Comparisons between Red Sea and South Atlantic

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Abstract

The interpretation of regional potential field and seismic data in the South Atlantic and in the Red Sea continental margins provides important insight for the birth and development of divergent margin sedimentary basins. Several authors have suggested alternative models for the crustal architecture of conjugate margin sedimentary basins, which usually involve pure shear or simple shear mechanisms. Some models also suggest that the early stages of margin development involve either mantle exhumation or magmatic addition to the crust and development of incipient spreading centers before continental breakup. The Red Sea is a modern analogue for Atlantic-type divergent continental margins, and can be used as a natural laboratory to study the rifting processes active in the South Atlantic during the Early Cretaceous. The sedimentary basins between the Arabian and African plates show several similarities with Atlantic-type continental margins, particularly when restored to the time of breakup and initial plate divergence. These passive margins are characterized by oceanic basins that evolved from an earlier phase of magmatism, intracontinental rifting, salt deposition and continental breakup by mantle exhumation or by development of oceanic spreading centers, which is normally preceded by igneous intrusions and extrusions during the transition from continental to oceanic crust. Based on a regional integration of different geophysical and geological datasets, this work compares the early tectono-magmatic phases in the South Atlantic and in the Red Sea, as well as salt tectonic provinces and structural styles from the rift border towards the oceanic crust.

Introduction

This work discusses alternative interpretations for syn-rift stratigraphic sequences and salt distribution in regional seismic profiles from conjugate margins in the Red Sea, which are integrated with results of a few exploratory wells along the Arabian and African margins. For some parts onshore, such as in the Midyan Basin near the Gulf of Aqaba, there is good well control for the rift architecture. However, a relatively small number of exploratory wells have penetrated the stratigraphic section below the thick evaporite layers in deep waters. The analysis of syn-rift structures, magmatism and salt deposition in the Red Sea passive margins can be compared with similar tectono-stratigraphic settings in the South Atlantic, which are constrained by hundreds of exploratory wells in shallow and deep waters. The temporal development of magmatism, syn-rift tectonics, salt deposition, oceanic propagators and development of the divergent margins suggest that the Red Sea constitutes a better analogue for the early evolution of the South Atlantic divergent continental margins than the Iberian margin, which has been used as a paradigm for the South Atlantic margins by many recent works (e.g., Unternehr et al.,2010, Zalán et al., 2011; Perón-Pinvidic et al., 2013). As the Red Sea is still in the gulf stage, the interpretation of regional seismic profiles provides a template to constrain conceptual models for the early phase of passive continental margins that are in more advanced stages of development, such as the Atlantic Ocean (Figure 1). Most continental margin tectonic models involve either pure or simple shear extensional mechanisms, as previously proposed for the Red Sea (e.g., Lowell and Genik, 1972; Ghebreb, 1988) and for Atlantic-type divergent margins (Mckenzie, 1978; Wernicke, 1985). These models are critically analyzed in this work based on available geological and geophysical datasets.

The tectono-stratigraphic features observed in the Red Sea are discussed from the proximal rifts onshore and in the platform (e.g., Midyan Basin, Tubbs et al., 2014) towards the transitional and oceanic crust in the deep-water province, where extremely thick allochthonous salt masses are advancing towards the oceanic crust axial trough (Mitchell et al., 2010; Mohriak and Leroy, 2013; Augustin et al., 2014). Based on plate restorations and analyzed in the light of recent geophysical acquisition of modern seismic refraction and reflection data that have been acquired by the oil industry and research institutions (e.g., Klingelhoefer et al., 2015), these observations and models can be extrapolated to the South Atlantic conjugate margins,

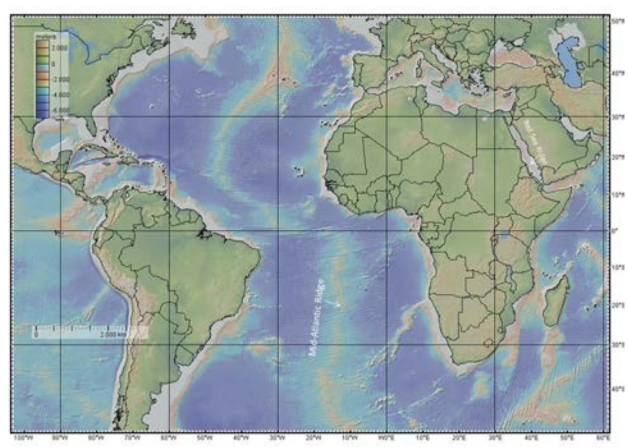

Figure 1: Continental margin basins in the South and North Atlantic and in the Red Sea. The mid-ocean ridge is well developed in the Atlantic Ocean, whereas in the Red Sea it is still in an embryonic phase.

