Tectono-Stratigraphic Evolution of South Atlantic Extensional Rifted Margins: Constraints from Sandbox Analogue Modeling*

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Abstract

A series of 3D sandbox analogue models with the support of 2D structural restoration on selected regional transects were used to analyze the pre-salt tectono-stratigraphic evolution of the Central segment of the South Atlantic Ocean (Figure 1). Seafloor spreading in the study area took place at the Aptian-Albian boundary, and the conjugate West Africa and Brazil rifted continental margin segment is classified as a "magma-poor" margin segment characterized by the presence of an intermediate/transitional crust between the continental and the oceanic crust.

This contribution presents the results of a set of sandbox modeling experiments aimed to elucidate the structural elements and features reflecting the syn-rift basin evolution and the processes that governed the pre-breakup lithospheric extension at a rifted margin. The extensional sandbox analogue models were performed at full lithospheric-scale: a 4-layers setup (upper and lower crust/mantle) with alternating layers of sand and silicone putty, representing different rheological layering (strength-depth functions). Lateral anisotropy in the viscosity of the lower crust or upper mantle has been introduced in some 3D models to represent cold and/or warm lithosphere condition, as largely accepted to occur in both African (the High Velocity Layer of Contrucci et al., 2004, and Pan African Fold Belt

of Gray et al., 2006) and South America margins (e.g. Walvis Ridge and Abimael failed ridge; Scotchman et al., 2006; Carminatti et al., 2008).

One of the main analogue modeling result shows that crustal in-homogeneities/discontinuities give rise to asymmetry of the rifted conjugate margins by coupling hard-soft or soft-hard geometry, thus affecting the geological evolution by focusing the deformation in thick and isolated or thin and widespread syn-rift basins.

Introduction

The crustal-scale structure of rifted passive margins represents an issue of relevant academic and commercial hydrocarbon-industry interest, and has been extensively investigated in the last decade, using geophysical prospecting, numerical and analogue modeling. In spite of the efforts, some basic questions are still open to debate, mostly concerning the amount and mode of crustal and lithospheric thinning (e.g. Reston, 2009), and the possible depth-dependency of lithospheric stretching (e.g. Huismans and Beaumont, 2011; Aslanian et al., 2009). Although hampered by obvious limitations, sandbox analogue modeling has proven to be an effective way to investigate lithospheric-scale deformation, and particularly to visualize the 3D modeling evolution of modeling (Michon and Merle, 2003).

Diachronous rifting ended with the final lithospheric breakup and opening of the South Atlantic. The rifting propagated along the northern Argentinean margin in the Middle Jurassic (180-160 Ma) and reached the Central Atlantic Segment (Figure 1) by Late Jurassic-Early Cretaceous (140-132 Ma) (Mohriak et al., 2008). Initially, the divergent motion was directed E-W, but progressively changed to a NE-SW direction leading to the breakup at 112 Ma.

The geological interpretation resulting from 2D restoration of regional seismic lines of both Brazilian (Figure 2) and Angolan margins represented the starting point for the analogue modeling. The latter is a forward modeling based on the sandbox technique that allowed us to reproduce, through the building of 3D space- and time-scaled physical models, the 3D tectono-stratigraphic evolution of the Central Segment of the Southern Atlantic margin.

Setup and Results

Modeling has been performed in a sandbox using a 4-layers setup, with alternating layers of sand and silicone putty, representing the brittle and ductile rheology, respectively, of crust and mantle. The layer-cake has been set so as to float above a glucose solution, that represents the asthenosphere, and the density of modeling materials has been appropriately scaled, in order to reproduce crustal and mantle rocks of a realistic lithospheric structure. Lateral anisotropy in the viscosity of the lower crust has been introduced in some 3D models.

