

# Rifting and Salt Deposition on Continental Margins: Differences and Similarities Between the Red Sea and the South Atlantic Sedimentary Basins

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## Abstract

The results of regional deep seismic acquisition in the South Atlantic continental margins provide new constraints on the birth and development of sedimentary basins formed during the Gondwana breakup. The interpretation of these seismic profiles integrated with gravity and magnetic potential field data suggest alternative models for the birth of oceanic basins that evolve from an earlier phase of intracontinental rift, salt deposition and continental breakup by mantle exhumation or by development of oceanic spreading centres preceded by igneous intrusions and extrusions in the transition from continental to oceanic crust. The analysis of regional deep-penetrating seismic profiles in the South Atlantic and Red Sea, integrated with potential field methods and plate reconstructions, provides a template for the interpretation of the tectono-sedimentary features that are characterized from the proximal rifts onshore and in the platform. Basinward, more elusive features are characterized toward the transitional and oceanic crust in divergent margins. This work discusses alternative interpretations for syn-rift successions and salt distribution in regional seismic profiles from the Red Sea, which have been integrated with results of wells that penetrated the stratigraphic section below the evaporites in a few exploratory wells along the Arabian and African conjugate margins. These interpretations can be compared with similar tectono-stratigraphic settings in the South Atlantic, which are constrained by several exploratory wells that penetrated the syn-rift sequence in both shallow and deep waters. The temporal development of syn-rift structures, magmatism, salt deposition, oceanic propagators and development of the divergent margins suggest that the Red Sea constitutes a better analogue for the development of the South Atlantic divergent continental margins than the Iberian margin.

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## 1 Introduction

The Red Sea is a natural laboratory for studying continental breakup processes at an embryonic stage, whereas the Central and South Atlantic Oceans correspond to more developed divergent margins with tectonic plates in advanced drift stages. Classical works on plate tectonic concepts (as for example, in the pioneering publications by Wegener (1912) and Wilson (1966)) have pointed out the Red Sea as a present-day paradigm for the early stages of development of continental margins. The Red Sea has also been used by geoscientists in basin analysis studies as a modern analog for sedimentary environments, structural geology, and salt tectonics, particularly in comparisons of rift development, magmatism and halokinesis (see for example, Purser and Bosence 1988; Mohriak and Leroy 2013; Bosworth 2015; Rasul et al. 2015).

Several exploratory plays in the South Atlantic have analogs in sedimentary basins across conjugate margins (Brazil—West Africa). These pre-salt and post-salt reservoirs can be analyzed in an earlier stage of development in the Red Sea, which offers a perspective of an early post-rift stage in some areas where breakup has occurred (Mohriak 2014). Risk analysis of petroleum exploration plays in the deep-water setting of the South Atlantic includes the assessment of rift architecture and distribution of source rocks and reservoirs, as well as salt tectonics, migration pathways and trap development. The Red Sea and Gulf of Aden provide important constraints on tectonic models for divergent continental margins and their petroleum systems in the early phases of plate divergence.

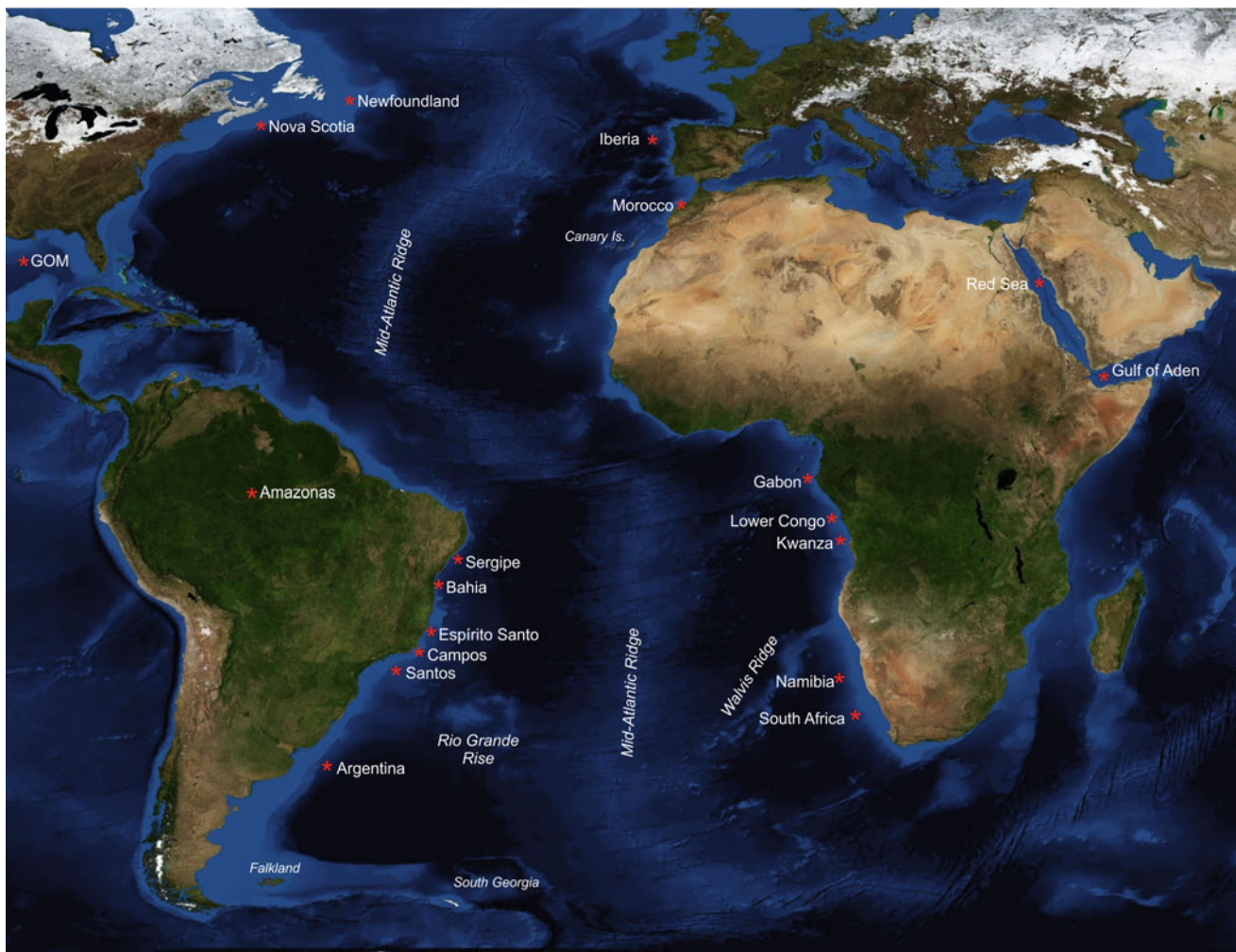
This work will briefly summarize some petroleum exploration highlights from the South Atlantic's largest oil fields, and thoroughly discuss the tectonic analogies between the South Atlantic, the North Atlantic and the Red Sea, aiming to provide clues on how divergent margins form and develop through time. Based on a regional integration of the central Red Sea potential field (gravity and magnetic) and

seismic datasets, fundamental aspects of rifting, evaporite deposition, continental breakup and early stages of margin divergence are analyzed. The interpretation is based on the structural and stratigraphic analysis of the regional geoseismic profiles extending across the proximal and distal rift basin near the Mabahiss Deep in the north-central Red Sea, and by discussing seismic profiles reaching the main trough in the Nereus Deep or crossing the axial trough spreading centre in the Thetis Deep. Seismic interpretation of selected structures along transects in this segment of the Red Sea, from the platform toward the embryonic oceanic crust,

provides a template to compare with the South Atlantic and other rifted continental margins.

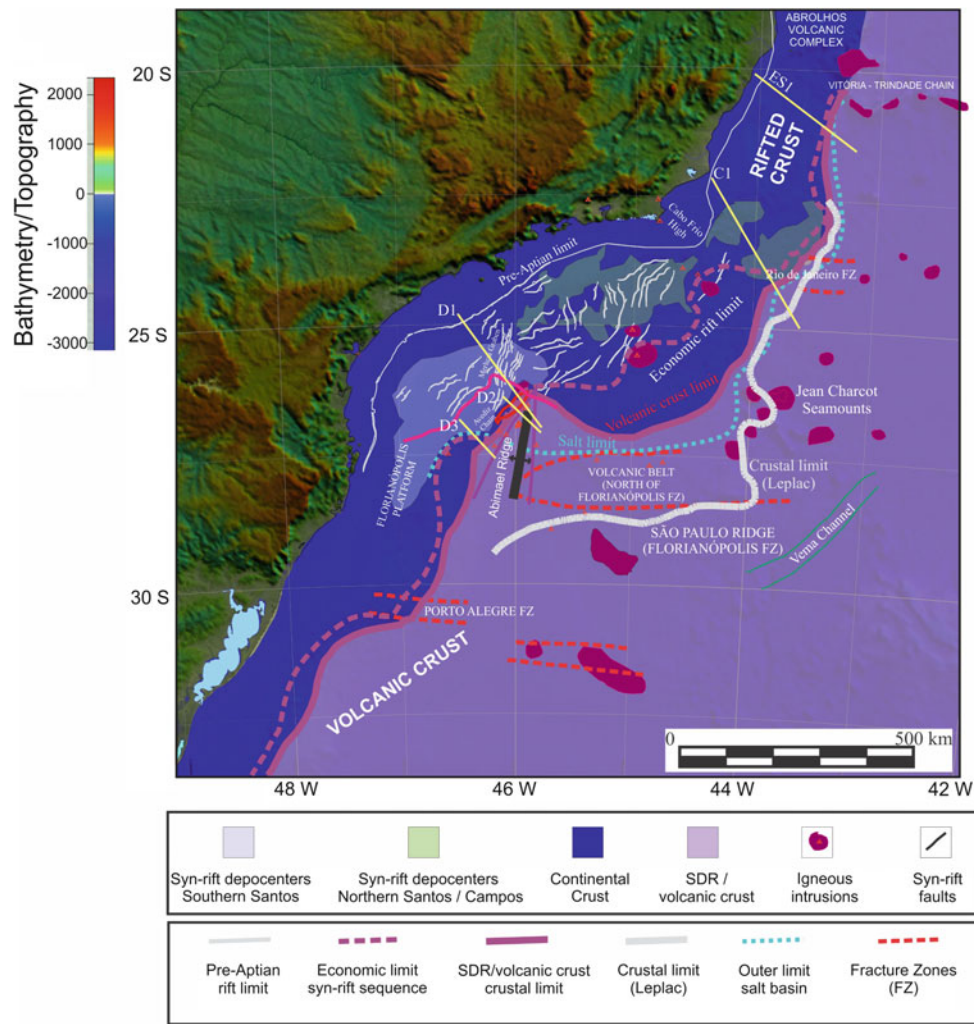
## 2 Petroleum Exploration and Giant Oil Fields in the South Atlantic

The South Atlantic sedimentary basins that occur from onshore to offshore along the continental margins of Brazil, Uruguay, and Argentina (Fig. 1) are characterized by Mesozoic rifts associated with the Gondwana breakup and



**Fig. 1** World satellite map showing archetypal divergent margin sedimentary basins in the Atlantic Ocean, associated with an active Mid-Atlantic Ridge. Newfoundland and Iberia are conjugate margins characterized by magma-poor sedimentary basins with mantle exhumation during continental breakup. In the Brazilian margin, the Santos, Campos and Espírito Santo basins are prolific hydrocarbon provinces with rich synrift lacustrine source rocks overlain by thick salt layers. The conjugate margin basins in West Africa (Kwanza, Lower Congo and Gabon) are also characterized by major salt structures developed

after deposition of the evaporites in the Late Aptian. The Argentina and Namibia/South Africa basins are volcanic margins where salt is absent in the transitional sequence, which is characterized by wedges of seaward-dipping reflectors. The Red Sea and the Gulf of Aden are divergent margins in the early stages of plate tectonics. The Middle to Late Miocene salt layer in the Red Sea extends from the Gulf of Suez toward the triple junction in the Afar region, where the Red Sea rift joins the East African and the Gulf of Aden rifts



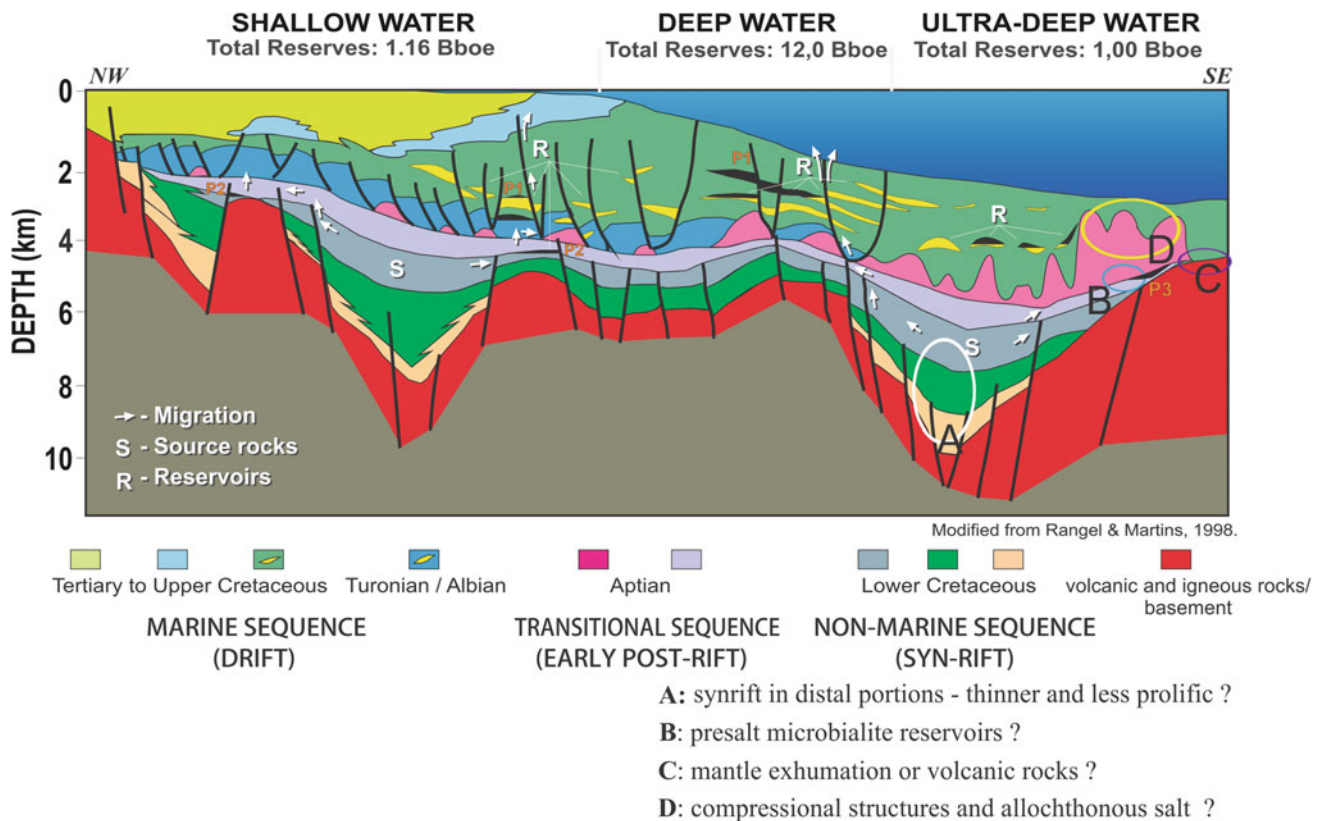
**Fig. 2** Simplified tectonic map of the Pelotas, Santos, Campos and Espírito Santo basins offshore SE Brazil. This map shows a comparison of different interpretations of the continent-ocean boundary (COB) based on analysis of potential field data. The Leplac limit by Gomes (1992) and the volcanic crust limit by Mohriak (2001), are similar in the Campos and Espírito Basins, but very different in the southern Santos Basin. The distribution of syn-rift depocenters is based on seismic interpretation and exploratory well control. Basinward of the dashed purple line (economic rift limit) the syn-rift succession is not clearly visible in the seismic profiles along the Campos and Santos

Basins, suggesting a volcanic basement below the salt layer. In the southern Santos Basin, the thick salt diapir province extends basinward of the economic rift limit, reaching the possible oceanic crust that is indicated by the solid purple line (volcanic crust limit). Observe that the Abimaël Ridge (triangular shaped feature westward of the volcanic belt located north of the Florianópolis Fracture Zone) propagated into the salt basin of the southern Santos Basin. The location of the regional profiles ES1 (Espírito Santo Basin), C1 (Campos Basin) and D1, D2 and D3 (Santos Basin) are indicated by yellow lines

development of divergent margins that are conjugate to the West African basins offshore South Africa, Namibia, Angola, Gabon and Rio Muni. The Santos, Campos and Espírito Santo basins (Fig. 2) are the most prolific basins of offshore Brazil, with reservoirs ranging in age from Neogene (Miocene) to Early Cretaceous (Rangel and Martins 1998; Davison 1999; Beglinger et al. 2012). These basins are characterized by a thick Late Aptian salt layer that is also observed in the conjugate margin basins of offshore Angola and Gabon (Davison 2007; Mohriak and Fainstein 2012). Regional deep seismic profiles extending from the

continental to oceanic crust along the SE Brazilian margin (Fig. 2) will be presented and discussed in the analysis of the rift architecture and salt tectonics.

Petroleum exploration in the South Atlantic has been dominated in the early years of the 21st century by giant discoveries in the deep-water region of the Brazilian and West African continental margins. The largest oil fields discovered in the world's southern hemisphere in the past 15 years (2000–2015) are characterized by carbonate rocks as the main reservoir, with thick evaporite layers forming the seal for the traps (Mohriak 2015). The Tupi discovery in the



**Fig. 3** Schematic (but insightful) geological section of the Campos Basin, from the platform toward the oceanic crust. Many changes in geological interpretation and petroleum assessment have been observed in the past decade. New models have been proposed by applying modern geophysical acquisition and processing of long cable regional 2D deep seismic data and 3D surveys covering large areas in the deep-water salt wall province. Interpretations challenging old paradigms in the ultra-deep-water province are shown by ellipses and marked as A, B, C and D. Conceptual geodynamic models still remain

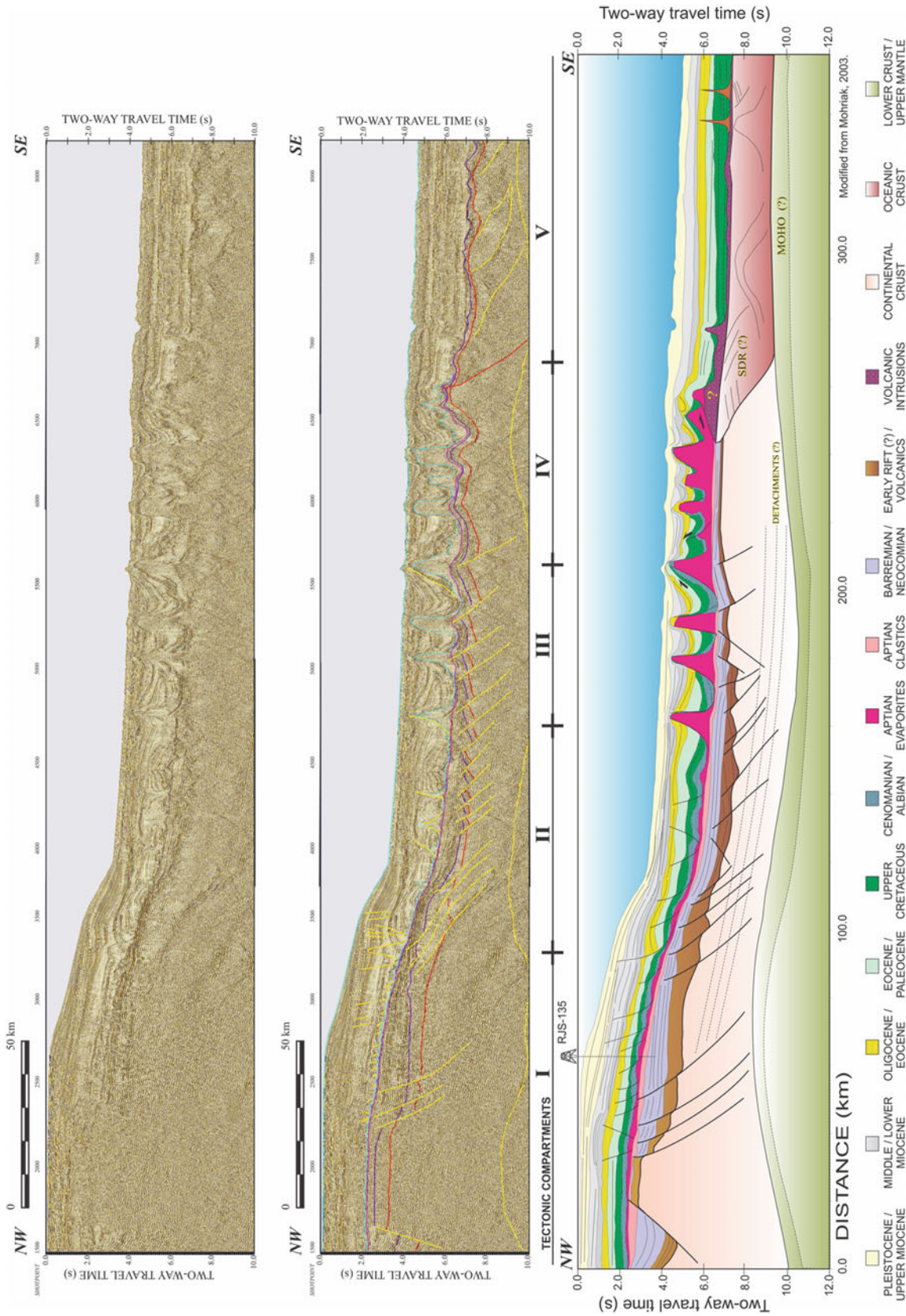
to be tested in the transition from continental to oceanic crust. P1, P2 and P3 (orange coloured letters) are the main exploratory plays and petroleum systems in the Campos Basin. P1: post-salt carbonate and siliciclastic (turbidite) reservoirs; P2: pre-salt source rocks and reservoirs (coquinas); P3: pre-salt carbonates (microbialites and coquinas) constitute a deep-water new play in the distal margin. Total petroleum reserves are now estimated to exceed 50 Bboe with the discovery of the presalt carbonate play in the ultradeep-water region

Santos Basin, which heralded a new era of Brazilian offshore oil production, is characterized by microbialites sealed by Late Aptian evaporites (Berman 2008; Carminatti et al. 2009; Mohriak et al. 2012). Salt deposition along the incipient continental margins is thus considered an essential element for this type of exploratory play.