Method

The analysis of industry and academic seismic profiles in the Red Sea and Gulf of Aden indicate that the known distribution of volcanic structures onshore and offshore are associated with the development of an incipient (Red Sea) and a more mature (Gulf of Aden) divergent margin basins corresponding to elongated gulfs filled with Tertiary sediments (Mohriak and Leroy, 2013; Mohriak, 2014).These two gulfs are characterized by an axial trough locally associated with active to embryonic spreading centers.

The Iberian model of mantle exhumation by simple shear detachment faults has been extensively applied to the interpretation of several continental margin sedimentary basins in the Eastern Brazilian and Western African conjugate margins (Unternehr et al., 2010; Zalán et al., 2011; Péron-Pinvidic et al., 2013). Several authors have recently suggested that the Eastern Brazilian and Western African margins are magma-poor, and extensive mantle exhumation has preceded the development of oceanic crust. This model has also been applied to the Red Sea, assuming a wide stretch of exposed mantle rocks across both sides of the axial trough (Ghebreab,1988), which implies salt deposition directly on exhumed mantle rocks in the deep-water province (Rowan, 2014). However, integration of potential field, seismic data and exploratory wells in the Red Sea and in the South Atlantic suggests that a pure-shear model associated with lithospheric stretching and development of magmatic centers in the axial trough may be considered as a rather consistent model that better fits the geological and geophysical constraints (Mohriak et al., 2008; Lentini et al., 2010; Ligi et al, 2012; Mohriak and Leroy, 2013, Mohriak, 2014).

Results

The central Red Transect by Lowell and Genik (1972) (Figure 2 - Model 1) is located north of the Dahlak Islands, offshore Eritrea, and extends across the conjugate margin landwards of the Farasan Islands in southern Saudi Arabia. It assumes continental breakup by pure shear extension, with the Tertiary rift basins and evaporites separated by oceanic crust in the axial trough. This model implies high angle normal faulting affecting the rifted continental crust. Salt was deposited on continental crust but is presently advancing towards oceanic crust. In this interpretation, the axial trough spreading center is covered by Tertiary sediments.

The Transect by Ghebreab (1998) is located just offshore of the Danakil Depression and extends across the conjugate margins (Figure 2 - Model 2). It assumes continental breakup by simple shear extension, with the Tertiary rift basins and evaporites separated by upper mantle peridotites in the axial trough. This model implies low angle normal faulting affecting continental crust (crustal detachments and hyper-extended continental crust rotated by faults), with upper mantle peridotites exposed in the axial trough. Salt overlies continental crust and exhumed mantle. Asymmetric dyke swarms may occur along the conjugate margins