The sandboxes used are made of plexiglass and have a width of ca. 30 cm and a length ranging from 40 to 50 cm. One of the short walls of the sandbox is pulled using a computer-controlled motor to impose extension at a velocity of 1 to 3 cm/hour; this wall is attached to two moving sidewalls that help pulling the sand/silicone layer-cake. Two end-member sets of models have been performed, based on the relative length of the two mobile sidewalls: a) the two sidewalls are of the same length miming thus an orthogonal rifting parallel to the pulled wall, joining the tip of the sidewalls; and b) the two sidewalls have different lengths and, thus, an oblique rifting is produced. In the latter case, weak seeds in the brittle mantle are used to impose segmented boundaries whereas in the orthogonal rifting both weak (warm) and rigid (cold) discontinuities represented Lower Upper Crust “thermal” inhomogeneities. At the end of extension (typically 12-20 cm), the models have been frozen and cut into vertical serial slices so as to analyze the fault geometry in the volume unaffected by sidewall shearing, and to study the eventual 3D variations imposed in the model setup.

The results show a pure shear affecting the ductile mantle lithosphere, in the initial stages, which is subsequently followed by a necking of the ductile lithospheric mantle and lower crust that join together, following the breakup of the brittle mantle. Since the 3D analogue modeling is “box confined” it represents a non-depth dependent stretching rifting process. Nevertheless, the performed non-depth depending pure shear models promote a simple shear deformation, typically dominated by one major extensional fault that soles out into the underlying ductile unit with the possibility to have mantle exhumation. The crustal in-homogeneities/discontinuities give rise to asymmetry of the rifted margins by coupling hard-soft or soft-hard conjugate margin geometry. Thus, resulting extensional basins located close to the discontinuities are affected both in subsidence and development (Figure 3). The rift focuses laterally or on the other conjugate margin in respect to the Rigid Massif (avoiding hard rheologies and preferring a weak material to develop) giving rise to wide early rift structures/basins development (early syn-rift deposition in a wide area) as in Brazilian Campos Basin (Figure 2) or close to Lower Congo and northern Kwanza basins transition (e.g. Lentini et al., 2010). Presence of warmer in-homogeneity within the lower crust support focused extensional faults above the discontinuity giving rise to a main listric (detachment) half-graben basin with thick sedimentary succession as in Santos Basin (Figure 2) or northern Lower Congo Basin.

Conclusions

The observed pre-salt Central Atlantic along-margin segmentation and basin evolution largely depends on pre-rift/inherited lower crust and lithosphere rheology. Development of depocenters (in space and time) is then a function of lower crust/brittle mantle rheology. Weaker, warmer, crystalline lower crust rheology promotes deeper basins, whereas relatively stronger, cold, crystalline lower crust rheology makes the upper crust more “brittle”, resulting in more tectonically guided basins (Figure 3).

Along margin changing in symmetry to asymmetry is a common feature that occurs in several models and seems to be related to the main detachment (i.e. crust rheology dependant), affecting the rifting geometry. Both oblique and orthogonal extension models support the influence of inherited rheology in-homogeneities, affecting the conjugate South America–Africa rifting process. These inhomogeneities drive an early stage of the rifting evolution dominated by asymmetric rift basins and structures, whereas in a later stage, when the necking has been focus, the rifting basins became more symmetrical (close to the continent ocean boundary, e.g. Blaich et al., 2011).

Full lithospheric-scale analogue modeling of the rifting process reconstructed how crustal inhomogeneities could have affected the Central Atlantic Margin rifting evolution giving thus important insights and suggestions on hydrocarbon exploration activities of deeper sub-salt plays.