This play type is very similar to the Kashagan Field, which was discovered in 2000 in shallow waters of the North Caspian Sea, and corresponds to the largest discovery worldwide in 21st century (Mohriak et al. 2012). In addition, the largest hydrocarbon discoveries in the Eastern Mediterranean Sea, including the Zohr gas field discovered in 2015, are also associated with carbonate build-ups sealed by evaporites (Skiple et al. 2012; Esestime et al. 2016).

The interpretation of a schematic geological section in the Campos Basin (Fig. 3), one of the most prolific basins in the South Atlantic (Guardado et al. 1989; Mohriak et al. 1990b; Rangel and Martins 1998) shows three main tectono-stratigraphic sequences: The syn-rift (non-marine, Lower

Cretaceous), transitional (evaporitic, Aptian) and the drift (marine, Albian to Tertiary) sequences (Winter et al. 2007). The petroleum systems in the basin are associated with the Barremian syn-rift lacustrine source rocks, which occur below the Late Aptian evaporites (Mello et al. 1994; Beglinger et al. 2012). The giant oil fields in deep waters are associated with siliciclastic and carbonate reservoirs in the post- and pre-salt stratigraphic successions respectively (Fig. 3). In the mid- to late-1970's, the first hydrocarbon accumulations in the Campos Basin were found in the post-salt Albian carbonate rocks and Late Tertiary to Late Cretaceous turbidite sandstone reservoirs (Play P1 in Fig. 3), and also in the pre-salt lacustrine carbonate reservoirs (coquinas) in the proximal basin (Play P2). More recently, giant accumulations have been discovered in the distal part of the basin, where new plays are characterized by carbonate rocks (microbialites and coquinas) as the main reservoir rocks with stratified evaporites forming the top seal (Play P3).



**Fig. 4** Regional deep seismic profile in the Campos Basin (profile C1 in Fig. 6) with uninterpreted seismic (top), a simplified seismic interpretation (middle), and a schematic geoseismic interpretation (bottom) based on integration with potential field data and other regional seismic profiles. The salt tectonics compartments (Domains I–IV) are illustrated in the geoseismic profile, from the platform toward the oceanic crust. The shallow water extensional domain (I) is characterized by small listric faults resulting in the collapse of the Albanian carbonate platform; the deep-water extensional domain is marked by large roll-overs (II), the compressional domain is associated with tall salt diapirs (III), the strongly compressional domain is marked by allochthonous salt tongues advancing above transitional crust basement or volcanic highs (IV); and the oceanic crust domain is characterized by lack of salt structures (V). Assuming this interpretation, the syn-rift sediments pinch-out toward the salt wall province. The transition to oceanic crust is characterized by volcanic intrusions, magmatic accretion and possibly by wedges of seaward-dipping reflectors

**Table 1** Interpretation concepts in the Campos Basin

Previous interpretation	Alternative interpretation	Observations
Thickest syn-rift troughs occur over the deep-water province <sup>a,b</sup>	Syn-rift sediments show a reduced thickness below the massive salt walls in deep waters <sup>e,f</sup>	Figure 3 illustrates the interpretation of a thick syn-rift trough in the ultradeep-water region; Fig. 4 illustrates the interpretation of a reduced syn-rift thickness in the ultradeep-water province, underlying the salt walls
Continent-ocean boundary is related to pre-rift basement structural highs (with pinch-out of syn-rift sediments) <sup>a,b</sup>	Outermost highs interpreted as post-rift structures <sup>e,f</sup>	New seismic data indicate that the outermost highs were formed after the syn-rift deposits and are overlain by allochthonous salt structures; locally SDR wedges and volcanic highs can be observed in the transition from continental to oceanic crust
Autochthonous salt walls and diapirs occur over the continent-ocean boundary <sup>a,b,c</sup>	Allochthonous salt tongues occur in the continent-ocean boundary <sup>d,e,f</sup>	Allochthonous salt is clearly indicated by modern 3D seismic acquisitions; Tertiary reservoirs below Aptian salt have been drilled both in Brazil and West Africa
Minor amounts of hydrocarbons occur over the transitional crust <sup>a,b,c</sup>	Giant fields have been identified in the ultradeep-water province associated with pre-salt carbonate rocks <sup>g,h,i</sup>	Figure 3 showed an estimated 1 Bbbl of oil in ultradeep-water settings in the late 1990's; nowadays the pre-salt discoveries in microbialite reservoirs may exceed 50 Bbbl of oil according to mid-2010's estimates

## Key references

<sup>a</sup>Guardado et al. (1989), <sup>b</sup>Rangel and Martins (1998), <sup>c</sup>Guardado et al. (2000)

<sup>d</sup>Demercian et al. (1993), <sup>e</sup>Mohriak et al. (2008), <sup>f</sup>Mohriak et al. (2012)

<sup>g</sup>Berman (2008); <sup>h</sup>Carminatti et al. (2009); <sup>i</sup>Jones and Chaves (2015)

The tectonic evolution of the Campos Basin is associated with lithospheric extension and crustal thinning that resulted in development of an Early Cretaceous rift phase with lacustrine sedimentation (Guardado et al. 1989; Mohriak et al. 1990a; Winter et al. 2007; Karner 2000). This is followed by a late syn-rift to early drift phase of thermal subsidence that resulted in the deposition of Late Aptian evaporites and marine Early Albian carbonates. A regional deep seismic profile in the central part of the Campos Basin (Fig. 4, modified from Cainelli and Mohriak (1998) and Mohriak (2003)) shows the interpretation of the crustal architecture and the distribution of the rift depocentres. The geoseismic section interpretation (Fig. 4-bottom) illustrates the interpretation of the Moho uplift in the platform and a thinned continental crust at the transition to oceanic basement at the distal end of the massive salt diapir province. This interpretation assumes a pure shear mechanism for lithospheric extension and a transition to oceanic crust characterized by increasing magmatic activity (Mohriak et al. 1990a, 2008; Meisling et al. 2001; Mohriak 2003; Blaich et al. 2011).

With the advance of petroleum exploration from deep to ultradeep waters, several important changes in the geological interpretation of the Brazilian divergent margin basins have been proposed in recent years by different authors. These interpretations are based on integration of potential field (gravity and magnetics) and modern seismic acquisition, including 2D deep seismic profiles extending from the platform to the oceanic crust, and also huge 3D acquisition

in large exploratory areas, allowing a better imaging of syn-rift structures and salt tectonics. For example, alternative interpretations that have changed or challenged previous paradigms for the Campos Basin are implicit in the geoseismic profiles presented in Figs. 3 and 4. Table 1 presents some of these concepts and also includes a few key-references for the alternative interpretations:

In the late 1990's and early 2000's a large number of tectonic models for continental rifting and breakup forming divergent margins have increasingly assimilated the results from the Ocean Drilling Program (ODP), one of the most significant international scientific endeavours ever undertaken in the study of ocean basins. In the North Atlantic, seminal projects sampled peridotites from many drilling sites of offshore Iberia (Shipboard Scientific Party 1985, 1998). These models assume that mantle exhumation precedes the inception of oceanic crust in magma-poor margins, as indicated by the presence of peridotite ridges near the continental-oceanic crust boundary (Boillot et al. 1980, 1987; Whitmarsh and Wallace 1998; Manatschal 2004; Péron-Pinvidic et al. 2013).

Some authors (e.g., Unternehr et al. 2010; Zalán et al. 2011) have proposed a direct application of the Iberia mantle exhumation model for the South Atlantic, using deep seismic profiles integrated with potential field data (e.g., Figure 5). Based on these interpretations, the salt diapir province in the deep-water region of the Campos Basin overlies sag basin sediments deposited directly on exhumed mantle rocks, with a top-basement detachment fault controlling a block of

continental crust that separates the proximal from the distal segments of the margin (Lavier and Manatschal 2006). However, the extensive application of the Iberian model for the South Atlantic is highly controversial, given the striking differences of tectono-magmatic evolution between these divergent margins, and the general lack of seismic evidence for a Moho reflector rising up to intersect the base Aptian salt in the Campos and Kwanza basins (e.g., Mohriak et al. 2008; Lentini et al. 2010; Mohriak and Leroy 2013).

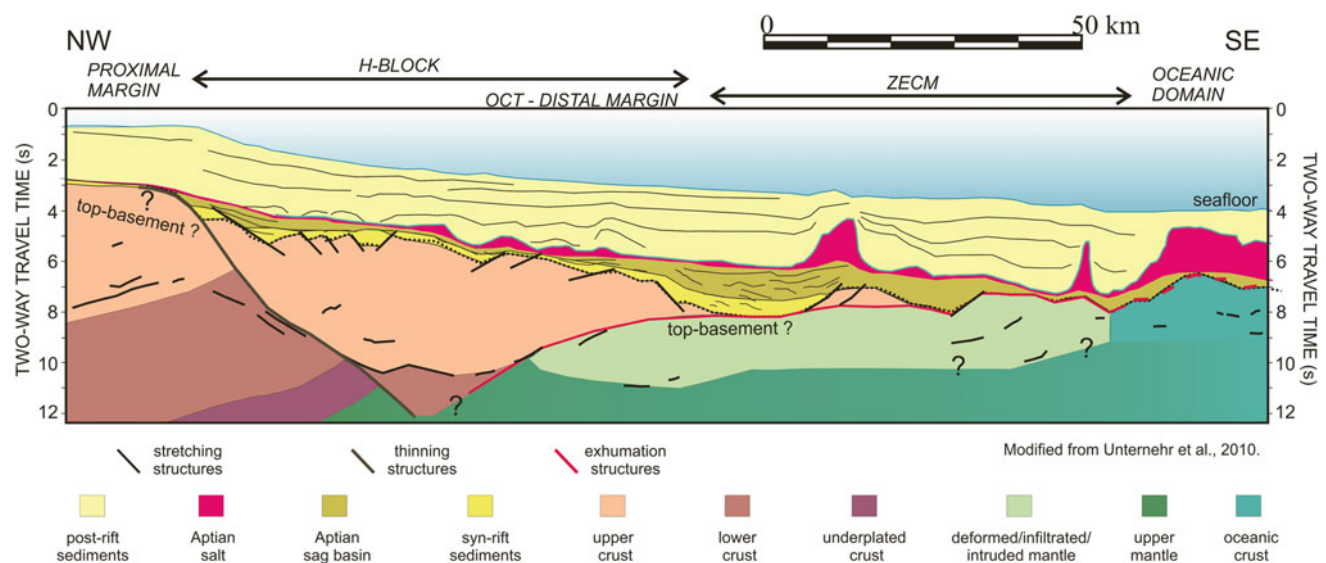
This work presents an overview of the rift architecture of the Red Sea sedimentary basins, from the onshore area toward the offshore distal margin and oceanic crust, comparing their characteristics with the South Atlantic and Central Atlantic margins, where regional deep seismic profiles have been available since the 1980's (Mohriak et al. 1990a, 2008). The line interpretations of regional seismic profiles in the Red Sea are included to show the geological and geophysical characteristics of the syn-rift succession and salt deposition in the onshore and offshore segments of the continental margin. The incipient spreading centre in the central Red Sea is also discussed using seismic and potential field data. This aims at providing clues on how the continents are split during the rift phase, how salt basins are formed at the conjugate margins, and the relative ages of rifting, salt deposition, magmatism and continental breakup. Understanding the differences and similarities between the South Atlantic and the Red Sea sedimentary basins and their tectonic controls has important implications

for tectonic and exploratory models, particularly in the evaluation of active petroleum systems in the early stages of development of rifted continental margins.

### 3 Tectonic Models for the Formation of the Atlantic Continental Margins

The tectonic models for the development of divergent margins are most often based on industry seismic data acquisition and potential field data integrated with results of exploratory wells. A recent review of these geological and geophysical interpretations for the Central and South Atlantic suggests that these continental margins might be compared to the Iberian margin, where a predominantly simple shear model of lithospheric extension associated with detachment faults resulted in mantle exhumation (Perón-Pivindic et al. 2013). Regional 2D and 3D seismic data acquired in the Iberian margin have been used to investigate fundamental basin-forming processes, and several Ocean Drilling Program (ODP) scientific wells have confirmed that serpentinized peridotites outcrop along ridges near the continent-ocean boundary (Perón-Pivindic and Manatschal 2009).

Based on results of ODP scientific wells, numerous authors have proposed a tectonic model for the Atlantic continental margins (such as Newfoundland and Iberia) involving mantle exhumation associated with detachment faults before the emplacement of oceanic crust (Boillot et al. 1980;



**Fig. 5** Regional seismic profile in the Campos Basin assuming the exhumed mantle model by Unternehr et al. (2010). The proximal margin is characterized by reduced thickness of the syn-rift sediments and a residual salt layer overlies the syn-rift and sag basin sediments in the platform and deep waters. An H-Block is interpreted between the shelf-break and the deep-water basin, with increasing thickness of the Aptian sag basin sediments. The salt diapir province overlies the sag

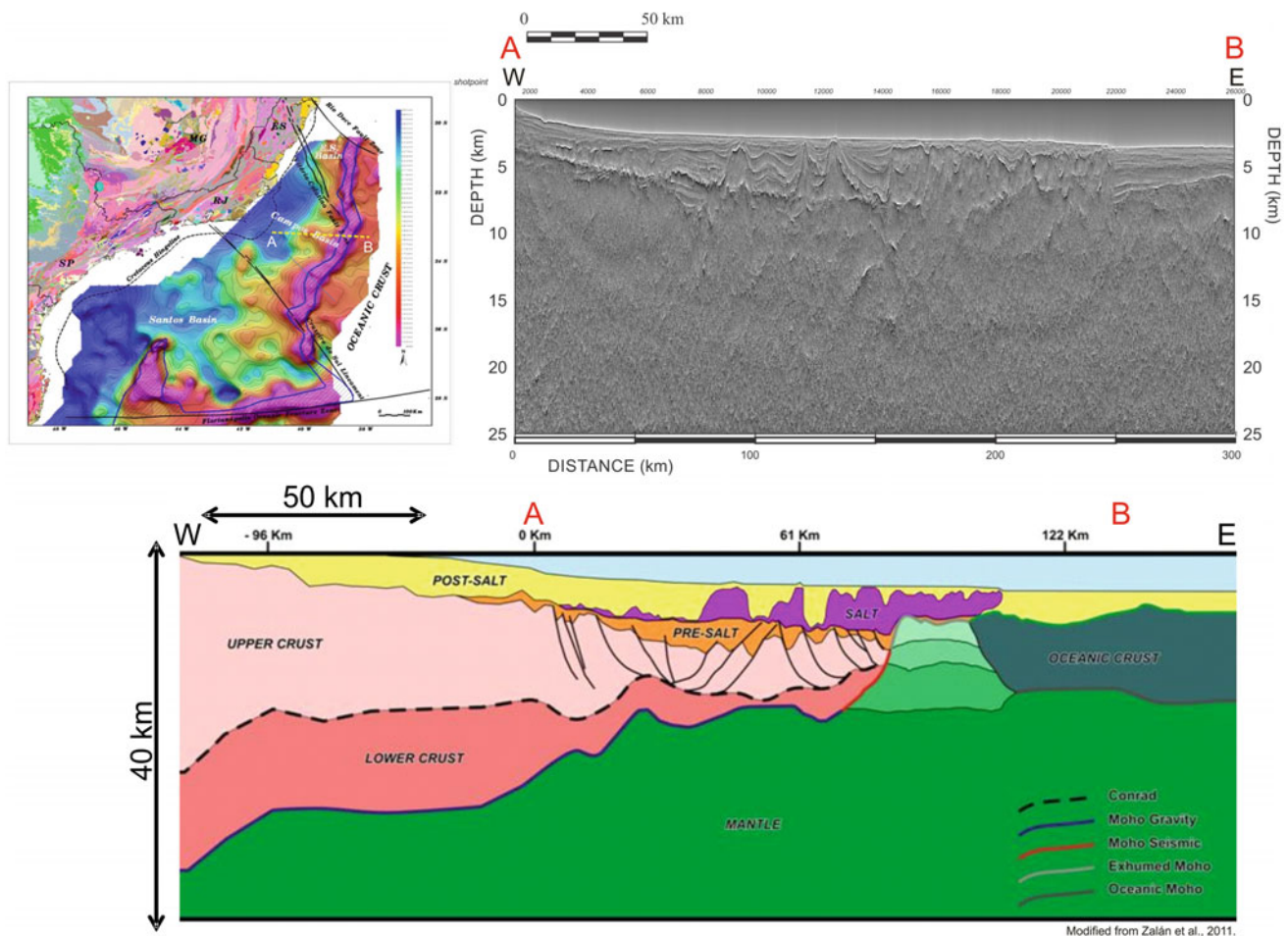
basin in the distal margin (where the continental crust is abruptly thinned by a top-basement detachment fault), whereas the syn-rift sediments pinch-out basinward and are not present in the zone of extended continental mantle (ZECM). The compressional salt wall province is interpreted to overlie the ZECM with Late Aptian sediments and evaporites deposited directly on the upper mantle peridotites

Perón-Pinvidic and Manatschal 2009). Reconstructions of regional deep seismic profiles in magma-poor basins along the conjugate margins of Canada and Iberia indicate that lithospheric stretching is associated with crustal thinning and mantle exhumation by detachment faults in the deep-water region before emplacement of oceanic crust (Pérez-Gussinyé 2012).

The Iberian model of mantle exhumation involving simple shear detachment faults has recently been extensively applied to the interpretation of several basins in the Eastern Brazilian and West African conjugate margins. Some authors have re-interpreted the Eastern Brazilian and West African margins as magma-poor (Unternehm et al. 2010; Zalán et al. 2011; Péron-Pinvidic et al. 2013), contradicting the results of the exploration wells drilled in the deep-water region of these prolific basins, which indicate an abundance of volcanic rocks underlying and within the syn-rift

sequences (Mohriak et al. 2008). A recent work by Alvarenga et al. (2016) has convincingly interpreted the presence of hydrothermal vents in the deep-water region of the Campos Basin. These features, imaged within the Early Cretaceous rift sequence, commonly occur in volcanically active areas worldwide, and have been characterized in present-day settings such as the East African Rift System as well as in ancient rift basins, as for example the Vøring Basin, offshore Norway (Planke et al. 2005).

