c). The SDRs surfaces show a seaward increase in dip and the SDR wedge thickens with depth. The area between the top reflector of the SDRs and the outer volcanic high (area above dark blue line in Figures 2b and 2c) were interpreted as flat-lying volcanic flows [*Franke et al.*, 2007, 2010; *Bauer et al.*, 2000]. The break-up unconformity (dark green in Figures 2b and 2c), merges with the top of the SDR wedges to suggest that the SDR formed before seafloor spreading. The earliest oceanic crust is interpreted immediately seaward of the SDRs [*Koopmann et al.*, 2014a; *Franke et al.*, 2010; *Becker et al.*, 2014]. The postrift sediments on the South American margin reveal a thickness of 3.5 km at the seaward end of the SDRs, which thins to 2.5 km at the feather edge. In contrast, 2 km thick postrift sediments at the seaward end of the SDRs on the South African margin thicken to 2.5 km at the feather edge of the SDR wedges (Figures 2b and 2c). The HVLC body is asymmetric, with a much greater cross-sectional area on the South African margin, as discussed by *Becker et al.* [2014]. It remains an open question, to what an amount of continental crust is found below the SDRs. We consider the presence of continental crust below the landward edge of the SDRs very likely. Probably there is a seaward increasing contribution of magmatic material at the down-dip ends of the SDR's, which resulted in a transition from predominantly continental to mainly mafic oceanic crust. As confirmed by refraction seismic studies, a HVLC (high velocity lower crustal) body with velocities above 7 km/s and a maximum thickness of 4 km at the South American and 10 km at the South African margin is present at deep crustal levels. The top of the HVLC body dips below the SDRs at a depth of 14 km to about 18 km (American) or 20 km (African), toward the continent. Wide-angle seismic refractions constrain the Moho depth to 17–18 km below the top SDR reflector and to 23 (American)/25 km (African) below the bottom SDR reflector. The continental crust at the landward end of both lines, at the tip of the lowest SDR reflector, is around 25 km in thickness and thins seaward.

4.2. Modeling

The data reveal that the SDRs on the two conjugate margins have very different inclinations and structures (Figure 2). Compared to the SDRs on the South African side, the South American SDRs are considerably shorter and more inclined.

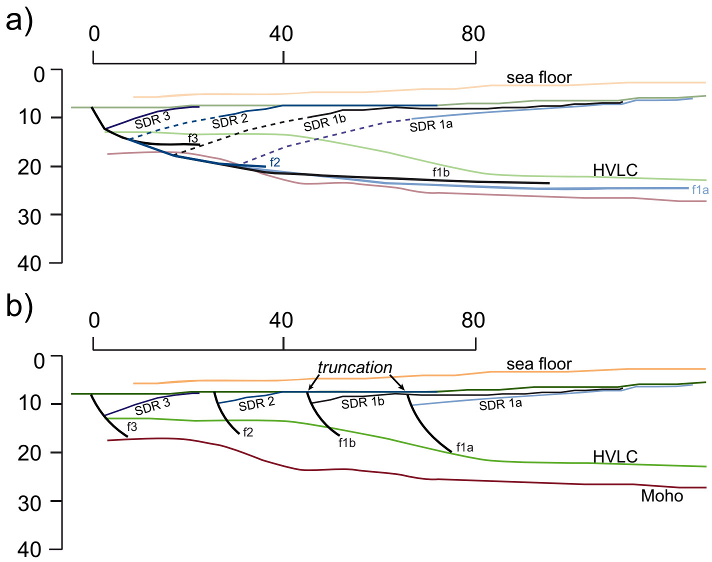

Figure 4. Possible but unlikely models of SDRs on the South African margin. (a) Four different fault traces (f1a-f3), constructed using constant slip, based on the shape of the four individual seaward-dipping reflector surfaces (SDR1a-SDR3). Note that this also requires the SDRs to be projected between 20 (SDR2) and 35 km (SDR1a). (b) Interpretation of the SDR so that each belongs to one of four landward-dipping normal faults (f1a-f3). Each tilted fault block is truncated by the following SDR emplacement.

Using the constant-slip method, we began by constructing a listric fault with a dip of 45° (Figure 3). For each SDR, the shape of the resulting fault was plotted. Remarkably, all three SDRs suggest a very similar listric fault-plane trace that detaches at a depth between 10.3 and 11.2 km (Figure 3). Therefore we propose that the SDRs of the South American side can be modeled as hanging-wall surfaces above a single westward-dipping listric fault. We interpret that the fault crosses the lithospheric crust to sole out on top of the HVLC and then reaches the continental Moho, so that it detaches the upper crust from the lower crust in an asymmetrical manner (Figure 3). According to this scenario, the SDRs were deposited in a synsedimentary fashion against the fault over several million years, before the system was replaced by seafloor spreading in the footwall of the fault. A minimal horizontal extension of 28 km occurred during this phase of SDR deposition and faulting.