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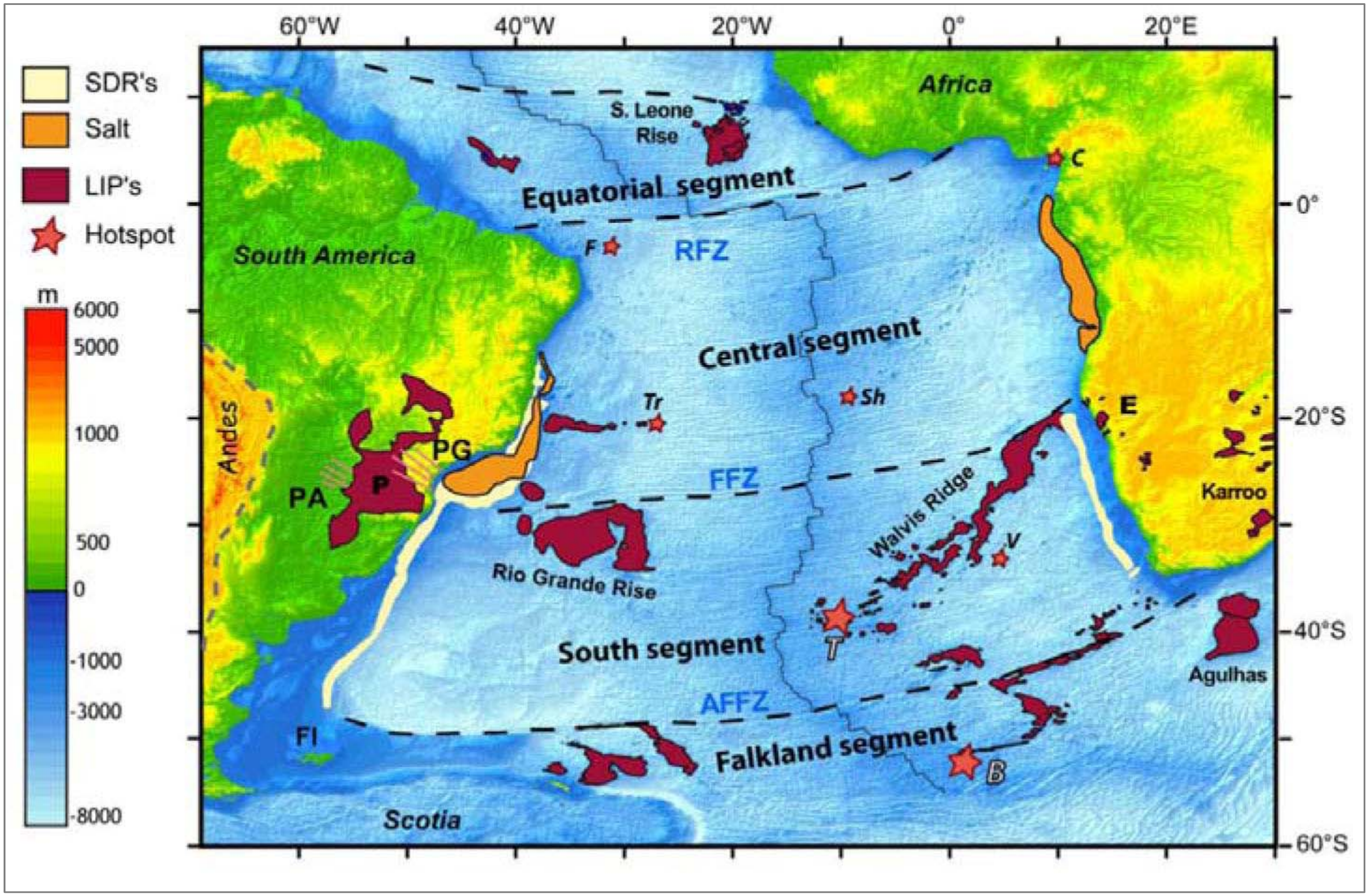

Figure 1. General structural map of the South Atlantic Ocean draped on topographic/bathymetric map from GTOP 30 (FFZ, Florianopolis Fracture Zone; RFZ Romanche Fracture Zone; SDR's, Seaward Dipping Reflectors; LIP's, Large Magmatic Provinces), from Torsvik et al., 2009.