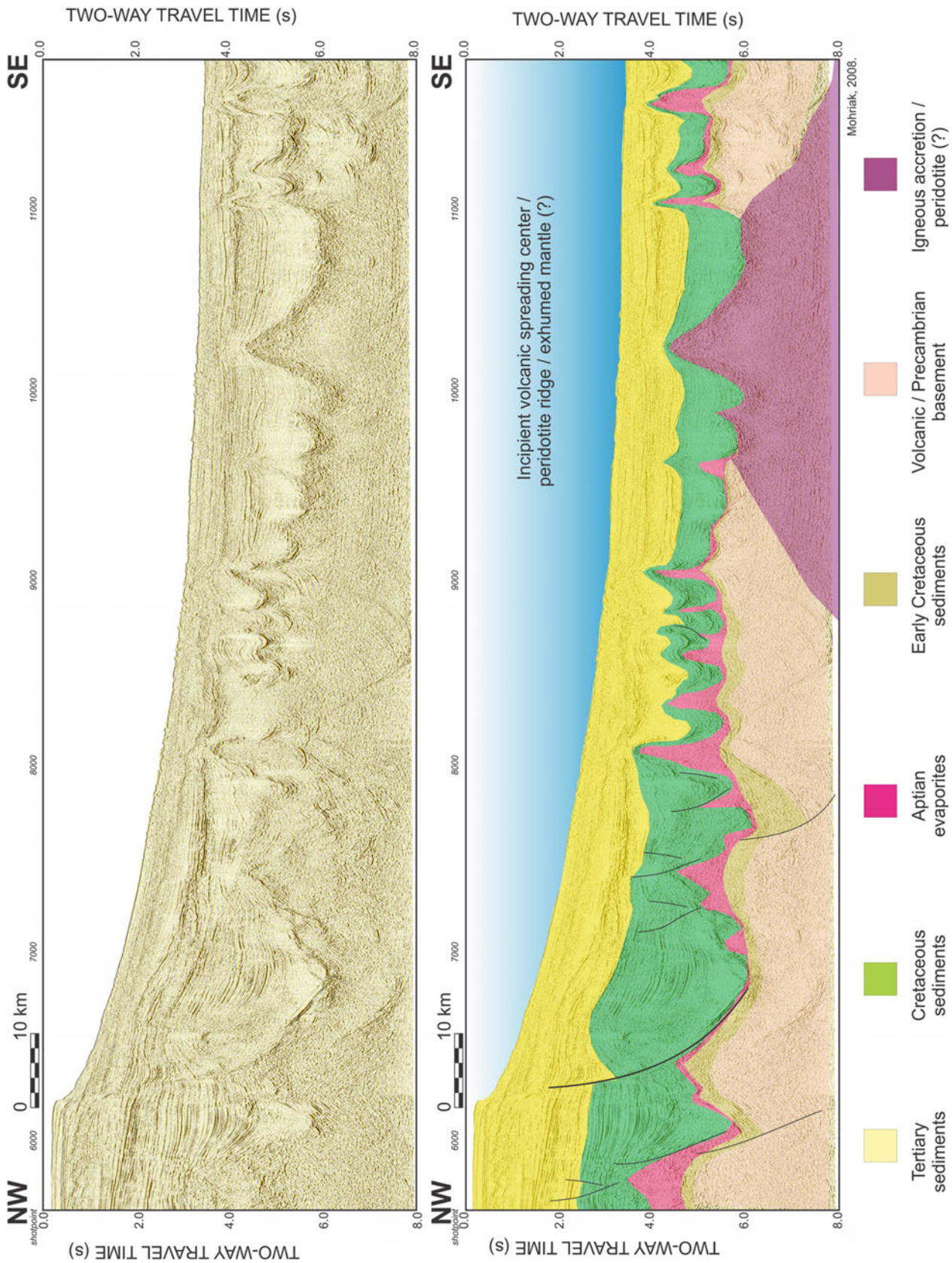
A direct, but questionable, application of the Iberian model for the South Atlantic margin (Fig. 6) assumes that the sedimentary basins in southeast Brazil and West Africa are magma-poor margins where the outermost high at the eastern limit of the salt diapir province corresponds to serpentinized peridotite rocks (Zalán et al. 2011). In this model, the exhumed mantle in the outer high has been divided into



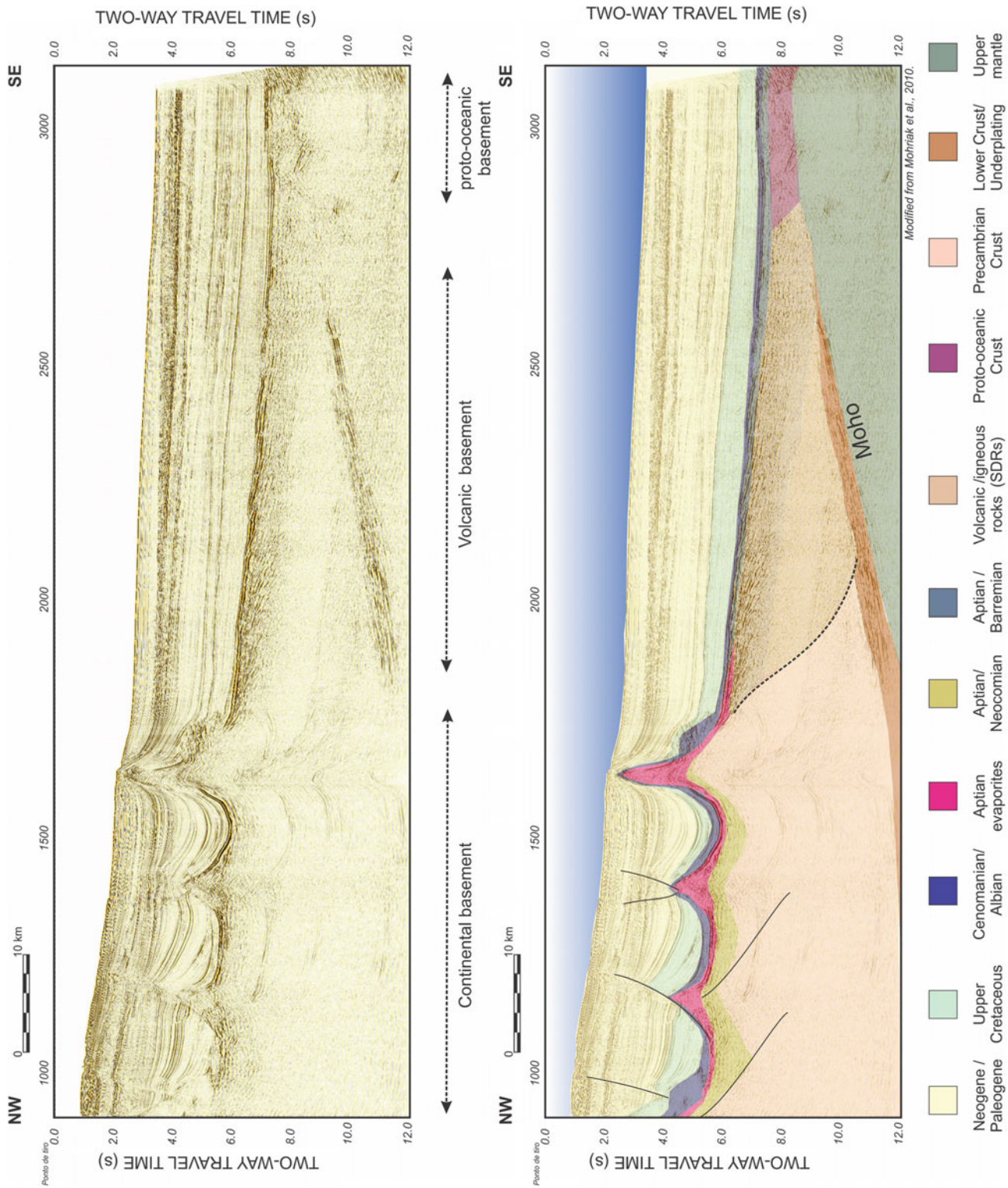
**Fig. 6** Top left: Structural map showing the interpreted top of the Moho Discontinuity in depth (blue colours: structural lows; red to purple: structural highs), with a blue line outlining the regions with interpretation of peridotite ridges or exhumed mantle (modified from Zalán et al. 2011). A regional deep seismic profile extending along a W-E direction (top right, line A-B on the map) shows a reduced amount of salt in the Cabo Frio Platform and massive salt diapirs in the

ultradeep-water region, where an allochthonous salt tongue is imaged advancing toward the oceanic crust. The gravity model of a regional profile based on the interpretation of the seismic profile A-B (bottom) shows the exhumed mantle between the continental and oceanic crusts. According to this interpretation, serpentinized peridotites occur below the salt tongue that has advanced basinward of a conspicuous structural high that previously formed a barrier for salt deposition

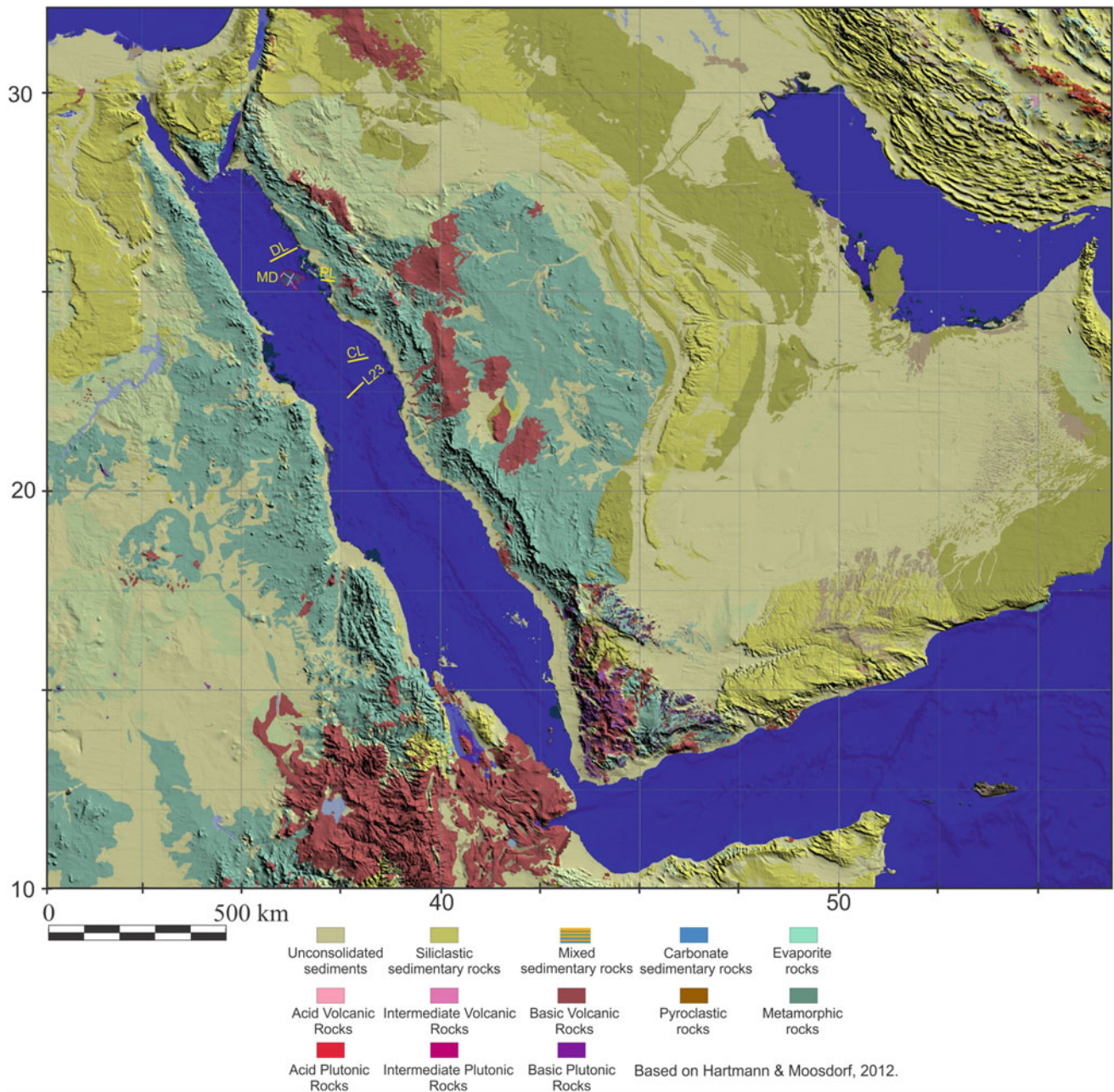




**Fig. 7** Seismic Profile D1 (uninterpreted on top, interpretation below), from the platform toward the deep-water region of the Santos Basin. It shows two salt basins split by a triangular-shaped structure characterized by a strong positive gravity anomaly, which is associated with seaward-dipping reflectors toward the Pelotas Basin. This feature probably corresponds to an igneous intrusion associated with an oceanic propagator that split the main salt basin in the southern Santos Basin and was aborted after Late Aptian times (Mohriak 2001). The remnant distal salt basin located at the SE extremity of the profile is limited by a volcanic belt north of the Florianópolis Fracture Zone



**Fig. 8** Seismic Profile D3 (uninterpreted on top, interpretation below), showing the southern limit of the salt basin limited by a volcanic basement characterized by seaward-dipping reflectors that are not as well developed as in the Pelotas Basin. Basinward of the salt basin there is a strong reflector package at the base of the crust which abruptly rises from 10 to 9 s TWT. The proto-oceanic crust of the Aibmael propagator is characterized by a very shallow Moho discontinuity between 9 and 8 s TWT, but with no clear indication of mantle exhumation



**Fig. 9** Regional geological map of the African and Arabian plates with main lithological units draped on topobathymetric data. The location of the proximal and distal profiles (PL and DL) are located near the Mahabiss Deep (MD) in the north-central Red Sea. The seismic lines published by Colombo et al. (2014) and Mitchell et al. (2010) are indicated as CL and L23. Extensive lava fields (harrats) are observed on

the Arabian plate, and these basalts range in age from about 30 Ma to Recent. Volcanic islands have been formed in the southern axial trough, particularly offshore Yemen. The volcanic rocks in the Afar area are associated with the triple junction between the Red Sea and Gulf of Aden oceanic ridges and the northern branch of the continental East African Rift System

zones of different densities (related to variable degrees of serpentinization) to fit the measured and modeled gravity data. However, other authors (e.g., Blaich et al. 2011) have conducted similar gravity modelling using regional seismic profiles and obtained very different results for equivalent geoseismic transects across the Brazilian margin. The exhumed mantle interpretation for the Campos and Santos

basins (Unternehm et al. 2010; Zalán et al. 2011; Gomes et al. 2012) suggests that the outer high and the Florianópolis Fracture Zone (FFZ) are characterized by serpentinites outcropping at the bottom of the ocean. Assuming this model, even the oceanic propagator (Abimael Ridge, compare Fig. 2 with Fig. 6) that has been postulated to advance from the northern Pelotas Basin toward the southern Santos

Basin (Mohriak 2001) should correspond with peridotites formed in a magma-poor setting. In this work, we present seismic data suggesting that the propagator in the Santos Basin is locally associated with wedges of seaward-dipping reflectors (SDRs), and thus might be related to igneous intrusions and extrusions derived from mantle melting. In addition, recently acquired wide-angle seismic profiles acquired in the distal part of the Santos Basin suggest velocities compatible with thinned continental crust until normal oceanic crust is reached south of the Florianópolis Fracture Zone (Evain et al. 2015).

The model of propagating rifts as proposed by Courtillot (1982) assumes that continental breakup starts with a phase of continental rifting and continues with the propagation of rifts toward locked zones, where the crust is deformed by extension whereas oceanic crust is generated in the wake of the V-shaped rift zone. The conspicuous Abimael Ridge has been interpreted as a failed oceanic propagator in the Santos Basin (Mohriak 2001; Mohriak et al. 2008; Carminatti et al. 2009; Gomes et al. 2012; Kumar et al. 2012; Dehler et al. 2016) and is characterized by a strongly positive gravity anomaly indicating denser rocks in the lower crust, and the peculiarly negative magnetic anomalies suggest that the feature is associated with a volcanic belt north of the Florianópolis Fracture Zone (Fig. 2). The positive Bouguer gravity anomaly associated with this feature has had several interpretations in the geological literature, including volcanic rocks on continental crust (Karner 2000), an aborted spreading centre with volcanics on salt (Meisling et al. 2001), a volcanic wedge of proto-oceanic crust (Gomes et al. 2012; Evain et al. 2015), and exhumed mantle (Zalán et al. 2011; Pindell et al. 2015). However, seismic interpretations from regional 2D seismic profiles indicate it might correspond to an igneous feature (Fig. 7), locally associated with seaward-dipping reflectors at the transition from the southern Santos to the northern Pelotas basins (Mohriak et al. 2008, 2010; Quirk et al. 2013). The volcanic basement interpretation is supported by deep seismic profiles that show the Moho discontinuity rising abruptly basinward of the salt basin (Fig. 8), and this discontinuity appears to occur below volcanic rocks and igneous crust characterized as a proto-oceanic basement oceanward of the salt basin. Although this proto-oceanic basement adjacent to the Abimael Ridge has not been drilled in the Santos Basin, the potential field data and seismic interpretation suggest a relationship with the volcanic belt north of the Florianópolis Fracture Zone (FFZ, see Fig. 2).

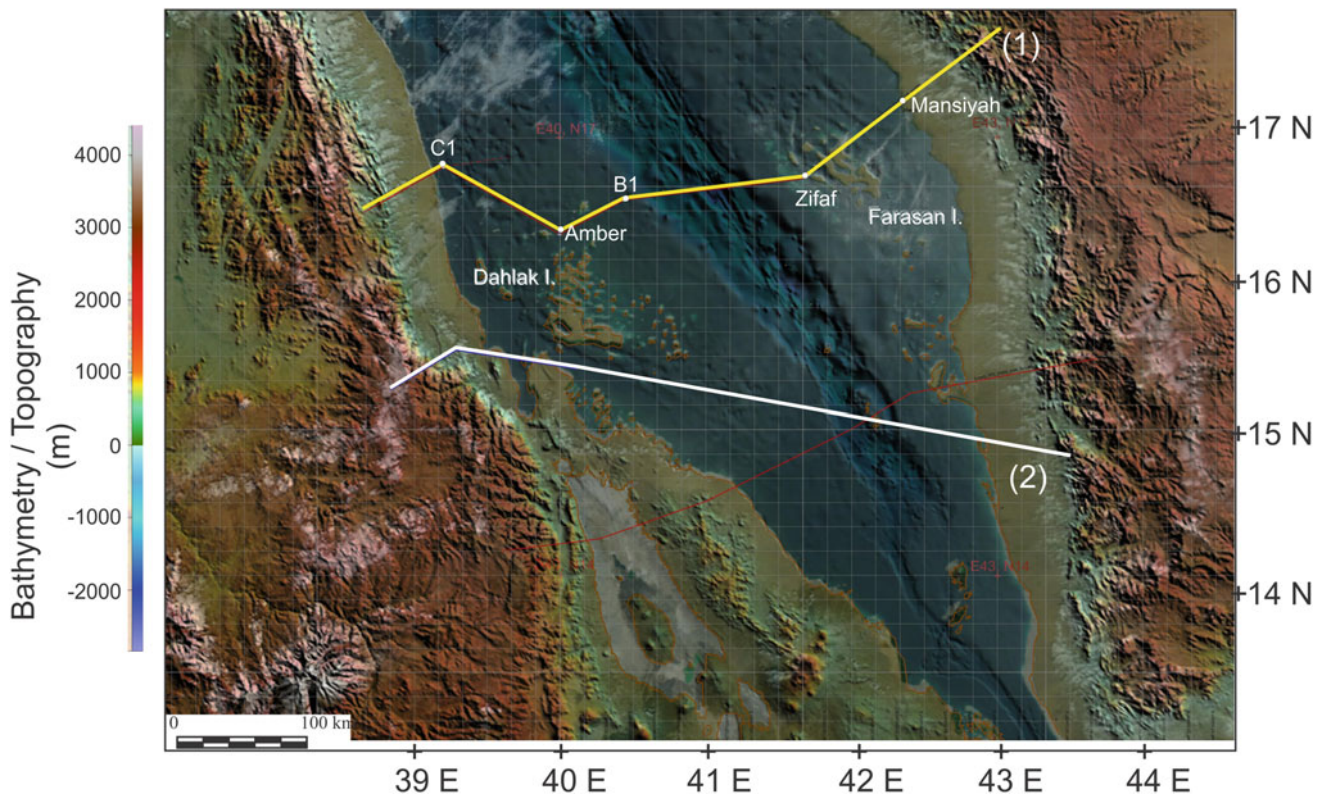
Apparently, the region where the magmatic accretion is observed (and interpreted as proto-oceanic basement oceanward of the incipient SDRs in Fig. 8) acted as an oceanic propagator that advanced from the Pelotas Basin, where well-developed wedges of SDRs are clearly visible in seismic profiles (e.g., Koopmann et al. 2014). The

propagator penetrated the salt basin in the southern Santos Basin, westward of the Florianópolis Fracture Zone (FFZ), during the last stages of the Gondwana breakup. The salt layer was incipiently split and the embryonic spreading centre was aborted, resulting in a ridge jump that transferred the mid-ocean ridge to an eastward position (Mohriak 2001). It is remarkable that the largest transform fault zone in the Santos Basin, the FFZ, is associated with the tip of the Abimael propagator. Similar relationships between propagators and fracture zones have been observed and discussed in other rifted continental margins as well (e.g., Courtillot 1982; Taylor et al. 2009; Franke 2013).

#### 4 Tectonic Models for the Formation of the Red Sea Continental Margins

The Red Sea (Fig. 9) is one of the largest salt basins in the world, comparable in size with the South Atlantic salt basins offshore Brazil and West Africa, and much larger than the salt basins in the Central Atlantic (NE North America—NW Africa conjugate margins). Regional deep seismic profiles have been extensively acquired in the Central and South Atlantic continental margins in the past decade, particularly along the Brazilian and West African margins (Kumar et al. 2012). Refraction transects have been obtained in the Red Sea and Gulf of Aden (e.g., Mooney et al. 1985; Eglhoff et al. 1991; Watremez et al. 2011), but these regions are not as well sampled by long cable deep seismic reflection profiles as the South Atlantic, where the petroleum industry has extended the exploration frontiers beyond the continental-oceanic crust transition in ultradeep water settings.