Modeling the South African SDRs in the same fashion shows that the SDRs predict different fault trajectories (Figure 4a, f3-1), which detach within the HVLC at the depths of 15, 20, and 22–23 km, respectively. This is highly improbable. Alternately, it would be possible to assume each SDR has its own steep listric fault that flattens out along the top of the HVLC (Figure 4b), but this would mean each fault was active in strict temporal order, from landward to seaward (f1a-f1b-f2-f3), and every subsequent SDR event truncated the structures that occurred before it (Figure 4). This is equally improbable. Instead, differential subsidence seems to be the most likely explanation for the inclination of the South African SDRs.

Thus we envisage two different mechanisms to explain the SDR subsidence history of the opposing margins; a detachment fault for the South American margin and passive subsidence for the South African margin.

5. Discussion

Seismic observations reveal different inclination angles and lateral extents of the SDRs on the conjugate margins on the respective sections (Figure 2). Due to the equal thicknesses of the crust on both conjugate margins we reject the hypothesis that differential subsidence was induced by overlying postrift sediments. Symmetrical subsidence models also cannot explain such different SDR patterns. Landward-inclined listric faults on the South African margin, which would be necessary to establish a pure shear mode of rifting, were not verified by the kinematic modeling. Others have questioned the concept of SDR subsidence on the basis of onshore investigations. For instance in east and west Greenland, *Geoffroy* [2005] interpreted SDRs as syn-magmatic, roll-over tectonic flexures that are controlled by major continent-dipping normal faults. This concept was also applied to regional SDRs in the Pelotas Basin [*Stica et al.*, 2013]. Unlike *Stica et al.* [2013], whose seismic lines cross the northernmost South Atlantic; our lines are located at the southernmost edge of the South Atlantic, where magmatic break-up occurred first. However our seismic data do not show landward-inclined faults within the SDRs wedges, as required by the model of *Geoffroy* [2005]. The initial configuration of the Icelandic lava pile has also been explained by an opposing pair of listric