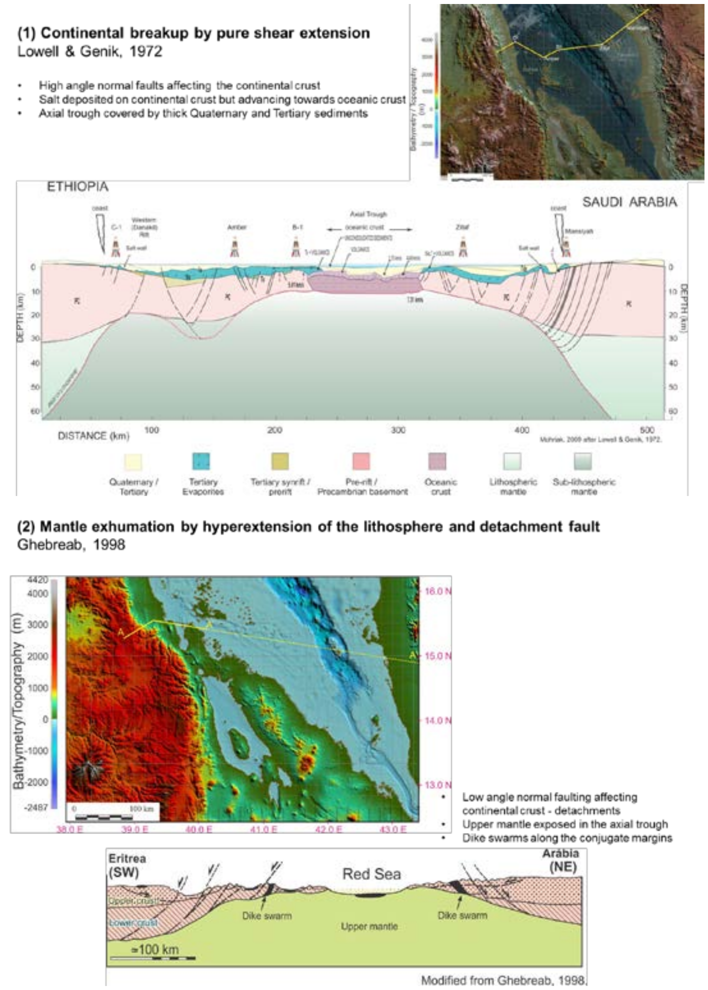

Figure 2: Conceptual models for continental breakup by pure shear (1) and simple shear (2).

The tectono-magmatic chart for the central Red Sea (Figure 3) suggests that the rifting was preceded by widespread volcanism in the Mid-Tertiary. This volcanic event was focused on the Afar mantle plume in Ethiopia but extended towards Sudan-Egypt and Yemen-Saudi Arabia in the conjugate margin (Mohriak and Leroy, 2013). The rift sequence may be subdivided into two phases (Figure 3): an early syn-rift stage with tilted blocks controlled by normal faults, and a late syn-rift stage where faults were less active. There is evidence that late syn-rift sediments (Burqan Fm., Lower Miocene) were deposited in a marine environment before the widespread salt deposition in the Middle to Upper Miocene (Hughes and Johnson, 2005). The rift – drift transition is characterized by incipient oceanic spreading centers in the Central Red Sea (Michell et al., 2010; Mohriak and Leroy, 2013).

The tectonic-magmatic chart for the early central South Atlantic (e.g., Campos Basin, Figure 4) is also characterized by extensive and widespread magmatic activity predating the onset of the main rifting episode, which in this segment of the South Atlantic is associated with continental lacustrine sediments (Winter et al., 2007). A sag basin that is less affected by extensional normal faults can be interpreted above the unconformity that truncated the tilted syn-rift blocks. Salt deposition in the Late Aptian advances towards the volcanic basement, which is locally associated with seaward-dipping reflector wedges as observed in the southern Santos Basin (Mohriak et al., 2010). Marine carbonates overlie these evaporite layers, and in the distal part of the basin these Albian sediments seem to be condensed and deposited in deep-water environments, suggesting a rapid shelf-slope-deep basin development following salt deposition.

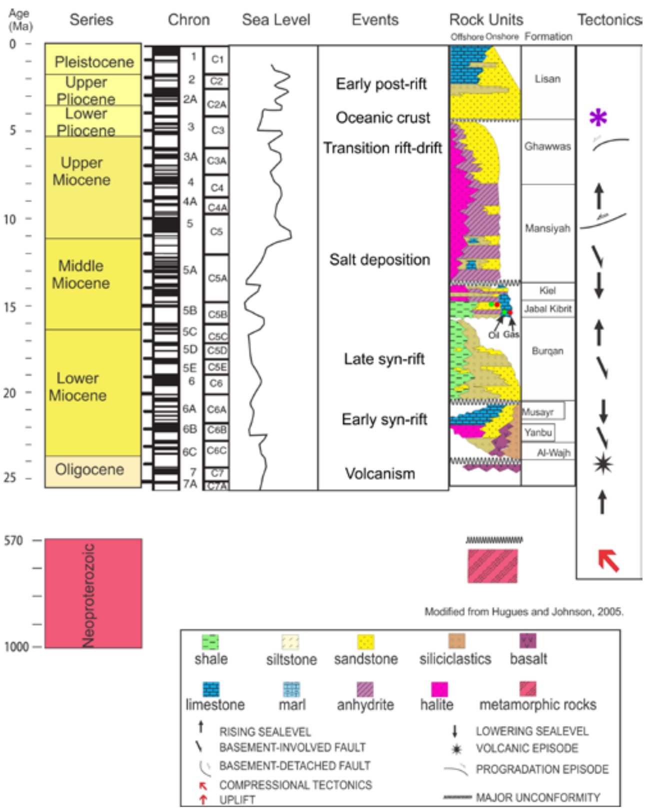

Figure 3: Tectono-magmatic events in the central Red Sea.