Concerning the petroleum exploration in the Red Sea, the tectonic interpretations have important consequences for the assessment of the deep-water frontier regions. Decades of activity in the conjugate margins offshore Egypt, Sudan, Eritrea, Saudi Arabia and Yemen resulted in acquisition of an extremely large dataset from the platform toward the axial trough. A huge thickness of more than 5 km of salt has been suggested by many researchers based on seismic interpretation of the evaporite layer in the deep-water region (Lowell and Genik 1972; Guennoc et al. 1990). These evaporites have been proved in the southern, central and northern Red Sea, and sampled by exploratory wells drilled both onshore and offshore, not only in the platform but also in the deep-water region (Beydoun 1989; Tubbs et al. 2014; Rowan 2014; Hadad and Abdullah 2015). These wells indicate that the heat flow is considerably higher in the main trough, reaching more than  $100 \text{ mW m}^{-2}$  off the Sudanese coast, for example (Hadad et al. 2016), thus making it a gas-prone basin. More importantly, the majority of wells that were drilled offshore the Red Sea and penetrated through the Miocene salt have not shown any significantly rich pre-salt



**Fig. 10** Regional transects across the southern Red Sea (north and south of Dahlak and Farasan Islands) with two models for the development of the continental margins. Transect (1), north of the islands, is constrained by exploratory wells drilled in the platform of

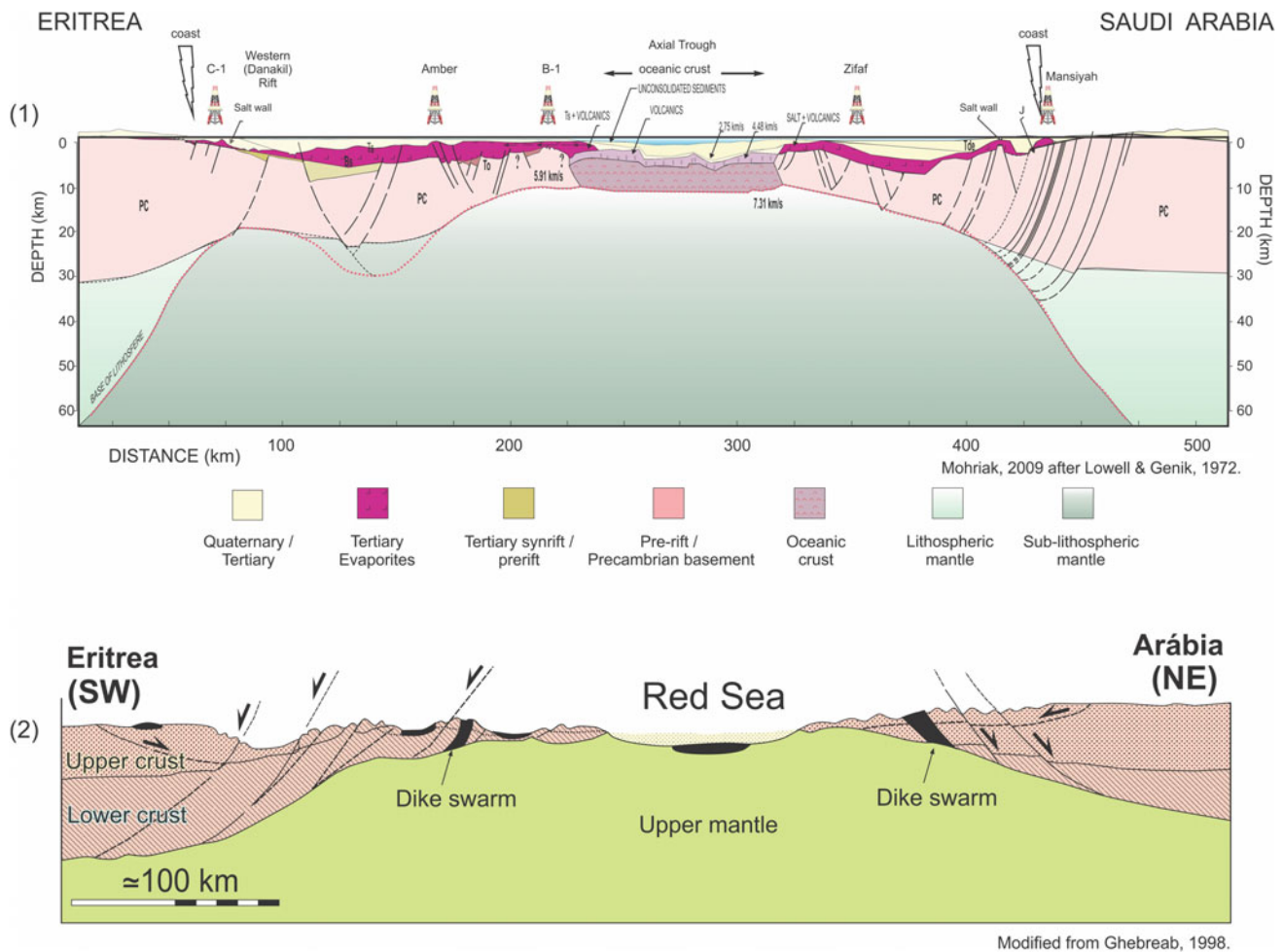
Eritrea and Saudi Arabia. Transect (2), south of the islands, extends from the onshore region north of the Danakil Depression in Ethiopia and reaches the Tihama Plain and the Yemen Escarpment in the conjugate margin

(pre-rift or syn-rift) oil-prone source beds. Although the syn-rift sediments in the Gulf of Suez and Red Sea have similar quality kerogen and potential for hydrocarbon generation, they are genetically different in terms of biomarkers (Alsharhan and Salah 1997) and the maturity is higher in the Red Sea than in the Gulf of Suez (Hadad and Abdullah 2015). The imaging below the thick salt layer in the Red Sea is much poorer than the resolution presently available with the modern seismic technologies applied to the interpretation of the South Atlantic prolific basins, and only a few wells have been drilled by the national oil companies in the deep-water region, resulting in small gas discoveries along the northern Arabian coast (Mohriak 2015).

The nature of the crust underlying the massive salt layer that is observed in the Red Sea axial trough has been debated for more than five decades (Almalki et al. 2015a). Several authors have gathered data that suggest that the oceanic basement is widespread throughout the Red Sea margins, extending almost from coastline to coastline (e.g., McKenzie et al. 1970; Hall 1979; Sultan et al. 1992). On the other hand, several geoscientists have proposed that most of the Red Sea is continental crust and oceanic spreading is only observed in the central to southern Red Sea with the oldest oceanic

crust dated as Late Miocene/Pliocene ( $\sim 5$  Ma) and confined to the axial trough (Bosworth et al. 2005; Cochran and Karner 2007; Lazar et al. 2012; Schettino et al. 2016).

Since the development of the early plate tectonics concepts, the Red Sea and Gulf of Aden regions have been considered as paradigms for the evolution of continental rift basins that evolved into a gulf stage with incipient divergent margins. However, up to the present there is no deep seismic reflection profile extending across the Red Sea and imaging the conjugate margins from Africa to Arabia to corroborate either the pure shear or the simple shear hypothesis. Nonetheless, a large number of tectono-sedimentary studies integrating geological and geophysical datasets of the Red Sea and Gulf of Aden have been published in the geological literature (see for example, Leroy et al. 2004, 2012; Almalki et al. 2015a) discussing the pros and cons of each hypothesis. Some of these studies (e.g., Ligi et al. 2012; Augustin et al. 2014) indicate that in some segments of the central and southern Red Sea there is an active spreading centre in the axial trough; moreover, volcanic rocks with mid-ocean ridge affinity have been recovered by dredging of the seafloor, or are indicated by indirect methods (seismic and potential field data) in areas partially covered by salt (Guennoc et al. 1990).



**Fig. 11** Two end-member models for the development of the Red Sea continental margins are presented for the two transects shown in Fig. 10. Transect (1) assumes a volcanic basement in the axial trough and is constrained by exploratory wells drilled in the platform of Eritrea and Saudi Arabia. The well Amber-1 offshore Eritrea penetrated a thick salt sequence and bottomed at pre-rift metamorphic rocks. The well

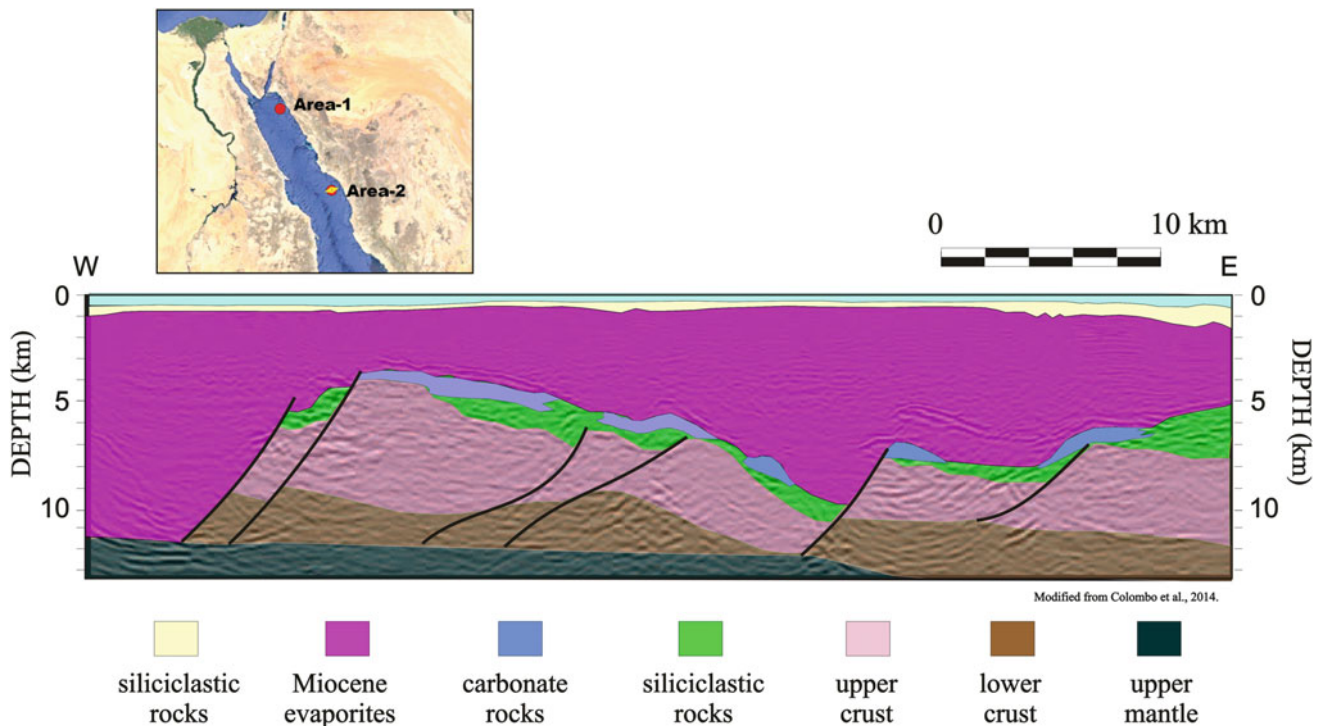
Mansiyah-1 onshore Saudi Arabia penetrated a thick sequence of evaporites and bottomed at volcanic rocks. Transect (2) extends from the onshore region north of the Danakil Depression in Ethiopia and reaches the Tihama Plain and the Yemen Escarpment. This model assumes mantle exhumation controlled by detachment faults that expose the upper mantle peridotites at the Red Sea axial trough

This work will analyze the crustal architecture of the central to northern Red Sea by integrating potential field datasets with seismic profiles from the proximal to the distal margin (Fig. 9).

Several authors have proposed different geodynamic models for the development of the Red Sea (e.g., Bonatti 1985; Voggenreiter et al. 1988; Bosworth et al. 2005). Mohriak (2014) has critically analyzed the pure shear and simple shear extensional models that have been proposed for the axial trough in the Red Sea (e.g., Lowell and Genik 1972; Ghebreab 1998). A comparison of these end-member models can be summarized by analyzing two geological cross sections in the southern Red Sea (Fig. 10), one north of the Dahlak Islands (Lowell and Genik 1972) and one south of these islands (Ghebreab 1998), in the offshore region just north of the Danakil Depression.

The geological transects in the southern Red Sea (Fig. 11) show two end-member models of continental breakup and formation of oceanic crust. Model 1 (Fig. 11-top, corresponding to the northern transect in Fig. 10) suggests continental breakup by pure shear extension and formation of oceanic crust in the axial trough, which might be filled with Late Tertiary sediments (Lowell and Genik 1972). This model is supported by the interpretation of high angle normal faults affecting the continental crust, and assumes that salt was deposited on continental crust, but is presently advancing toward oceanic crust in the main trough, and the axial trough might be covered by Neogene siliciclastic sediments overlying volcanic rocks (Ligi et al. 2012; Augustin et al. 2014).

The southern transect (Fig. 11-bottom, Model 2 in Fig. 10) assumes continental breakup by simple shear



**Fig. 12** 3D seismic profile in the Area 2 of the eastern central Red Sea, between the Mabahiss Deep and the Nereus Deep, eastward of Zabargad Island (about 24° N). The proposed interpretation (Colombo

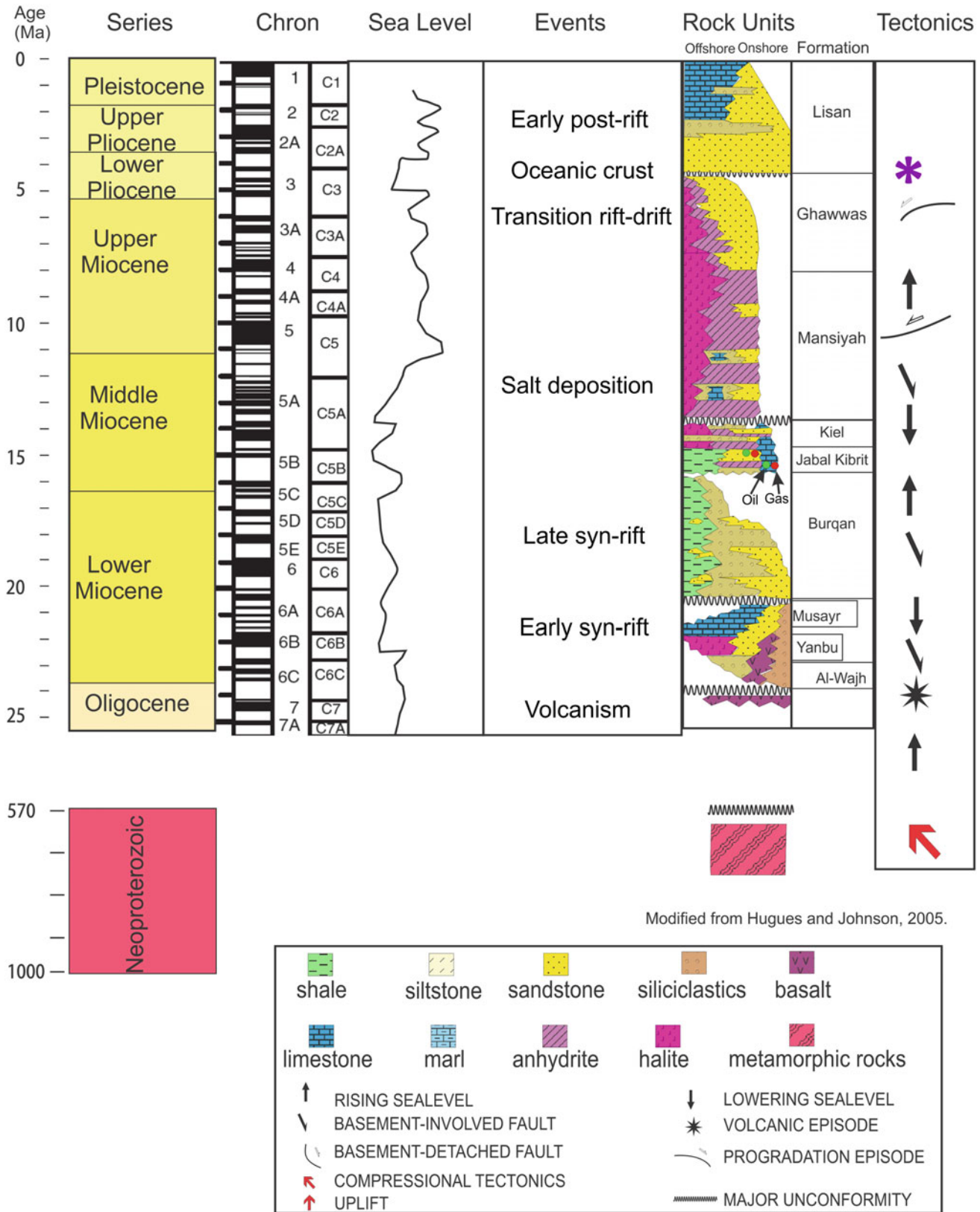
et al. 2014) shows a thick salt layer on hyperextended continental crust and a massive salt mass (more than 10 km of stratified evaporites) overlying upper mantle rocks in the main trough

extension, with the axial trough located adjacent to portions of the lithosphere where mantle rocks are exhumed by extensional faults that detach at the lower crust—upper mantle boundary (Ghebreab 1998; Voggenreiter et al. 1988; Voggenreiter and Hotzl 1989). This model implies low angle normal faulting affecting continental crust, with detachment faults soling on the upper mantle peridotites. Consequently, hyper-extended continental crust would be associated with rotated fault blocks, serpentinized upper mantle rocks might be exposed in the main trough, and dike swarms would be asymmetric along the continental margins. This model implies that salt may overlie continental crust and exhumed mantle, thus the salt layer might be associated with a syn-thinning desiccation process that resulted in massive evaporite deposition preceding the onset of oceanic spreading (Rowan 2014).

The mantle exhumation model has also been tentatively applied to the central Red Sea, assuming simple shear stretching and salt deposition directly on exhumed mantle rocks in the deep-water province (e.g., Colombo et al. 2014; Rowan 2014). A recent application of the exhumed mantle model, based on the interpretation of the large 2D and 3D seismic dataset available for the central Red Sea, is shown in Fig. 12. The seismic profile in Area 2 corresponds to a 3D seismic profile extending across the eastern central Red Sea main trough near the Nereus Deep (Colombo et al. 2014).

This model assumes that the Miocene evaporites cover hyper-extended continental crust in the platform main trough, whereas the axial trough is characterized by more than 10 km of salt directly overlying mantle rocks. Similar models have also been applied to several other basins worldwide, such as the Gulf of Mexico, as proposed by Pindell et al. (2015). Following the mantle exhumation model, it was assumed that in the early development of the Gulf of Mexico active detachment faults resulted in outer marginal collapse by the Early Oxfordian, and the spreading ridge that was active until the Middle Jurassic separated two salt basins offshore the USA and Mexico, with the distal parts of the slumped salt covering subcontinental mantle peridotites.