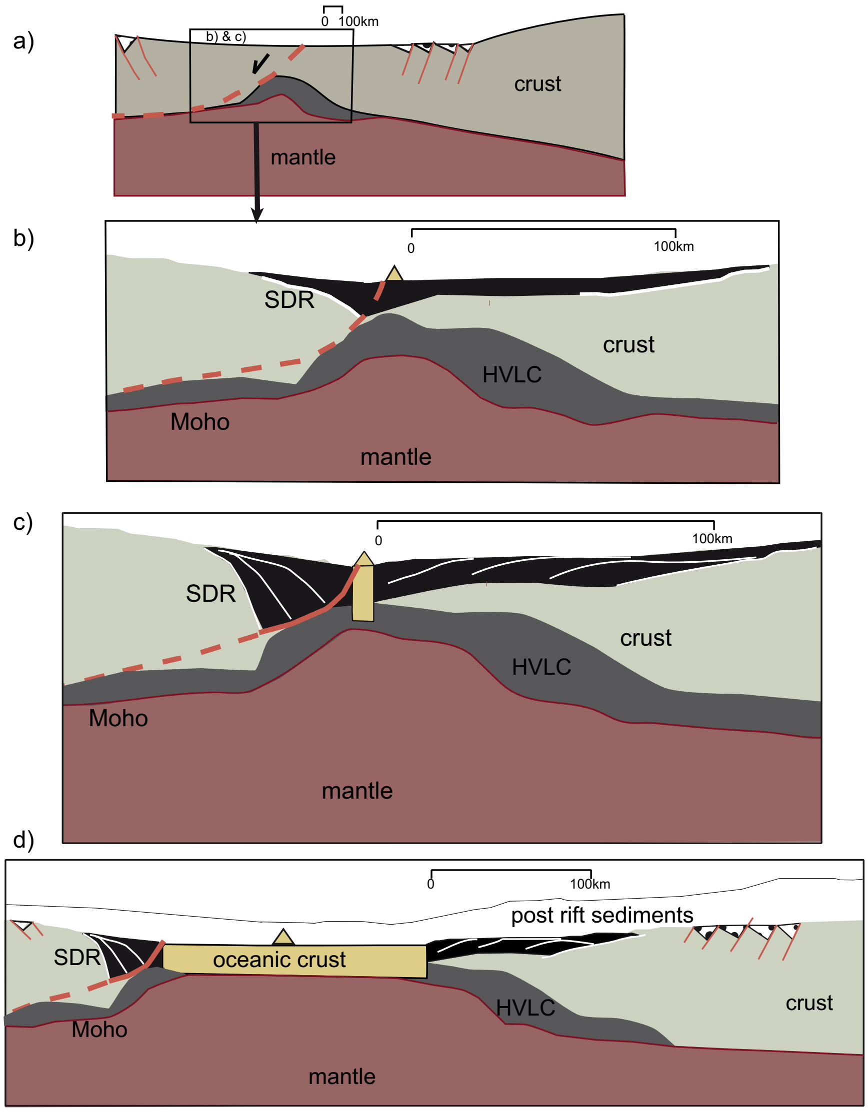

Figure 5. Conceptual model showing the stages of the South Atlantic break-up by simple-shear. (a) The first stage is characterized by thinned crust and a detachment fault. Synrift graben have already formed as indicated. The black box shows the locations of Figures 5b and 5c. (b) Formation of the first SDR wedge. Magmatic rocks are emplaced as flood basalts and intrusions (black color) in the crust over the footwall into the hanging-wall of the detachment fault. The triangle marks the eruption centre. (c) Emplacement of the SDRs wedges finishes and proper sea-floor spreading begins (oceanic crust in light brown, the triangle marks the spreading centre). (d) Present-day geological situation.

normal faults [*Gibson and Gibbs*, 1987]. This idea has been further applied to the SDRs of the Vøring Plateau [*Gibson and Love*, 1989; *Mjelde et al*., 2007]. The latter infer a system of opposing detachment surfaces that sole out at the top of the lower crust, that is, as a symmetrical system. *Mjelde et al*. [2007] interpreted the crustal-scale detachment faults to develop in the last phase of rifting, while in our model one main detachment fault was active since the first phase of rifting. *Mjelde et al*. [2007] argued for feeder dikes as magmatic pathways in the lower crust and related to continent-dipping normal fault, whereas magma in our model could rise in the footwall of the detachment fault and be extruded as flood basalts at the surface. Our seismic data do not resolve faults and feeder dikes within the upper crust. Our model does not exclude footwall deformation, but considers one fault, which may have also served as a magmatic conduit. The lower crust (the future HVLC), below the detachment fault, was probably ductile [*Clerc et al*., 2015] and therefore may have not been able to obtain the stresses necessary for the initiation of fractures to allow diking. Alternatively, we hypothesize there was a major dike that fed an eruption center seaward of the detachment fault. If the HVLC was formed by magmatic intrusions, then the detachment fault overlies intruded crust.

Compared to the model of *Blaich et al*. [2011], in which a large detachment fault offsets the whole upper crust, including the spreading center, our solution for the South American margin only offsets the SDRs along a listric fault landward of the spreading center (Figures 5c and 5d).

A number of authors have suggested faults exist within highly magmatic settings. An asymmetric detachment fault has been observed in the Afar region, where two stages of extension over listric faults are inferred to have caused faulted rollover anticlines [*Geoffroy et al*., 2014]. This differs from our prediction of SDR evolution, where we propose the crust was thinned in just one stage. *Quirk et al*. [2014] predict that magma rises due to a pressure gradient as the load decouples across the fault, which is a maximum at the point where the fault detaches (i.e., the detachment is subhorizontal). *Quirk et al*. [2014] also suggest the magma can rise along a normal fault. In our case, we suggest that ascent of the magma may occur along the detachment fault on the American margin, but that intrusive magma occurs only in the footwall of the fault and in a transition zone along the detachment fault. Extrusive magma in the form of SDRs was deposited from the spreading center, basinward of the fault, on to the hanging-wall of the fault.

We propose that the differing shape and extent of the SDRs on opposing sides of the Atlantic, as well as the asymmetrically distributed high-velocity lower crustal zones, cannot be explained by a uniform stretching model involving pure shear. We suggest instead that west-dipping simple shear crustal detachment occurred during the break-up stage of the south Atlantic (Figure 5). This agrees with a recent study by *Clerc et al*. [2015] who propose that the lower crust of the Uruguayan volcanic rifted margin may have behaved in a rather weak and ductile way, that resulted in crustal-scale shear zones. The strong reflectors, interpreted as typical shear patterns [*Clerc et al*., 2015] may be the image of what we interpret as a crustal detachment.

6. Conclusions

The SDRs of the southernmost South American margin possess much steeper inclination angles and are shorter compared to the SDRs of the conjugate South African margin. We derive a model from the shape of the South American SDRs that describes a westward-dipping listric fault that detaches along the top of the HVLC and then enters the mantle. On the contrary, the flatter inclination of the South African SDRs might be attributed predominantly to subsidence. Our model does not need landward-inclined faults between individual SDRs. The single listric fault of our model offsets all the SDRs and detaches the crust from the mantle, but the fault neither exhumes the mantle nor does it offset the spreading center. We therefore propose an asymmetric rifting model with a major simple shear crustal detachment to explain the earliest magmatic break-up process of the southernmost South Atlantic.

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