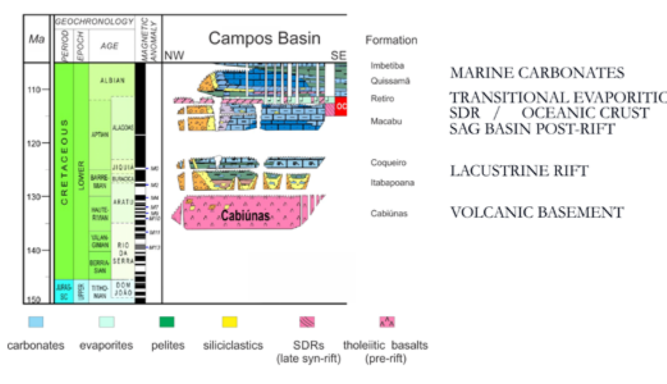

Figure 4: Tectono-magmatic events in the Campos Basin, offshore Brazil.

Conclusions

Several authors have proposed that the South Atlantic salt basin was initially formed in two isolated basins, separated by volcanic highs associated with early spreading centers (e.g., Jackson et al., 2000). Assuming the tectonic model based on the Red Sea observations, the South Atlantic in the Late Aptian formed a single salt basin between the Brazilian and West African rifted margins. This is also indicated by several tectonic reconstructions, as for example, Heine et al. (2013). Figure 5 suggests a very asymmetric salt distribution between the Santos and Namibe basins whereas the basins in the northern segment of the Central South Atlantic (Espírito Santo and Bahia in Brazil, Congo and Gabon in Africa) would have a larger extent of oceanic crust separating the rift basins. The sag and salt basins were probably split after salt deposition by igneous intrusions and embryonic spreading centers that propagated from regions where oceanic crust was already formed (as offshore Argentina and Namibia) to regions where continental rifting was still active (as in Santos and Kwanza basins). .

The oceanic propagators in the Red Sea and in the South Atlantic advanced towards mantle plume thermal anomalies and transform fault zones (Mohriak, 2015). The continental breakup is diachronous along the length of the continental margins, thus the age of the oceanic crust varies along different segments of the conjugate margins. This can be observed in the Red Sea, where the Afar mantle plume separates the salt basin from the Gulf of Aden, where no salt is observed. In the Gulf of Aden the magnetic anomalies suggest that the oceanic crust ages are younger westwards, towards the Afar plume. In the South Atlantic, the southernmost basins offshore Brazil, Uruguay and Argentina have no evaporites, and the age of oceanic crust formed in this segment is older than in region north of the Tristan da Cunha mantle plume.

A comparison of a Red Sea embryonic spreading center with a possible aborted spreading center in the Santos Basin (Abimael Ridge) is shown in Figure 6. In the Red Sea, the seismic profile corresponds to a snapshot of a passive margin at an early stage of divergence, about 10 Ma after salt deposition. In the Santos Basin, the continental margin is in a much more advanced stage at present, with the Mid-Atlantic Ridge located about 2000 km from the rift basins. Salt was deposited in the Late Aptian at about 112-115 Ma, and the volcanic basement associated with the embryonic spreading center was aborted by Early Albian (Mohriak, 2001).

Figure 7 shows a tectonic sketch of conjugate divergent margins (in plan view and in cross-section) associated with an oceanic propagator model that advances from south to north (Mohriak and Leroy, 2013).The tectonic domain A corresponds to an unthinned crust with no rift sedimentation or evaporites, but the basement or the pre-rift sequences may be covered locally by thermal phase sediments. The proximal and distal rifted continental crust in domains B and C are characterized by syn-rift blocks overlain by sag basin and evaporite sediments.

Salt migrated towards the newly formed oceanic crust axial troughs (Figure 7, domains D and E), after initial