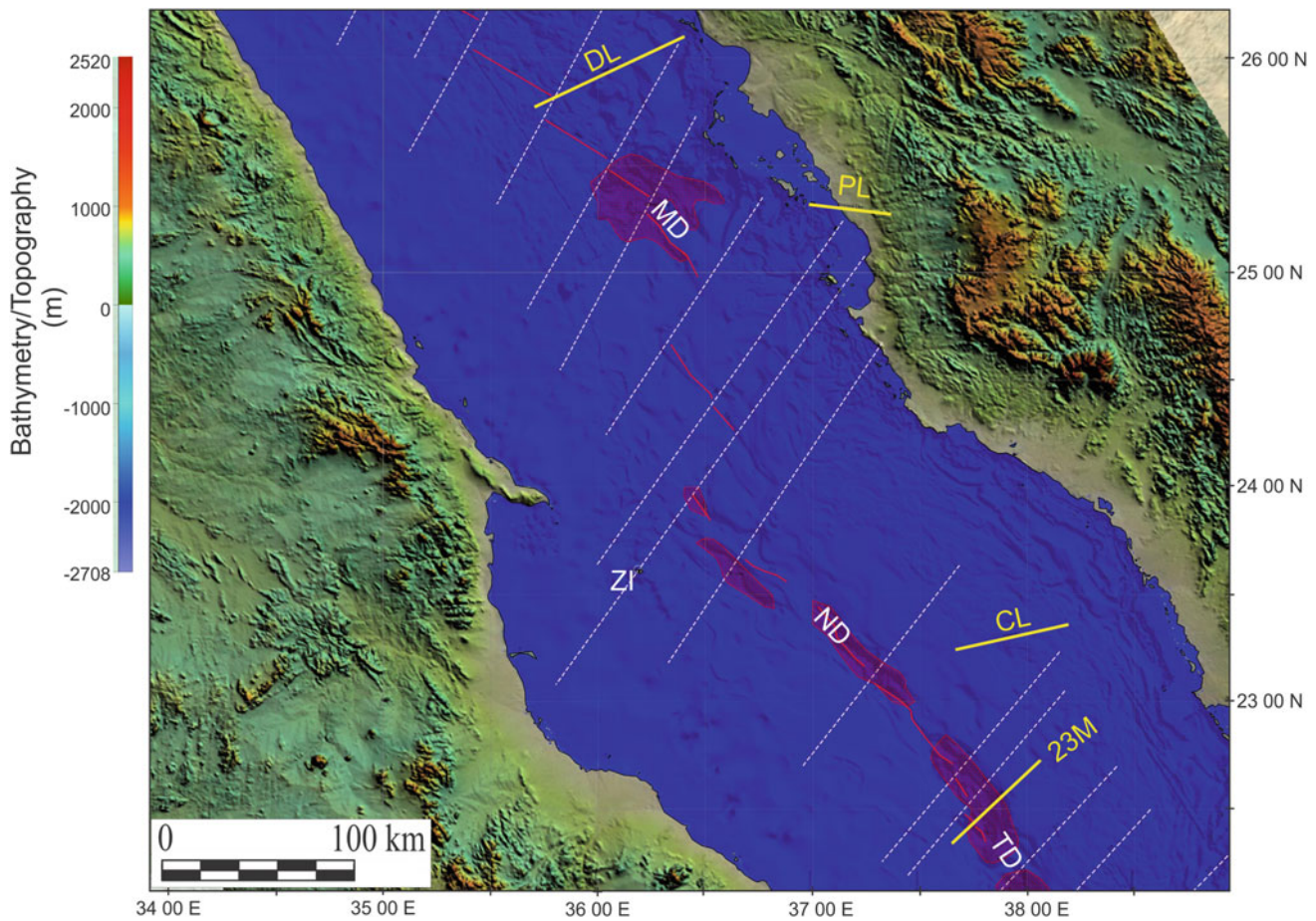
However, integration of potential field and seismic data, and exploratory wells in the Red Sea suggest that a pure-shear model associated with lithospheric stretching and development of magmatic centres in the axial trough may be considered as the model that better fits the observations of syn-rift structures, magmatism and salt deposition in the conjugate margins of Saudi Arabia-Yemen and Egypt-Sudan-Eritrea (Mohriak and Leroy 2013). The simple shear model of mantle exhumation would imply very asymmetric basins, whereas the gravity and magnetic anomalies, as well as P-wave receiver function modelling, are indicative of symmetric structures relative to the axial trough (see for example, Hosny



**Fig. 13** Schematic stratigraphic section of the Red Sea with magnetic geochrons, sea-level variations and main tectonic events. The Lower Miocene stratigraphic successions (Al-Wajh and Burqan Fms.) are interpreted as syn-rift, and the early Middle Miocene Kiel and Jabal Kibrit formations are interpreted as deposited in a late syn-rift stage or sag basin. The Middle to Upper Miocene Mansiyah Fm. evaporites are interpreted as deposited in the rift-drift transition, although some

authors assume these evaporites are late syn-rift. The Pliocene-Pleistocene post-salt successions include the Ghawwas Fm. and the Lisan Gp., which are separated by a regional and widespread unconformity in the Red Sea. There is a possible correlation of this regional unconformity with the Messinian desiccation event, which some authors associate with the breakup unconformity, marking the inception of the oceanic crust (~5 Mybp)





**Fig. 14** Topobathymetric map of the central Red Sea with the locations of regional seismic profiles both onshore and offshore shown by yellow lines. The central Red Sea is characterized by an axial trough with depths that may reach about 2000 m in the Thetis, Nereus and Mabahiss Deep (TD, ND and MD). The volcanic basement in the Red Sea axial trough is indicated by a purple colour adjacent to the embryonic oceanic ridges. Transform faults are indicated by dashed white lines. Several seismic profiles have been acquired in the Thetis Deep by academic institutions; Seismic Line 23 M, which crosses the

axial trough spreading centre, is discussed here. The schematic geoseismic sections (proximal and distal profiles, PL and DL) present geological models for the onshore-offshore rift architecture and the alternative interpretations for the deep-water rift basins, with important implications for the syn-rift sediments and salt distribution. The approximate position of the seismic profile interpreted by Colombo et al. (2014) is also shown as CL, extending from the platform toward the Nereus Deep, located eastward of Zabargad Island (ZI) offshore Egypt

and Nyblade 2014). The bathymetry and development of basin depocentres and salt distribution are more or less symmetric across the margins (Mohriak and Leroy 2013). With the exception of the Mabahiss Deep, which is clearly offset toward the Arabian side, most of the Red Sea deeps are located in the centre of the axial trough, resulting in approximately symmetric margins. However, geological maps indicate a much larger area of Tertiary to Quaternary pre- and syn-rift volcanic rocks on Arabia's continental crust when compared to the African crust (Fig. 9). The harrats (lava fields) onshore Saudi Arabia extend for more than 200 km in length along a N–NW direction, and geological maps (e.g., Bosworth et al. 2005; Hartmann and Moosdorf 2012), indicate that the African side of the Red Sea margin lacks

extensive lava fields, except toward the Afar province in the south, where large volcanoes such as Erta Ale are presently outpouring basaltic lavas in the Danakil Depression. Davison et al. (1994) emphasized that the major episodes of lava flows in Yemen span the interval of Oligo-Miocene (30–20 Ma), but volcanism is also registered in the Afar area onshore Ethiopia from Middle to Late Miocene to the present-day, concomitant with the syn-rift and early drift phases that affected the Red Sea region (Corti et al. 2015). Volcanic structures are also characterized below the salt in the Red Sea main axial trough, and in modern times a number of new-born volcanic islands have grown above sea-level offshore Yemen (e.g., Gass et al. 1973; Xu et al. 2015).

## 5 Rift Development, Stratigraphic Successions and Salt Tectonics in the Red Sea Continental Margins

Similar to the South Atlantic, the stratigraphy of the Red Sea continental margins can be divided into three main tectonic phases (Fig. 13); the syn-rift, the transitional, and the post-rift or early drift phases. The syn-rift phase, dated as Early Miocene, post-dates the volcanic rocks that have been dated by Ar–Ar at  $\sim 30$  Ma both in the Afar region in the southern Red Sea, as well as in the onshore region of Yemen and Saudi Arabia, where the youngest flood basalts show Ar–Ar isotopic ages of about 26 Ma (Baker et al. 1996). These volcanic rocks probably constitute the pre-rift volcanics that have been sampled by several wells in the Red Sea, such as the onshore Jizan wells at the border between Saudi Arabia and Yemen (Hughes and Johnson 2005).

The late syn-rift phase or sag basin is less affected by basement-involved faults, which locally penetrate the Middle to Late Miocene Mansiyah Fm., which corresponds to the main evaporite layer in the Saudi Arabian Red Sea (Bosworth et al. 2005; Hughes and Johnson 2005; Tubbs et al. 2014). Above the salt layer there is a thick sequence of Late Miocene to Pliocene sediments (Ghawwas Fm.) locally associated with salt mobilization. Finally, the Pleistocene to Recent siliciclastic and carbonate rocks of the Lisan Gp. cover the previous stratigraphic successions. These stratigraphic sequences will be discussed in the geoseismic profiles that extend from the border fault in the onshore region (proximal profile, PL in Fig. 9) toward the Red Sea axial trough (distal profile, DL in Fig. 9). A detailed map of the central to northern Red Sea (Fig. 14) shows the location of these profiles and the interpreted outline of the Mabahiss Deep, with the inferred position of the axial trough oceanic ridges and transform faults (Bonatti and Seyler 1987; Guennoc et al. 1990).

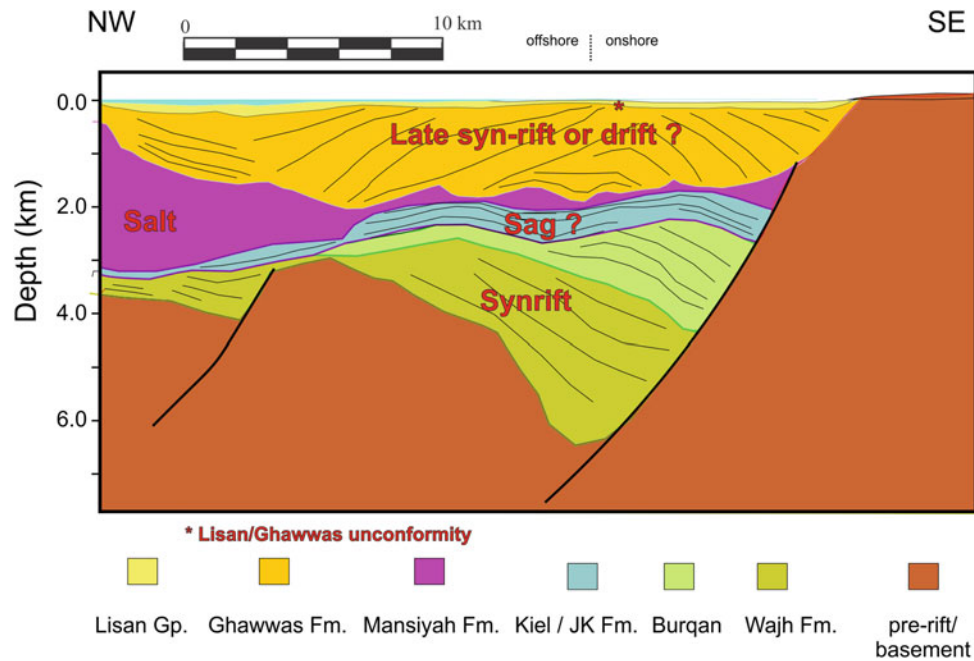
The age of oceanic crust formation in the Red Sea and Gulf of Aden has been discussed by many authors. Bosworth et al. (2005) advocated that seafloor spreading started in the Gulf of Aden at about 19–18 Ma and propagated westward toward the Afar plume, whereas in the Red Sea organized spreading commenced only at about 5 Ma. The model is based on stretching of continental crust simultaneously with magmatic activity (dyke intrusions and lava extrusions), and involves only a limited zone of oceanic crust in the axial trough of the Red Sea and Gulf of Aden, while allowing for the rapid thinning of the continental crust close to the coastline as indicated by geophysical studies in Saudi Arabia and Yemen (Mooney et al. 1985).

Several explorationists and researchers working in the Red Sea continental margins have interpreted that the Middle to Upper Miocene evaporites were deposited during the

syn-rift (Bosworth et al. 2005; Allen and Beaumont 2015) or syn-thinning phase preceding mantle exhumation (Rowan 2014). The regional and widespread unconformity that is observed above the salt layer might correspond to the rift-drift transition or to the breakup unconformity that followed the rift-drift transition in the Upper Miocene—Lower Pliocene, and is often associated with the inception of oceanic crust in the central to southern Red Sea (Fig. 13). The characterization of major unconformities in the transition from syn-rift to post-rift strata in continental margins worldwide has long been debated in the geological literature, and its relationship with uplift of continental blocks or to the development of oceanic crust is controversial (Benson and Doyle 1988; Braun and Beaumont 1989). However, there is geological and geophysical evidence that some of these unconformities are related to a change in the locus of extension, from the proximal to the distal margin. There is clear seismic indication of oceanward younging of fault activity until the locus of extension is focused on an embryonic spreading centre. The syn-kinematic sediments young basinward and an unconformity develops when extension abandons one area in favour of new faults forming oceanward. It is also noteworthy to observe that these unconformities are developed regionally, and may constitute the register of events formed elsewhere in the margin, as a result of the diachronous development of oceanic ridges, and multiple unconformities may span an interval of several million years, rather than correspond to an instantaneous or short-term event preceding the sea-floor spreading phase.

In order to elucidate the controversial issues related to where and when oceanic crust might have formed in the Red Sea, this work analyses four regional profiles in the Arabian margin, interpreted from seismic lines acquired both onshore and offshore by academic institutions and the petroleum industry (Figs. 9 and 14). Two of these profiles are shown as schematic line-interpretation diagrams (Mohriak 2014) based on seismic data acquired from the onshore rift basin border toward the platform (proximal line, PL), and from the platform to the deep-water region (distal line, DL). Alternative hypotheses for the rift architecture of the Red Sea will be discussed based on interpretations of the distal profile.

The seismic profile east of the Nereus Deep (seismic line CL in Fig. 14) is based on a 3D seismic program (Area 2, see Fig. 12) acquired in the deep-water region of the Red Sea, as indicated by Colombo et al. (2014). Its location in Fig. 14 is only approximately indicated, and is based on the bathymetric data and length of the published seismic line (about 55 km). Finally, this work discusses a 2D seismic line that extends across the axial trough spreading centre (Line 23 M from Mitchell et al. (2010) and Ligi et al. (2012)). The integration of these profiles provides a unique geoseismic transect from the basin limit near the Precambrian outcrops



**Fig. 15** Schematic geological section showing the onshore and the continental platform rift (proximal profile, PL in Fig. 14). The syn-rift stratigraphic successions (Al-Wajh and Burqan Fms.) are overlain by the late rift or sag basin deposits of the Kiel and Jabal Kibrbit Formations. The Middle to Late Miocene evaporites (Mansiyah Fm.) have been mobilized from the onshore region to inflate the large salt diapirs in the offshore region. The Pliocene-Pleistocene post-salt

successions (Ghawwas Fm. and Lisan Gp.) form a major roll-over structure associated with salt evacuation. The Lisan/Ghawwas unconformity (\*) has a regional occurrence in the Red Sea and is possibly associated with the Messinian desiccation event. Several researchers also suggest a possible correlation with the breakup unconformity, marking the inception of the oceanic crust (~5 Mybp)

toward the oceanic crust spreading centre, as will be discussed subsequently.

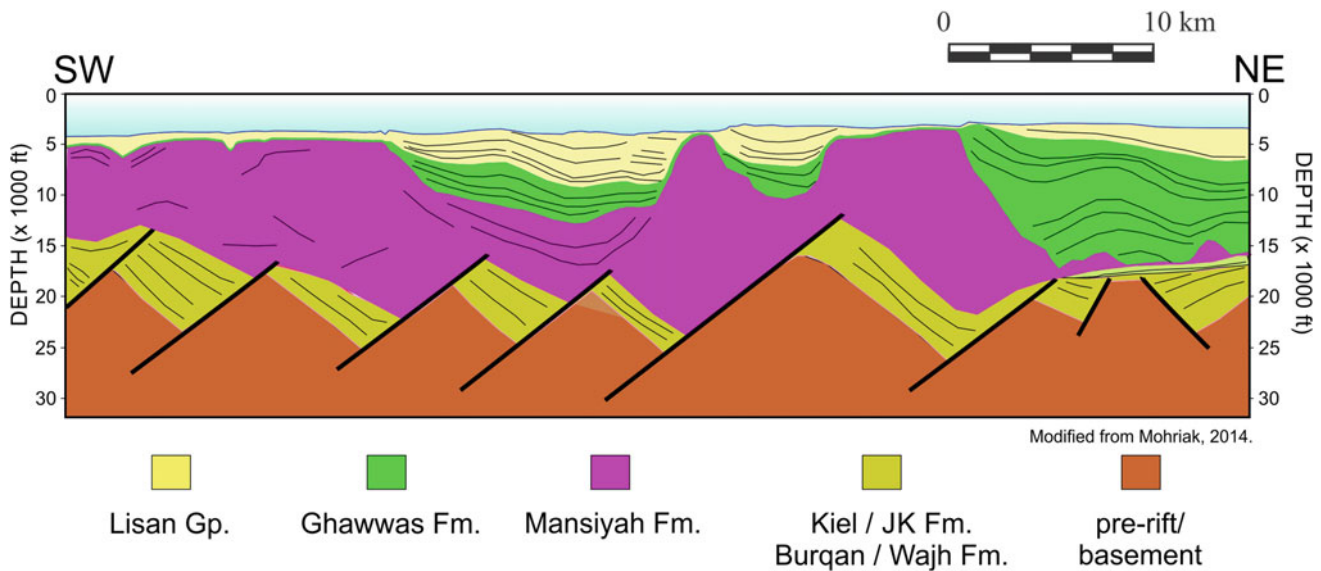
Figure 15 shows the schematic seismic line interpretation of the proximal profile at the transition from the onshore to the offshore region in the central Red Sea. The main structure is characterized by the high-angle rift border fault near the eastern extremity of the seismic section, where the Precambrian basement rocks outcrop at the surface. The rift unit is overlain by salt and siliciclastic sediments in the proximal basin, and salt evacuation resulted in development of large turtle structures and salt diapirs in the continental platform.

The Precambrian basement may be interpreted at depths exceeding 6 km in the transition from the onshore to the offshore region. The normal fault that controls the syn-rift depocentre offsets the basement and rotates the sedimentary packages (Al-Wajh Fm. and Burqan Fm.). The Early Miocene syn-rift sequence is associated with the Al-Wajh coarse clastic rocks, that are locally covered by evaporites (Yanbu Fm.) and reefal carbonates (Musayr Fm.). The Burqan Fm., which is typically characterized by fine-grained sediments, and the Kiel and Jebal Kibrbit Fm. successions, associated with Early to Middle Miocene carbonate and evaporite rocks, might correspond to a reduced phase of tectonic activity comparable to the sag basin in the South Atlantic (Mohriak 2014). These formations may be related to a deep

marine environment, particularly the Burqan Fm. (Hughes and Johnson 2005), and the shallow marine carbonate of the Kiel and Jabal Kibrbit formations may constitute reservoirs, as observed in the Midyan Basin (Tubbs et al. 2014). Some faults affect these layers and some even penetrate the base of the thick and widespread evaporite layer (Mansiyah Fm., Middle to Late Miocene).

The Middle to Late Miocene Mansiyah Fm. evaporites show indications of basinward salt flow forming large diapirs in the platform and deep water (Fig. 15). The post-salt stratigraphic succession is characterized by a thick halokinetic growth section controlled by listric basinward-dipping faults that form a major roll-over structure. This was produced by salt evacuation and migration to inflate the large salt diapirs in the platform, in a structural style that is similar to that observed in the Midyan Basin onshore, near the Gulf of Aqaba (Tubbs et al. 2014). Above the evaporites the stratigraphic sequences include the Ghawwas Fm., characterized by halokinetic growth sequences, and the Lisan Gp., which onshore is characterized by a thin veneer of sediments sealing the halokinetic structures.

The angular unconformity that corresponds to the boundary between the Ghawwas Fm. (Late Miocene) and the Lisan Gp. (Pliocene to Pleistocene) might be positioned around 5 Ma in the stratigraphic chart (Fig. 13). The



**Fig. 16** Hypothesis 1 for the interpretation of the Red Sea distal profile (DL in Fig. 14), assuming a magma-poor margin and salt deposited during a late syn-rift stage, before the continental breakup. No oceanic crust is present in the basin centre, as interpreted

for the northern Red Sea and Gulf of Suez. Maximum salt thickness overlying the rift sequence is estimated at about 15000 ft ( $\sim 5000$  m) of stratified evaporites

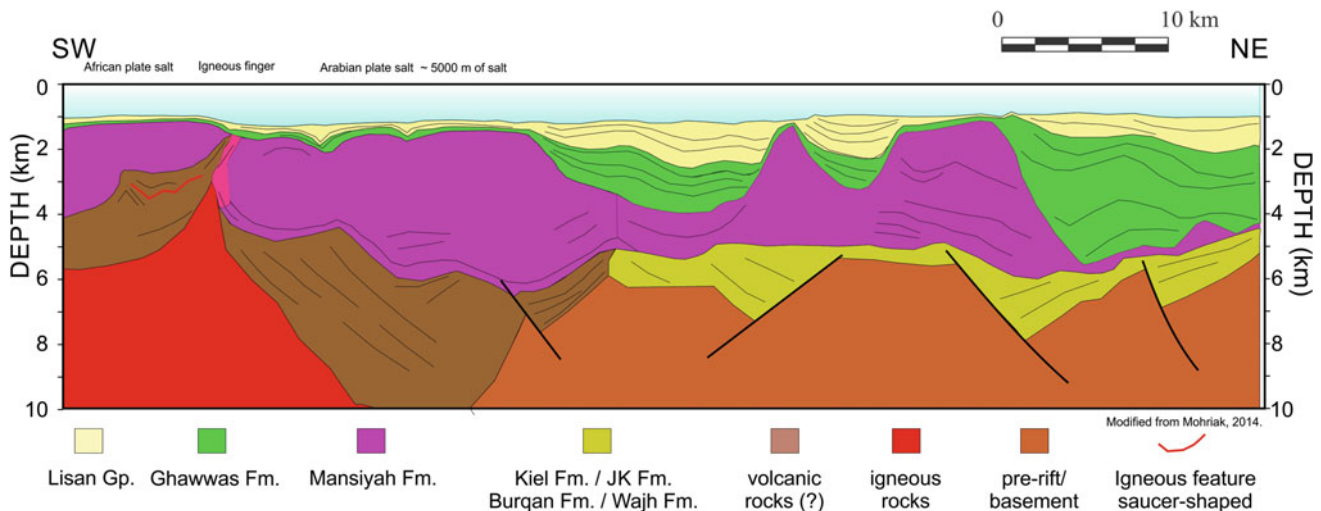
interpretations of the magnetic anomalies in the central to southern Red Sea have been correlated with the Chron C3n.2n ( $\sim 4.6$  Ma; Schettino et al. 2016), at about the same age of the transition from Late Miocene to Pliocene, thus corresponding with the unconformity between the Ghawwas Fm. and the Lisan Gp., which some authors also associate with the widespread Messinian Unconformity that is characterized in the Mediterranean but may also affect the Red Sea (Bosworth et al. 2005; Afifi et al. 2014). Many researchers and explorationists have envisaged a possible correlation of this regional unconformity with the breakup unconformity, which may herald the inception of oceanic crust as suggested by many authors (e.g., Falvey 1974; Esedo et al. 2012; Franke 2013). However, several authors consider there is no proven link between the inception of oceanic crust and a phase of uplift affecting the rifted continental crust prior to the breakup, and this unconformity might in fact correspond with a mantle upwelling developing a lithospheric breakup surface during the rift-drift transition (Duarte et al. 2012). The assumption that the unconformity observed in the Miocene/Pliocene boundary might correspond with the breakup would thus point to the generally accepted age of inception of the oceanic crust in the Red Sea around 5 Ma (Bayer et al. 1989; Bosworth et al. 2005; Cochran and Karner 2007).