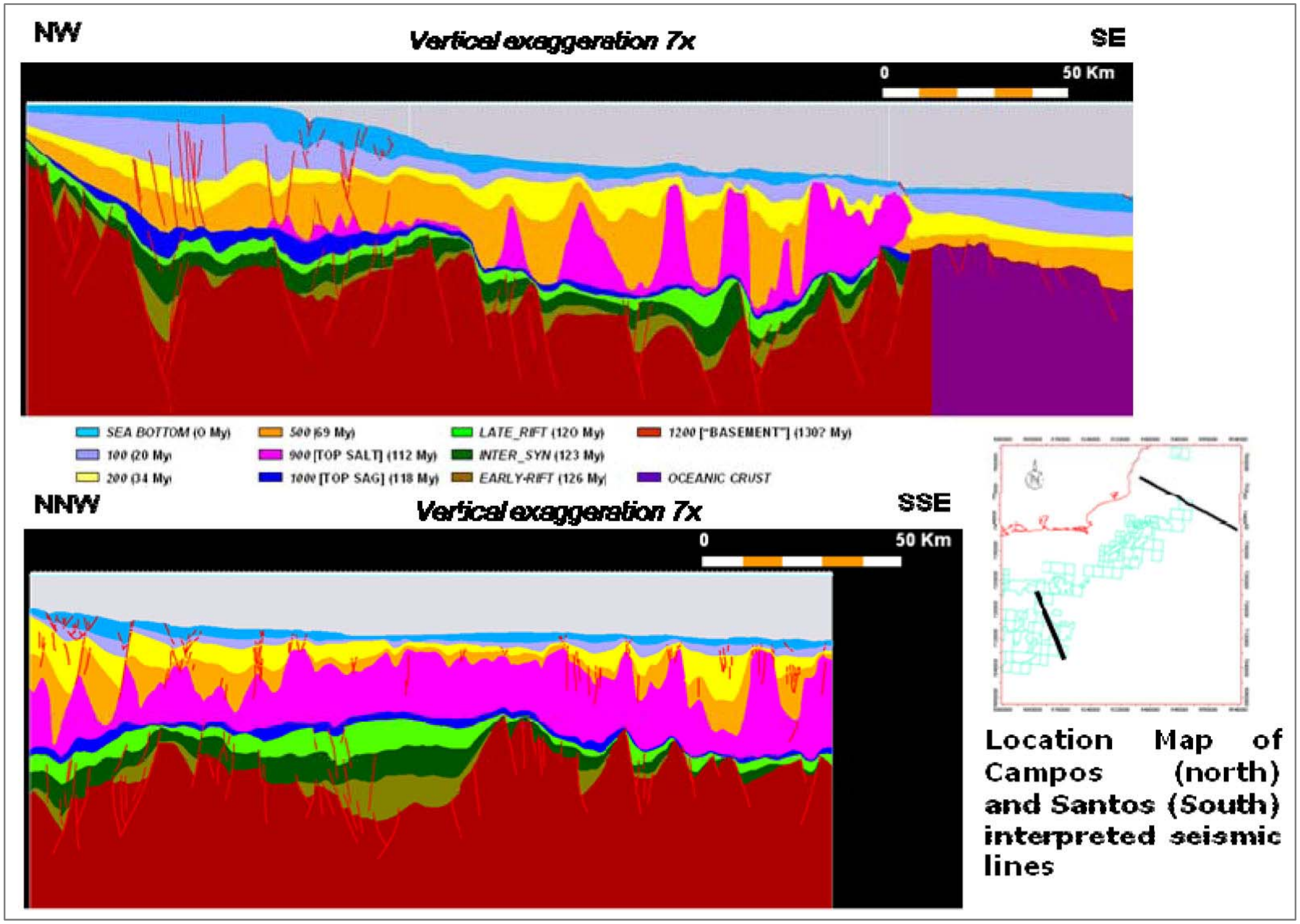

Figure 2. Depth-converted cross sections of Brazilian margin (salt in pink and basement in dark red).