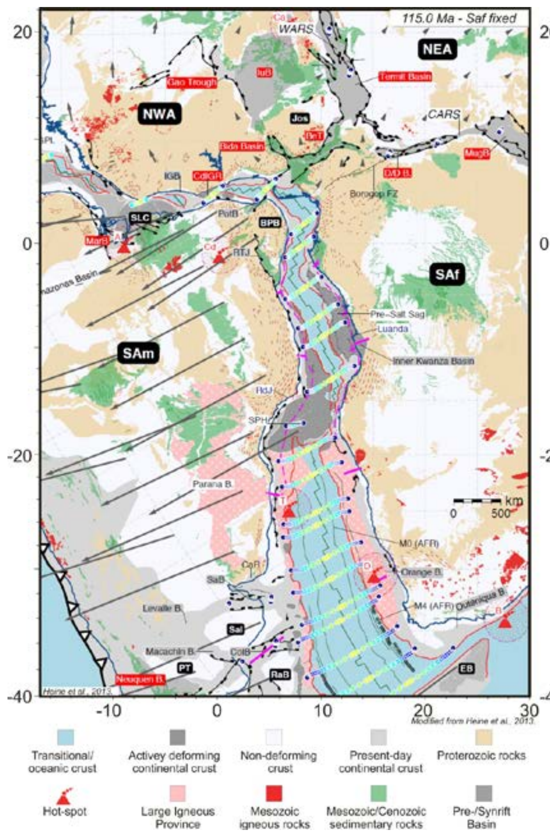

Figure 5: Reconstruction of the South Atlantic salt basins during the early drift phase (Late Aptian – Early Albian).

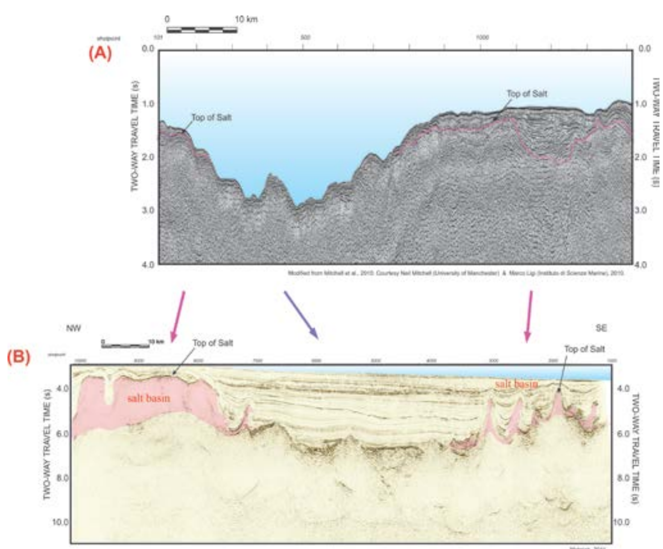

Figure 6: Comparison of the Red Sea embryonic spreading center (A) with the interpretation of a possible aborted propagator in the Santos Basin (B).

halokinesis, forming allochthonous salt tongues overlying volcanic basement. The salt layer accumulated very rapidly in the distal portion of the basins, and salt flow resulted in tectonic inflation of the original or autochthonous salt layers. Seismic data from the Red Sea indicates that the transition from tectonic domain C to D is characterized by allochthonous salt advancing towards the spreading center in domain E (Figure 7). No autochthonous salt is observed in the region of the newly formed oceanic crust, which in the South Atlantic may be locally characterized by wedges of seaward-dipping reflectors (Mohriak et al., 2008; Mohriak et al., 2010). However, later salt mobilization may result in the covering of the volcanic basement with evaporites

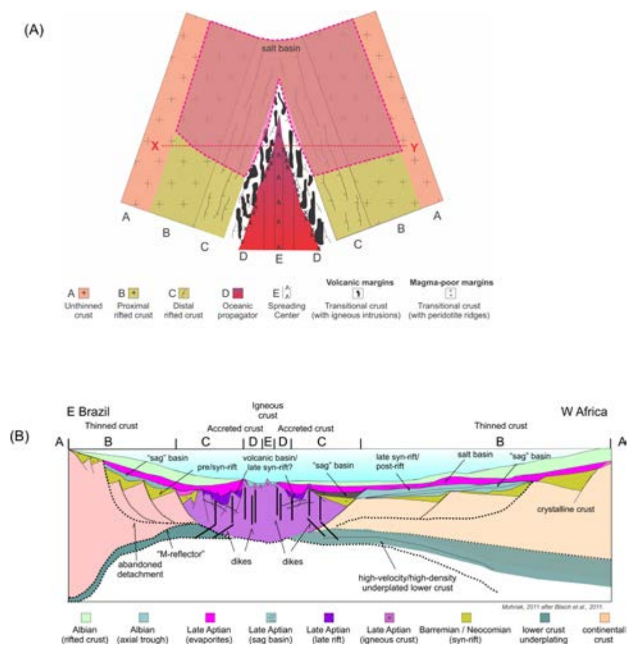

Figure 7: Schematic model showing the formation of divergent conjugate margins by oceanic propagators. (A) Map with different compartments affected by extensional tectonics (A-C) and development of oceanic crust with magmatic accretion (D-E). (B) cross-section of the conjugate margins with tectonic compartments.

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