This interpretation has important consequences for the Red Sea rift architecture in the distal margin, because if the breakup unconformity in the central Red Sea is the Messinian Unconformity, then there is oceanic crust only in the axial trough where the anomaly C3 is clearly identified, and

most of the area covered by thick salt masses might correspond to extended continental crust with syn-rift sediments, as suggested by several researchers (e.g., Cochran and Karner 2007) and also by explorationists working in the area (Tubbs et al. 2014). This possibility is illustrated as hypothesis 1 in Fig. 16, with tilted rift blocks covered by thick salt in the deep-water region (Mohriak 2014).

On the other hand, if the oceanic crust or volcanic basement extends landward of the axial trough, then the breakup unconformity should be older than the Chron C3. Comparing the proximal geoseismic profile (Fig. 15) with equivalent geoseismic sections in the South Atlantic, Mohriak (2014) suggested that the breakup unconformity might be positioned below the salt, and not above it. A number of authors have used the magnetic anomaly pattern in the Red Sea to suggest that the formation of the initial oceanic crust might be positioned closer in time to the development of the syn-rift sequence, in Early Miocene times (Labrecque and Zittelini 1985). This interpretation advocates that the main trough might be constituted by a thickened oceanic crust with effusion of large quantities of stratoid basalts during the initial phases of continental breakup. The axial trough would then correspond with a more advanced stage of focusing the magma production in the spreading centre developed in the past few million years.

The distal profile in the central Red Sea extends from the platform toward the main trough and axial trough north of the Mabahiss Deep (Fig. 14), which does not show bathymetric depressions similar to the depressions in the southern Red Sea, where the axial trough is clearly characterized by a



**Fig. 17** Hypothesis 2 for the interpretation of the Red Sea distal profile (DL in Fig. 14). Assuming this interpretation, salt was deposited above the breakup unconformity, at the transition from late synrift (sag basin) to an early drift phase. Salt deposition was concomitant with igneous extrusions and intrusions in the volcanic basement. Igneous fingers penetrate the salt layer in the axial trough, and volcanic

intrusions have started to split the evaporite basin into two conjugate margin salt bodies. Eventually one of these salt masses will be attached to the African plate (Egypt/Sudan) and the other to the Arabian plate (Saudi Arabia/Yemen). The salt mass in the Arabian side may reach more than 5000 m of evaporites overlying late syn-rift sediments and volcanic basement rocks

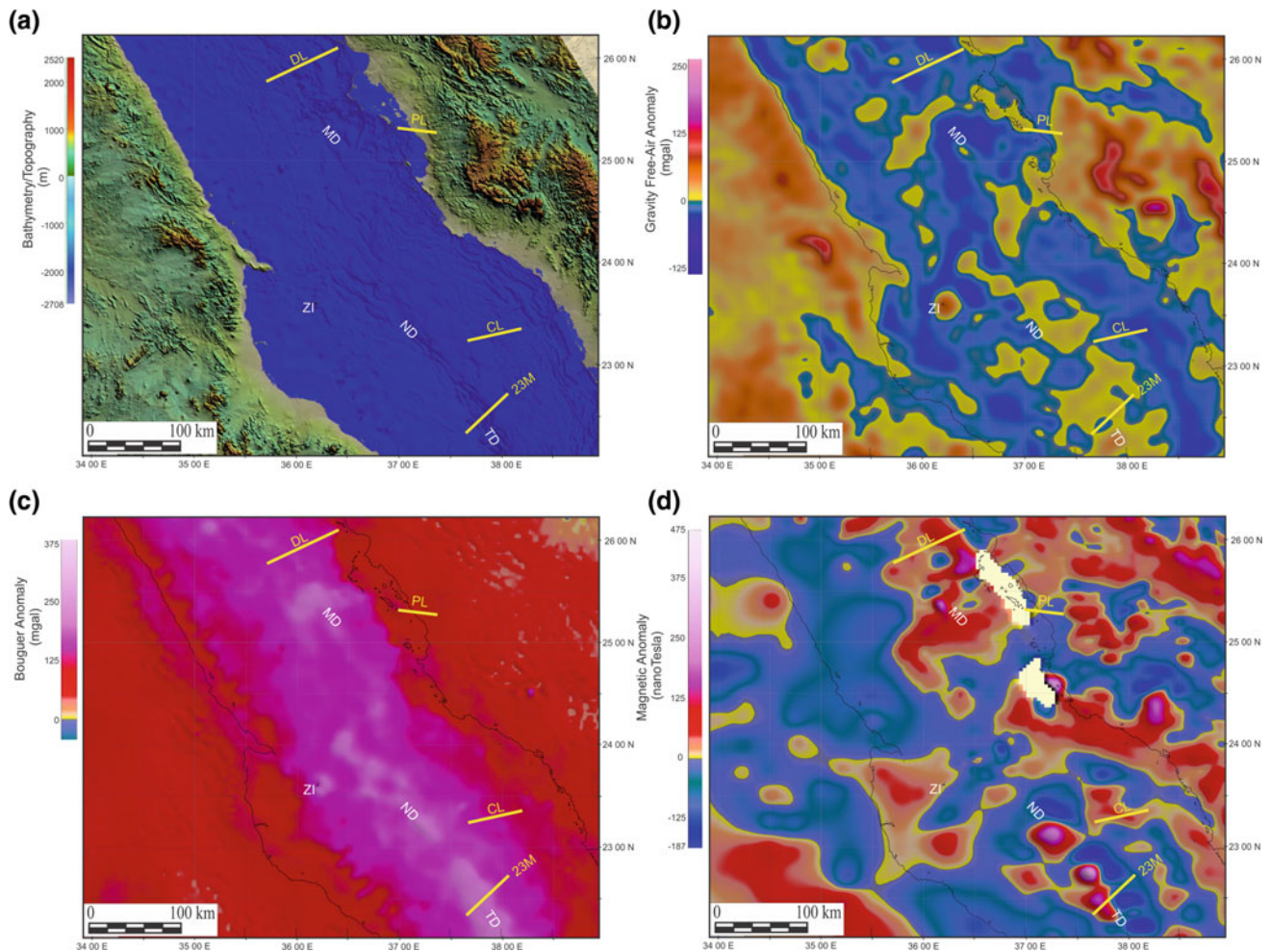
magnetic anomaly zebra pattern associated with organized spreading in the oceanic crust (Hall 1979; Zahran et al. 2003). Two hypotheses have been analyzed for the interpretation of this profile. Hypothesis 1 (Fig. 16) assumes that the thick salt masses in the axial trough cover tilted rift blocks on the continental crust, which may be affected by extensional faults with large offsets. Following this interpretation, the Mansiyah Fm. evaporites were deposited during a late syn-rift phase before continental breakup and no oceanic crust has been developed in the basin centre. This is similar to the interpretations of diffuse extension still active in the northern Red Sea and Gulf of Suez (Cochran 1983; Bonatti 1985; Bosworth and McClay 2001; Bonatti et al. 2015). This hypothesis has been favored by many explorationists working in the area, particularly along the northern Arabian Red Sea, which is considered much less volcanic than the southern Red Sea. The intrasalt reflectors might then be interpreted as a suture of sedimentary rock trapped below amalgamated salt bodies.

Hypothesis 2 (Fig. 17) suggests an alternative interpretation for the distal profile, assuming that the thick salt masses are advancing toward a volcanic basement associated with incipient oceanization and protracted magmatic activity that resulted in the formation of large volcanoes below the salt, and intrusive bodies might occur within the salt layer (Mohriak 2014). Assuming this interpretation, the continental crust has already been affected by igneous intrusions that will eventually split the salt basins apart by embryonic spreading centres. The Middle to Late Miocene evaporites were deposited during the transition from an early post-rift to

an early drift phase, overlying volcanic basement rocks in the distal basin. The model envisages that the salt masses in the margins are still amalgamated in the central to northern Red Sea, forming a single salt basin in the main and axial troughs. However, locally they are starting to be separated by embryonic spreading centres that have formed in the past few million years, with intrusive bodies or igneous fingers invading the crust and also penetrating the salt layer, which is mainly allochthonous at this portion of the basin. In other areas, the process is more advanced and the salt masses are totally separated by oceanic ridges and newly formed volcanic basement, as in the Thetis Deep and more incipiently in the Mabahiss Deep (Mohriak 2014).

These hypotheses might be tentatively tested by integration of the geoseismic interpretation with potential fields (gravity and magnetic datasets) and by analysis of seismic profiles in the axial trough, which might also be relevant to the interpretation of the simple shear and pure shear mechanisms of margin development (as discussed in the transects presented in Figs. 10 and 11). In addition, the analysis of the Mabahiss Deep, located about 50 km south of the Distal Line, might throw some lights on the tectono-magmatic processes that are presently occurring in the Red Sea axial trough.

Figure 18 shows (at the same scale) the potential field regional maps for the central Red Sea, based on worldwide datasets (Sandwell and Smith 2009; Maus et al. 2009; Balmino et al. 2012). These maps illustrate the topobathymetry (Fig. 18a), the free-air gravity anomaly field (Fig. 18b), the Bouguer gravity anomaly field (Fig. 18c) and the total field magnetic anomaly (Fig. 18d). The locations of the proximal



**Fig. 18** Regional maps of the central Red Sea with the location of the proximal ( $\sim 25^{\circ}\text{N}$ ) and distal ( $\sim 26^{\circ}\text{N}$ ) geoseismic lines. Simplified tectonic elements such as the interpreted oceanic spreading ridge (red line) and transform faults (dashed lines) are included in the maps and shown in more detail in Fig. 14. The central to northern Red Sea deeps (Mabahiss, Nereus and Thetis) are located in the axial trough and indicated as MD, ND and TD, respectively. The Colombo et al. (2014)

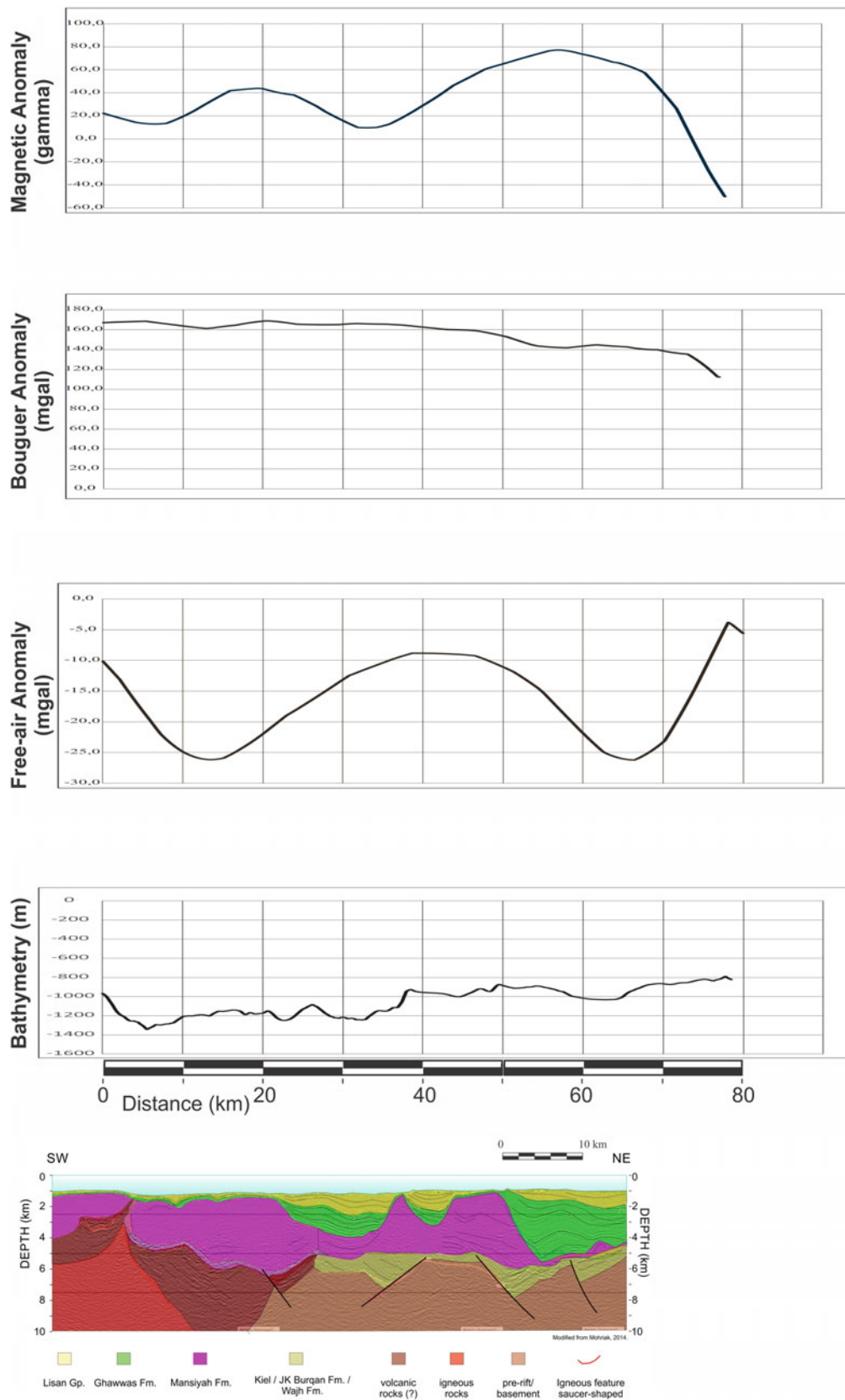
and Mitchell et al. (2010) seismic profiles (CL and 23 M), located between the Nereus and the Thetis Deep, are also located in the potential field maps, as well as Zabargad Island (ZI) offshore Egypt. **a** Topobathymetric map of the central to southern Red Sea; **b** Free-Air gravity anomaly map; **c** Bouguer gravity anomaly map; **d** Magnetic (total field) anomaly map

and distal geoseismic profiles (as well as the industry 3D seismic profile CL and the academic 2D seismic line 23 M), previously shown in Fig. 14, are also plotted on these maps. The seismic profile 23 M is particularly of interest for the interpretation, because it is located in deep to ultradeep waters, with bathymetry around 800 m in the NE end of the profile but reaching more than 2000 m in the axial trough at the Thetis Deep, where it crosses the embryonic spreading centre (Mitchell et al. 2010; Ligi et al. 2012).

The free-air gravity anomaly map (Fig. 18b) is characterized by N–NW positive anomaly trends onshore in both Egypt and Saudi Arabia. In the offshore region, the NW trends are also observed, but local NE trends are also conspicuous, and these might be associated with transfer zones or transform faults, as for example in the Zabargad Shear

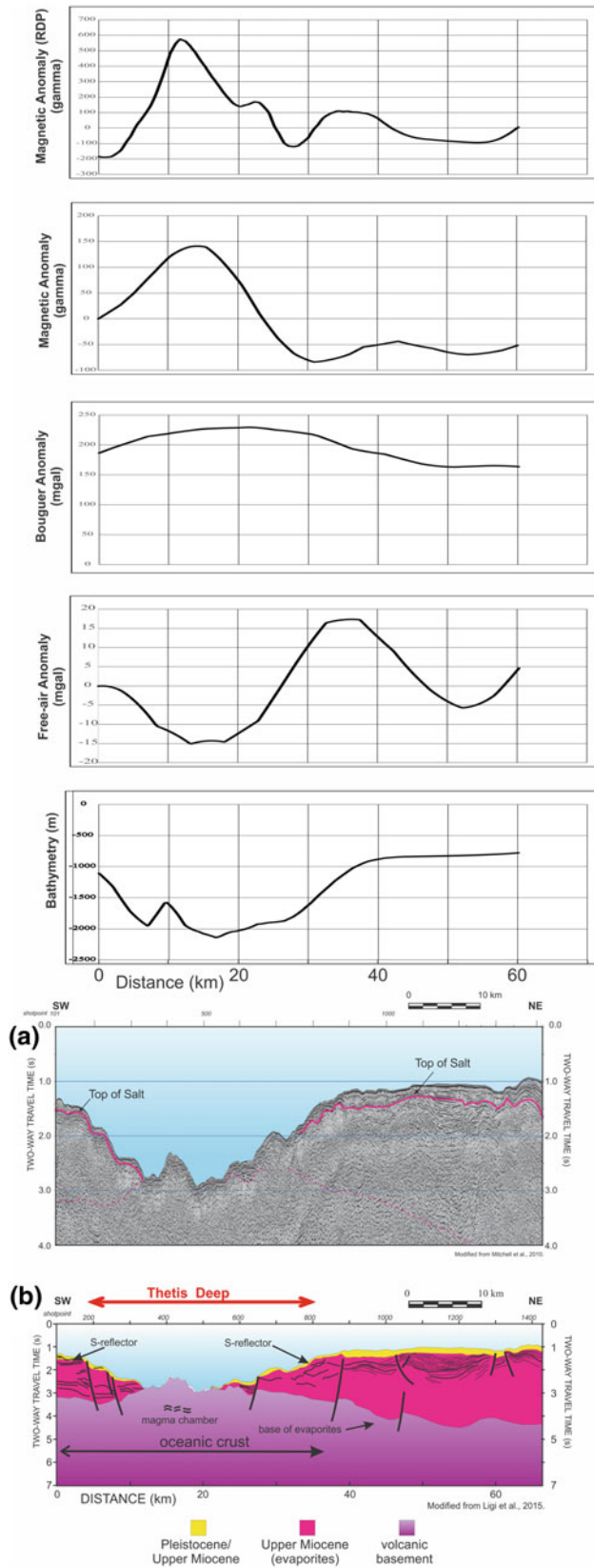
Zone (Bonatti et al. 1984; Ligi et al. 2012). Zabargad Island is associated with a major positive gravity anomaly in the African plate, which is associated with the lower crust and upper mantle rocks that outcrop at this island (Bonatti et al. 1981; Bonatti and Seyler 1987). The proximal line is characterized by a positive anomaly near the basement outcrop and by a negative anomaly toward the coastline. The distal line is characterized by a gravity anomaly that decreases from the platform toward the distal portion of the line, and rises again near the transform fault at the interpreted embryonic spreading centre.