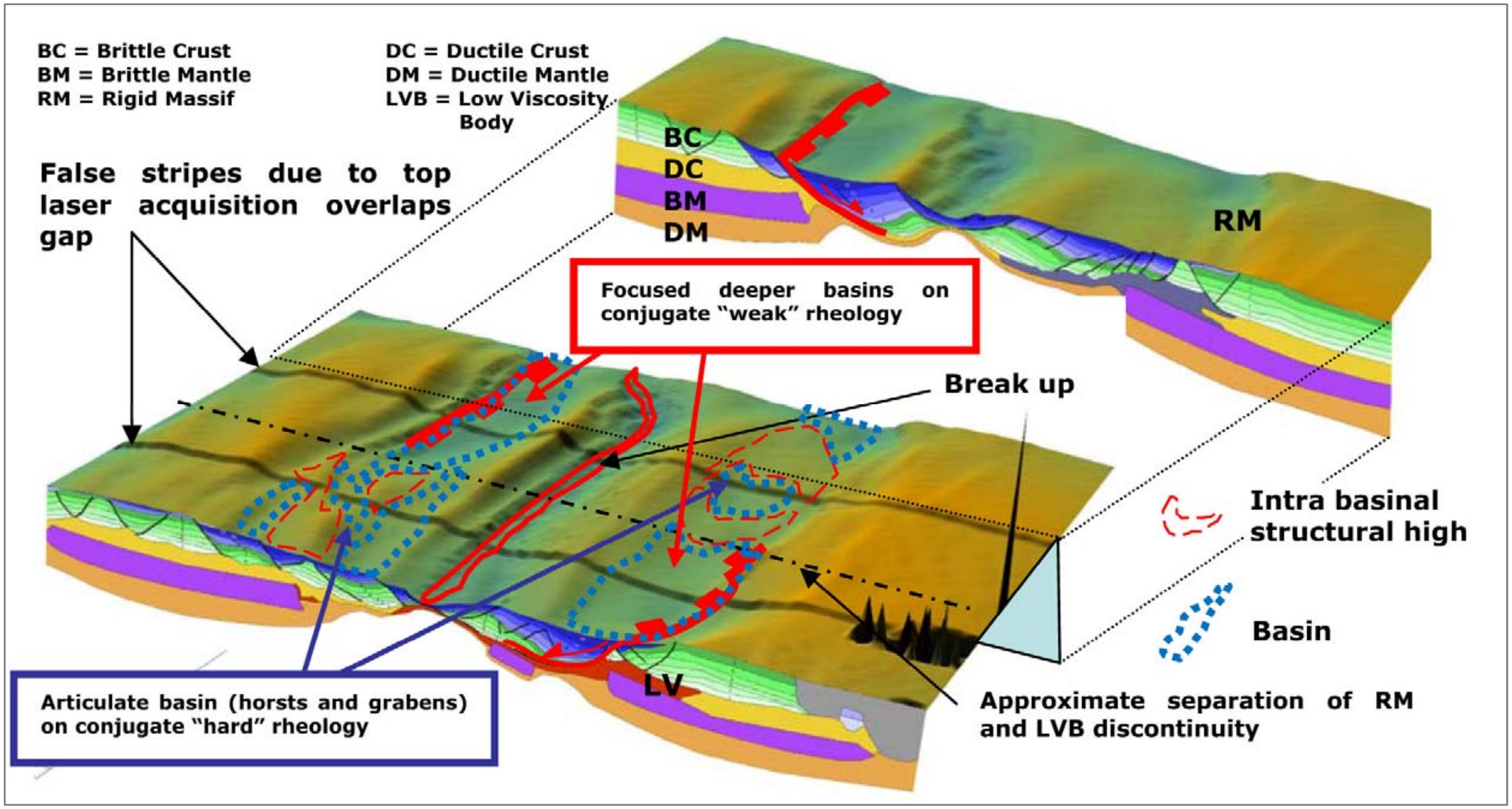

Figure 3. Two interpreted cross sections of a performed sandbox model and laser acquired top surface, highlighting the final (close to break up) basin architecture of the conjugate margins.