A cross-plot of the potential field anomalies with the interpretation discussed for hypothesis 2 for the distal transect is shown in Fig. 19. The distal profile shows the bathymetry reaching a maximum of about 1400 m in the



**Fig. 19** Bathymetry, Free-Air, Bouguer and Magnetic anomaly profiles for the distal profile based on industry high-resolution and world global geophysical datasets. The correspondence between the potential field data and the geoseismic profile is only approximate, based on the same horizontal scale and the bathymetry variation along the seismic

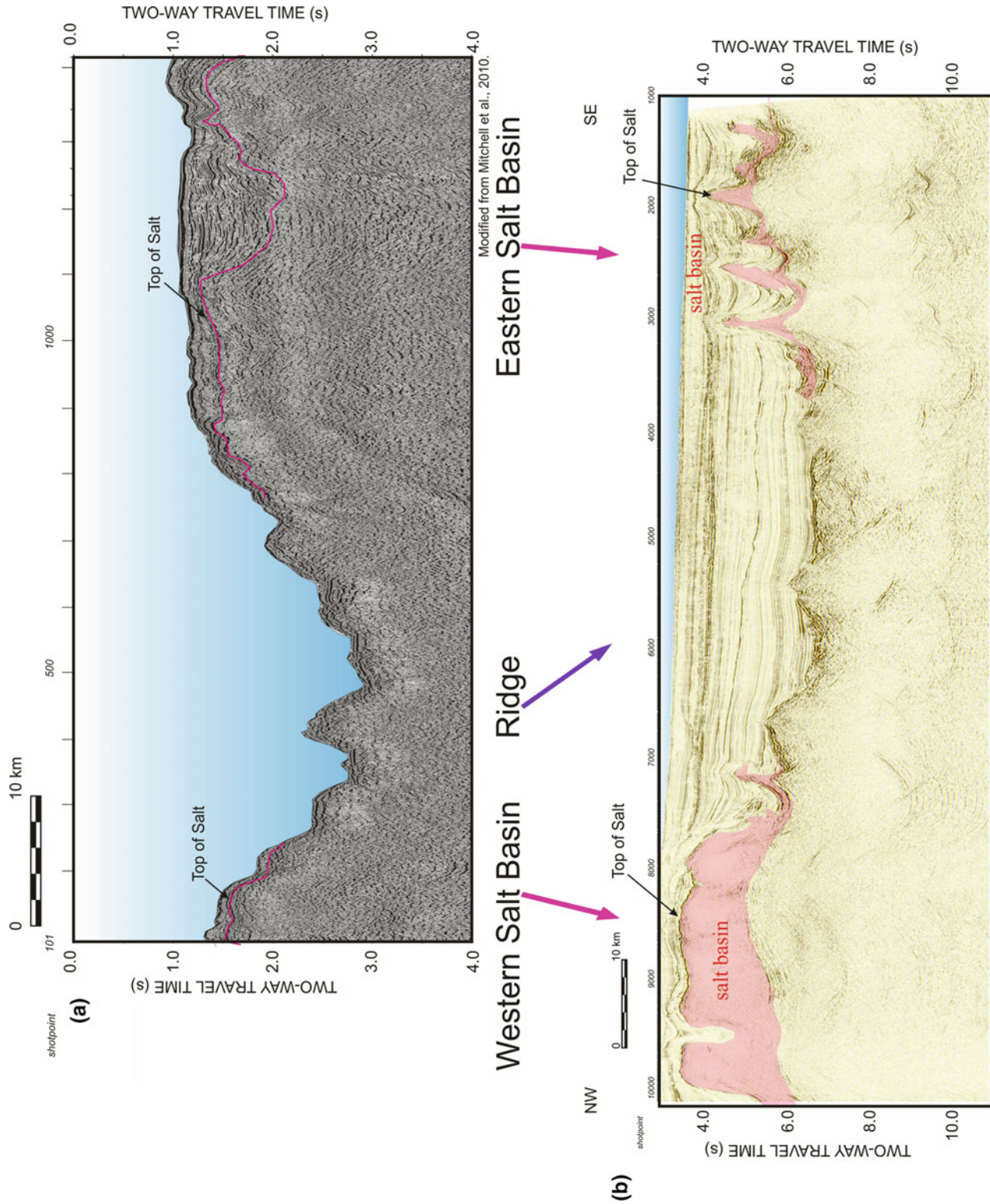
line position. The high-resolution gravity and magnetic anomaly datasets used to create the profiles do not extend toward the SW extremity of the seismic profile. On the other hand, the potential field datasets extend landward of the NE extremity of the seismic line



**Fig. 20** Bouguer, total field magnetic anomaly and reduced to the pole magnetic anomaly profiles for seismic line 23 M across the Thetis deep (Line 23 M in Figs. 14 and 18), in the central Red Sea, based on industry and world global geophysical datasets. The correspondence between the potential field data and the seismic/geoseismic profiles is only approximate, based on the same horizontal scale and the

bathymetry variation along the seismic line position. The interpretation of the seismic profile shows an incipient spreading centre separating two salt bodies that are attached to the Egyptian and Saudi Arabian conjugate margins. No sediments are observed above the active spreading ridge, but the allochthonous salt masses seem to be advancing toward the bathymetric abyss



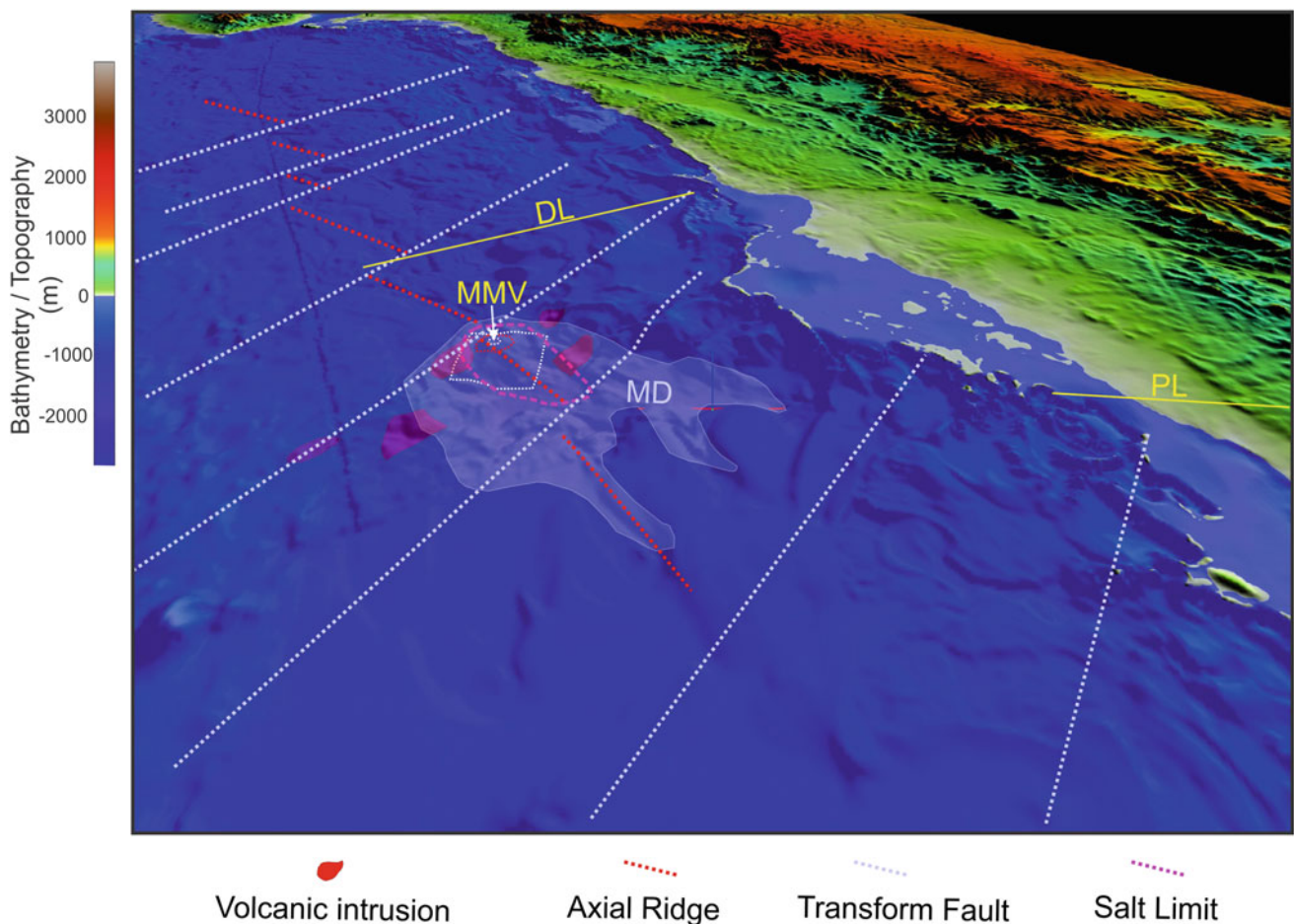


**Fig. 21** Comparison of the Red Sea spreading centre in the Thetis Deep (a), corresponding to Line 23 M in Fig. 14, with a possible aborted spreading centre in the southern Santos Basin (b), corresponding to the profile D2 in Fig. 2. The two salt basins in the central Red Sea, between the African and Arabian conjugate margins (a), are separated by incipient spreading centres in the axial troughs with no evaporites and no sediments above the structural high which may be associated with an embryonic spreading ridge developed in the last 2–3 Ma. Salt was deposited about 12–14 Mbpb in the platform and deep waters, and is now advancing as an allochthonous salt tongue toward the bathymetric abyss. This picture illustrates the development of a divergent continental margin 10 Ma after salt deposition. In the southern Santos Basin offshore Brazil (b) the two salt masses are split by a proto-oceanic crust (volcanic basement) associated with the Abimaël Ridge, and the embryonic axial trough has been filled with sediments deposited in the last 115 Ma. Only a residual salt basin is observed eastward of the ridge, and the southern salt limit is associated with a volcanic belt north of the Florianópolis Fracture Zone (Fig. 2)

axial trough, at the SW extremity of the profile, and the free-air gravity anomaly is negative in this region, which is characterized by a thick salt mass. The axial trough located south of 24°N (Nereus Deep) is characterized by a slightly positive free-air anomaly, with local gravity lows, as in the position of the interpreted spreading ridge. The seismic line 23 M when cross-plotted against the potential field data (Fig. 19) is characterized by a positive free-air anomaly, not only at the axial trough with the spreading centre, but also in the adjacent regions.

The Bouguer anomaly map (Fig. 18c) clearly illustrates the segmented character of the axial trough by the transform faults. The axial trough south of 24°N is characterized by a positive anomaly that deflects toward the NW north of 23°N. Zabargad Island is associated with a major transfer fault zone that offsets the Bouguer anomaly pattern toward the

Arabian side (Ligi et al. 2012). Compression due to shearing along the transfer zone might be responsible for uplifting the lower crust and upper mantle rocks that outcrop at this island (Bonatti et al. 1983, 2015). The proximal line is characterized by a positive anomaly that increases from the onshore to the offshore region. The distal line is characterized by a much higher gravity anomaly that gradually increases from the platform toward the distal portion of the line (Fig. 19). The 3D seismic profile published by Colombo et al. (2014) extends from the platform to the main trough, where the Bouguer anomalies are considerably higher. The seismic profile 23 M crosses the interpreted spreading centre of the Red Sea at 23°N (Thetis Deep), and is marked by a strongly positive Bouguer gravity anomaly centred at the bathymetric abyss (Fig. 18c).



**Fig. 22** Three-dimensional oblique visualization of the topobathymetric map of the central Red Sea with location of the Mabahiss Deep (MD), which is characterized by a volcanic basement with no evaporites in the NW part, indicated by a dashed magenta colour outline enveloping the axial ridge, where basement is exposed and salt is presently advancing as allochthonous masses flowing toward the bathymetric depression. The area with detailed bathymetric survey in the Mabahiss Deep (rectangle with dashed white line) is presented with

a 3D horizon visualization in Fig. 23. The Mabahiss Seamount (Mabahiss Mons Volcano, MMV) is located at the northwest corner of the white square, near the inferred spreading centre or axial ridge. Several igneous plugs have also been identified in the region by Guennoc et al. (1990) and are marked by red ellipses at the northern part of the Mabahiss Deep. The distal and proximal geoseismic profiles are also indicated by yellow lines (DL and PL)

The magnetic anomaly map of the central Red Sea (Fig. 18d) is more difficult to interpret due to low resolution of the world dataset and the structural and lithologic complexity of the basement rocks that occur both onshore and offshore (Blank 1977; Blank and Andreasen 1991). The axial trough south of 24°N is characterized by a positive-negative anomaly pair with a NE trend. Zabargad Island is associated with a major transform fault that offsets the magnetic anomaly along a NE direction. The proximal line is characterized by a negative anomaly onshore that slightly increases toward the coastline. The distal line is characterized by a much higher magnetic anomaly that shows a typical dipole at the axial trough. The 23 M seismic profile crosses the interpreted spreading centre at the Thetis Deep, and the strong magnetic anomaly dipole is indicative of igneous rocks along a NW trend, with NE trends associated with the interpreted transform faults.

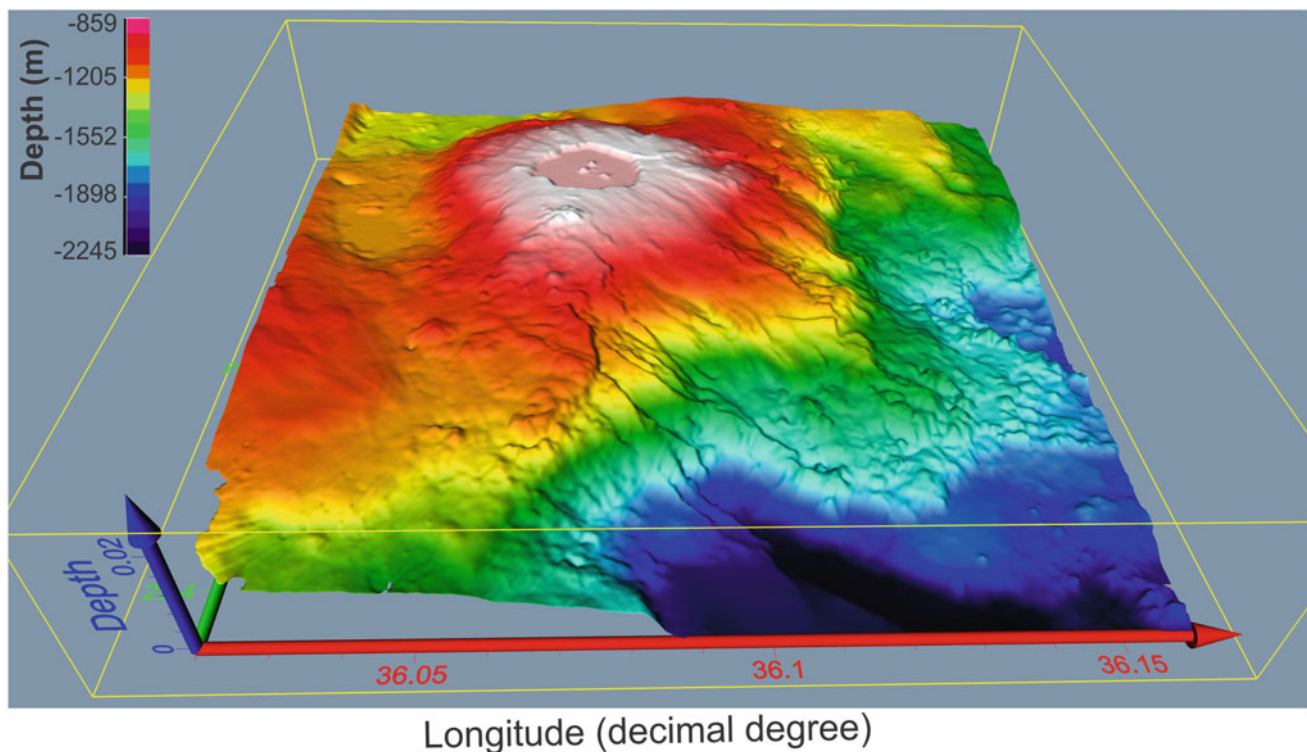
The potential field dataset is an important background to regionally assess the seismic interpretation of the proximal and distal profiles. Several researchers have used the gravity anomaly datasets acquired both onshore and offshore of the Red Sea to constrain the crustal architecture and propose tectonic models for the lithospheric extension that resulted in continental breakup in some parts of the axial trough (e.g., Saleh et al. 2006). Mitchell and Park (2014) have integrated

several geophysical methods and pointed out that refraction data collected east of Thetis Deep might indicate the presence of gabbros underlying the salt layer for a distance of about 65 km outside of the axis in the deep, thus leaving little space for rifted continental crust in the distal margin.

The seismic profile 23 M across the axial trough in the Thetis Deep (Fig. 20) shows that the salt basin only occurs in the elevated regions (with bathymetry less than 750 m), whereas in the bathymetric depression there is an abyss deeper than 1500 m, and there is no evidence of salt accumulation on the newly-formed volcanic basement. The reduced to the pole magnetic anomaly crossplot (Fig. 20-top profile) shows a large anomaly centred at the centre of the axial trough. The protuberant structural high in the internal zone of the abyss is interpreted to correspond to an active spreading ridge (Mitchell et al. 2010; Mohriak and Leroy 2013) that was formed about 2 Mabp (Ligi et al. 2012).

One important question is whether this type of structure, characterized as an embryonic spreading centre within an axial trough, might exist in other places in the South Atlantic salt basin, with implications for timing of the breakup, tectonics, sedimentary facies and petroleum systems in the Brazilian and West African conjugate margins.

Mohriak and Leroy (2013) suggested that the mid-ocean spreading centre in the central Red Sea (Thetis Deep) might



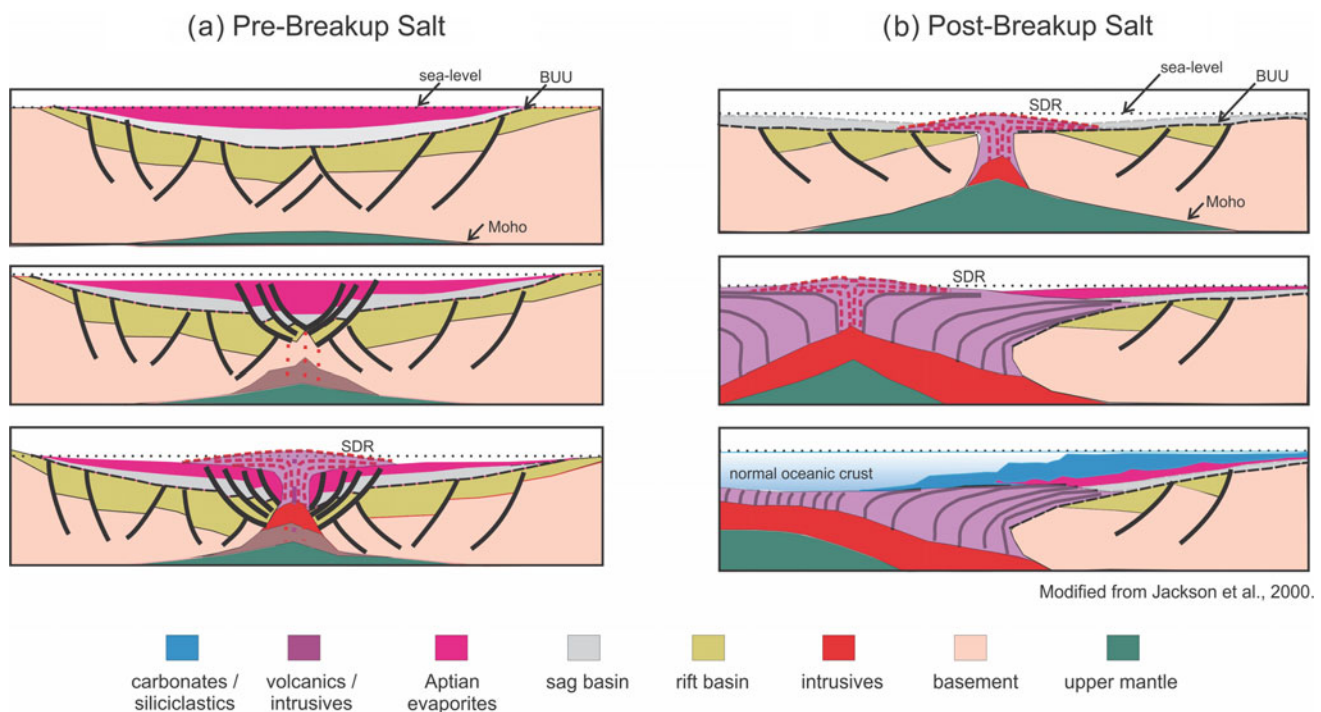
**Fig. 23** Three-dimensional view of the seafloor surface horizon at the northern part of the Mabahiss Deep in the central Red Sea (see location in Fig. 22). This remarkable structure, known as Mabahiss Seamount

(or Mabahiss Mons Volcano) is located at the inferred Red Sea spreading centre (longitude 36.1°E, latitude 25.5°N), south of the distal profile DL (Fig. 14)

be compared with the embryonic spreading centre in the southern Santos Basin (Fig. 21), which is associated with the Abimael propagator in the northern Pelotas Basin (Mohriak 2001). This feature may be interpreted as an igneous intrusion advancing northward, and it was active during and following salt deposition and initial breakup. After impinging on the salt basin, the propagator was aborted when the active spreading centre shifted eastward (Mohriak et al. 2008). The comparison of the seismic profile in the Thetis Deep (Fig. 21a) with the seismic profile in the Santos Basin (Fig. 21b) indicates that in both cases the salt masses pinch-out toward the abyss where the intrusive body is emplaced. In the Santos Basin, the pre-salt rift blocks are highly eroded below the main salt mass, and in the abyss only post-salt sediments are observed covering the volcanic rocks. The Red Sea profile might correspond to an instant photograph of the Santos Basin 10 Ma after salt deposition, with sediments filling up the initial abyss in the proto-oceanic axial trough (Mohriak 2014). If the propagator had not failed to propagate northward, then the residual salt bodies observed in the SE extremity of the Santos Basin profile would belong to the African plate, and oceanic crust would be observed between the two salt basins.

There are some important constraints on the early post-salt sedimentary environments and relative timing of salt deposition and breakup when the seismic data in the Red Sea is analyzed and compared with the South Atlantic salt basins. There is a marked unconformity below a thin veneer of sediments that covers the top of the salt mass (S reflector) that is observed in the Red Sea profile (Fig. 21a), and locally we observe undulating features that suggest mini-basins or internal deformation of the stratified evaporites, indicating early halokinesis. The salt masses in the central Red Sea are separated by newly-formed oceanic crust associated with an active spreading ridge, with possible magma chambers at depth (Ligi et al. 2015). In large areas covered by salt, huge volcanoes might be present, even in regions with subdued gravity and magnetic anomalies, such as in the Mabahiss Deep, which is located west of the proximal profile and south of the distal profile (see location in Fig. 14).

Figure 22 shows a three-dimensional visualization of the topography and bathymetry of the central Red Sea, with the outline of the Mabahiss Deep (light purple colour) and some tectonic elements such as the location of the inferred axial ridges and transform fault zones (Bonatti and Seyler 1987; Guennoc et al. 1990). Guennoc et al. (1990) suggest that the Mabahiss Deep might be associated with a young oceanic



**Fig. 24** Schematic diagrams showing conceptual models for salt deposition in the South Atlantic with two end-member hypotheses: **(a)** pre-breakup salt, with a single salt basin in the marine gulf between the Brazilian and West African margins; extensional tectonics and magmatism resulted in development of seaward-dipping reflectors (SDRs) that post-date the evaporites. Salt extends toward the active

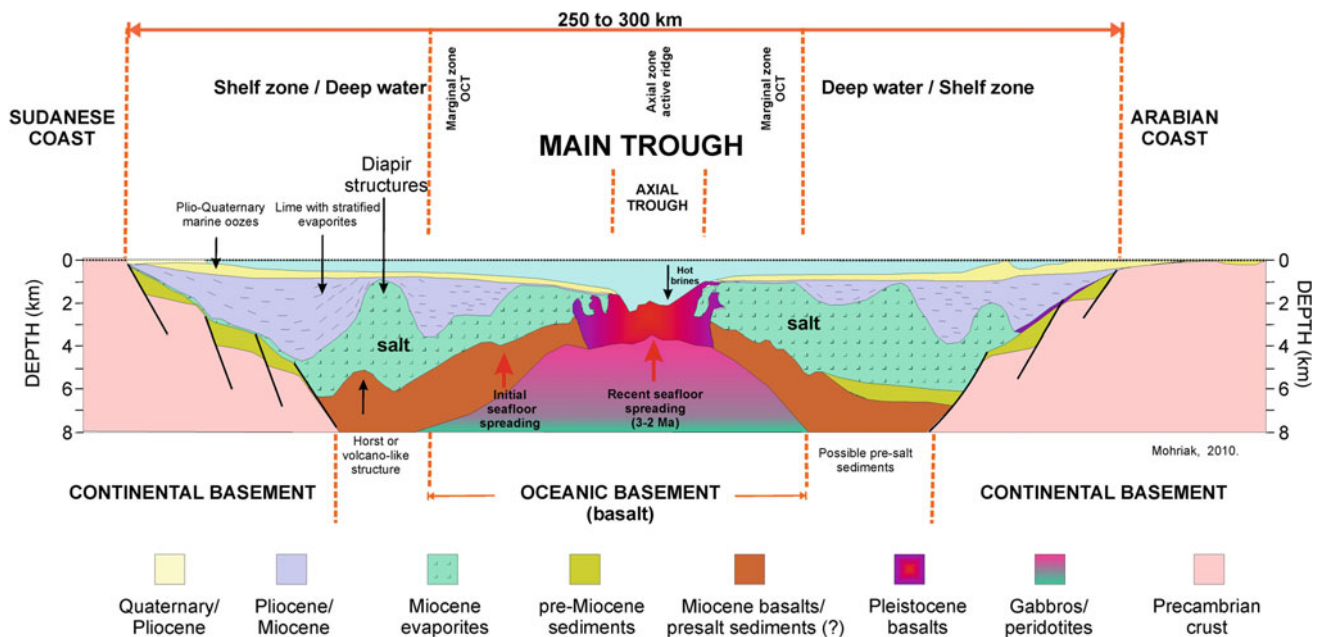
spreading ridges. **(b)** post-breakup salt, with magmatism and SDR following the rift phase but preceding the salt deposition; the SDRs and volcanic buildups constitute a barrier for the salt layer that develops only in one side of the margin, covering rifted continental crust and only part of the volcanic wedges feather edge. Assuming this model, salt does not advance toward normal oceanic crust

rift with an embryonic spreading centre, whereas Ligi et al. (2012) assume this bathymetric depression may be associated with a pull-apart basin floored by basalts, corresponding to the northernmost occurrence of oceanic crust in the Red Sea, formed in a tectonic setting of very slow spreading centres (about 0.5 cm/year).

The Mabahiss Deep is characterized by a large circular edifice at its northern segment, interpreted as a seamount with a pancake dome geomorphology (Fig. 23). This feature is known as the Mabahiss Seamount (or Mabahiss Mons Volcano) and represents one of the largest individual volcanoes in the Afro-Arabian rift system. It has a summit at the depth of about  $-860$  m (Guennoc et al. 1990) and detailed bathymetric surveys indicate a sub-circular crater with small cones inside (Augustin et al. 2016). This structure displays a radius of about 4 km and covers an area of about  $34 \text{ km}^2$ , with an average height of about 260 m above the surrounding seafloor and a conspicuous crater at depths less than 1000 m below sea level. Dredging of the seafloor on the volcano flanks at depths around 1000–1500 m recovered basalts with geochemical affinity with mid-ocean ridges.

The Red Sea distal profile in the central to northern Red Sea (Figs. 14 and 22) shows an incipient stage of plate

separation and is characterized by amalgamation of salt masses that are only beginning to split apart between Egypt and Saudi Arabia, north of the Mabahiss Deep. There are some interesting analogies between the Mabahiss Deep with the alternative interpretations of the Red Sea distal profile discussed previously. The first interpretation (hypothesis 1) assumes rifted continental crust throughout the basin (Fig. 16) and that the reflectors within the distal profile salt layer might correspond to sediments trapped in the suture between two colliding salt sheets. Hypothesis 2 (Fig. 17) assumes that the breakup processes might have already started in the central to northern areas by magmatic intrusions or igneous fingers piercing through the salt layer. This possibility is enhanced by (1) the occurrence of saucer-shaped structures or sills at the SW extremity of the distal profile; (2) the neo-formed volcanic basement in the Mabahiss Deep; (3) the separation of salt masses by active oceanic spreading in the Mabahiss Deep axial trough; and (4) by the large Mabahiss Seamount interpreted as a volcanic structure associated with a mid-ocean ridge at the northern end of the Mabahiss Deep (Guennoc et al. 1990; Augustin et al. 2016).



**Fig. 25** Schematic geological model for the central to southern Red Sea architecture, with syn-rift sediments extending from the coastline toward the platform and deep-water province, covered by a thick salt mass that is allochthonous at the transition from the continental to the oceanic crust. The axial trough is characterized by an embryonic spreading centre with allochthonous salt advancing toward the bathymetric abyss. Below the massive salt in deep water the basement is probably constituted by volcanic rocks. Large volcanoes can be identified in areas with significant salt thickness, and recent volcanic episodes at the main trough also indicate igneous activity associated

with the incipient divergence of the Arabian and African plates. The model also suggests the temporal development of structures from the platform, where the pre-salt sequences (syn-rift sediments) are observed, to the deep-water province, where volcanic basement and seaward-dipping reflectors might be present in the continent-ocean transition. In the distal salt basin, igneous fingers are intruding into the salt mass and eventually an embryonic spreading centre will form and separate the salt basins. Subsequently the spreading ridge will subside and allochthonous salt will advance toward the oceanic crust basement

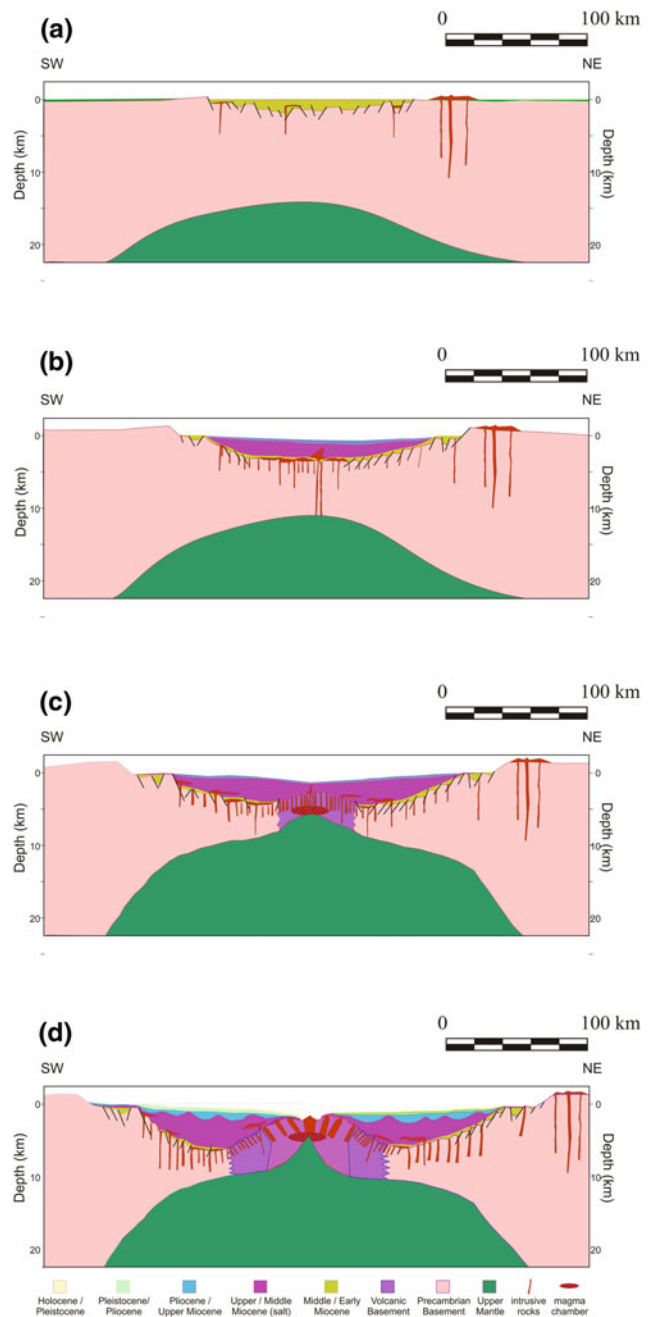
The salt thickness near the axial trough in the area north of the Mabahiss deep is extremely large, about 5–6 km, with the salt being thicker on the Arabian side (Fig. 17). Eventually, the inception of an incipient spreading axis in the central to northern Red Sea will result in allochthonous salt bodies overlying the volcanic basement, as presently observed in the Mabahiss and Thetis deeps (Guenoc et al. 1990; Ligi et al. 2012).

The central to southern Red Sea, south of the Zabargad Fracture Zone (Fig. 14) shows evidence of a more advanced stage in the tectonic evolution, with an active spreading ridge separating the salt masses by newly-formed oceanic crust in the Thetis Deep. The seismic profile across the axial trough (Fig. 21) corresponds to a snapshot 10 Ma after salt deposition, with allochthonous salt bodies split by igneous intrusions and an incipient proto-oceanic crust starting to develop, associated with an embryonic spreading centre formed less than 2 Mybp (Ligi et al. 2012).

Several igneous rocks dredged at the sea floor of the Red Sea deeps indicate volcanic rocks with a tholeiitic composition. Antonini et al. (1998) analyzed the glass and whole rock compositions of basalt samples dredged from the Nereus Deep (Fig. 14) and confirmed their affinity with mid-ocean ridge basalts. Volcanic structures as observed in the Red Sea deeps are not present in magma-poor margins such as the Iberian margin but are commonly associated with magmatic centres in active rift zones such as the East African Rift System, the Afar province and in the axial trough of the southern Red Sea. In 2011–2013, volcanic eruptions related to recent magmatic activity resulted in the birth of two volcanic islands in the Zubair Archipelago offshore Yemen, westward of the coastal village of As-Salif (Xu et al. 2015). In the conjugate margin setting, large volcanoes in the Danakil Depression (as for example the Erta Ale), are presently active, outpouring basaltic lavas through their calderas.

## 6 Rift Development, Salt Deposition and Continental Breakup in the South Atlantic: Analogies with the Red Sea

The interpretation of the salt basin development in the South Atlantic has been discussed by several authors over the past decades. Based on the analysis of geological and geophysical datasets along the West African and Brazilian continental margins, Jackson et al. (2000) in a classical paper that addressed the relationship between rift tectonics, salt deposition and magmatism in the South Atlantic, discussed two end-members models for the evaporites (Fig. 24), whose relative age of deposition might be constrained by the occurrence of seaward-dipping reflectors (SDRs), which were interpreted in the transition from continental to oceanic



**Fig. 26** Schematic geological model for the Red Sea evolution based on observations in the area of the Mabahiss Deep (Guenoc et al. 1990). **a** syn-rift sediments (Early to Middle Miocene) deposited on Precambrian basement, pre-rift sediments or volcanic rocks extruded from about 30 Ma; **b** Magmatic activity started to focus on the incipient spreading centre by Middle to Upper Miocene, when the basin was filled with evaporites, which were initially pierced by igneous fingers; **c** Increased magmatic activity associated with continued extension and thinning of the continental crust formed igneous intrusions and volcanic edifices in the salt basin by Upper Miocene; **d** finally, an embryonic spreading centre started organized spreading by Upper Miocene/Lower Pliocene, resulting in the development of oceanic crust that eventually separated the salt bodies in the conjugate margins. Allochthonous salt has migrated oceanward over volcanic basement highs and advanced toward the abyss where the active spreading centre has developed in the last 5 My

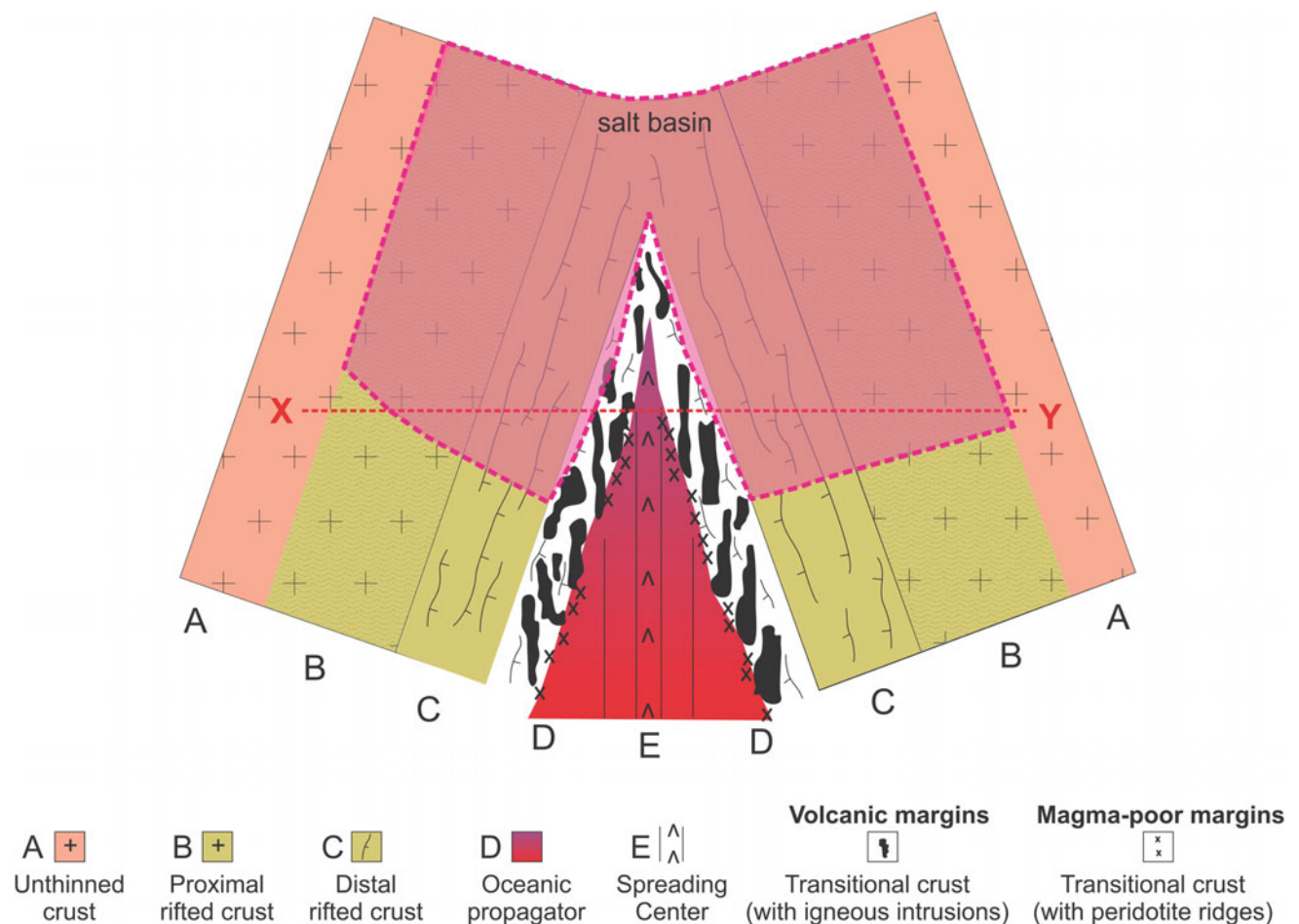
crust and also in the proximal basins along the West African margin.

There are two fundamental currents of interpretation, based on development of salt basins either before or after the breakup that split the conjugate margins (Jackson et al. 2000). The pre-breakup hypothesis (Fig. 24a) assumes that the salt basins were formed almost simultaneously, forming a continuous layer from the Eastern Brazilian to the West African margins. The post-breakup hypothesis (Fig. 24b) assumes these salt basins might have slightly different ages (e.g., Davison 2007; Karner and Gambôa 2007) or were formed completely separated by a spreading centre along the incipient gulf between the conjugate margins (Jackson et al. 2000).

The following themes were thoroughly discussed to test each hypothesis (Jackson et al. 2000): (1) tectono-stratigraphy of salt; (2) tectono-stratigraphy of SDRs; (3) seismic

characterization of the distal margin of salt basins; and (4) the map pattern of salt basins reconstructed for geological ages before the continental breakup and plate separation. These themes were focused on geological information mainly obtained from the African margins, and considering all lines of evidence that contradicted the pre-breakup hypothesis, strongly favouring a post-breakup origin for the Aptian salt basins of the South Atlantic margins, the authors advocated that the African and Brazilian salt basins must have always been separated by the mid-oceanic ridge, and a single salt basin could not have existed.

However, the analysis of the same themes for the Brazilian margin allows the following conclusions for the salt basins: (1) the evaporite layers post-date the main syn-rift phase and extend at least toward the proximal edge of the SDRs at the continental-oceanic crust transition (see for example, Fig. 8);



**Fig. 27** Propagator model with four types of crust representing different stages of breakup in the same ocean. The sectors A, B and C correspond to continental crust affected by increasing extensional factors associated with the rifting process, which in the South Atlantic and Red Sea is followed by salt deposition. A transitional crust between C and D might involve igneous intrusions and extrusions in volcanic margins, or mantle exhumation in magma-poor margins. Salt was

deposited in a single basin across the rifted conjugate margins. Allochthonous salt masses may advance toward the neo-formed volcanic basement region. The oceanic propagators (D–E) are associated with embryonic mid-ocean ridges or spreading centres that will develop oceanic crust splitting the salt basin along the conjugate divergent margins, which in the South Atlantic might correspond to the latest Aptian/earliest Albian

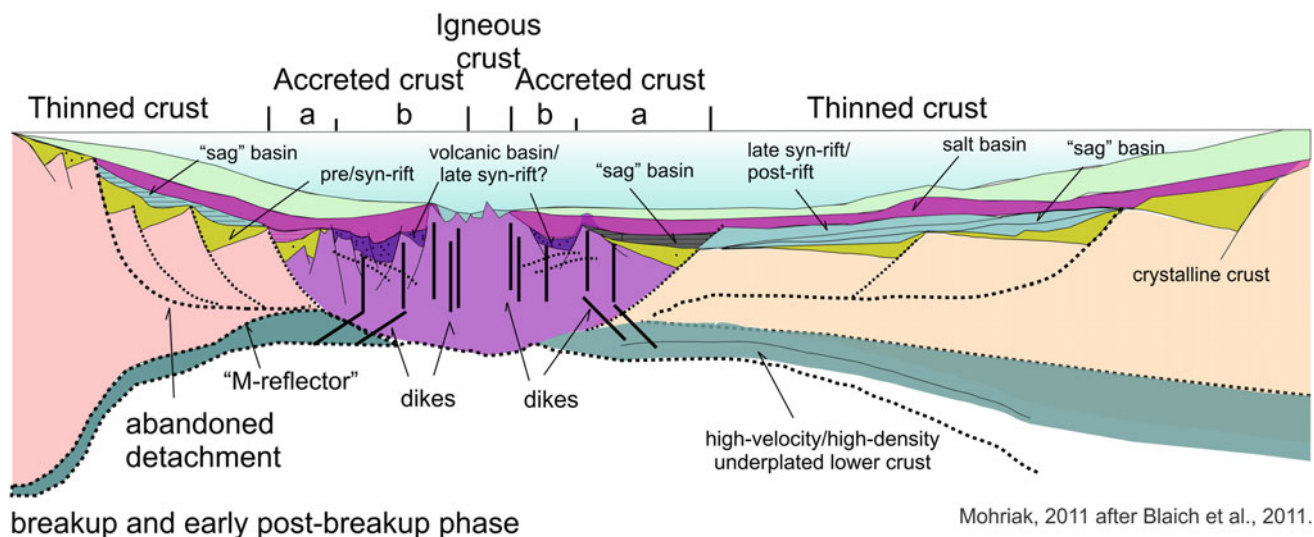
(2) some of the salt is allochthonous at the outermost highs that are located near the continent-ocean boundary (as, for example, the salt that occurs oceanward of the rifted crust in the Campos Basin, Fig. 4); (3) reconstructions of the plates for geological ages older than Aptian indicate that the salt masses may overlap in the distal portions of the conjugate margin basins (Heine et al. 2013), indicating that some of the salt may have advanced toward a volcanic basement, as suggested for the southern Santos Basin (see Fig. 2, with the salt limit oceanward of the volcanic basement limit); and (4) if we assume that the two salt basins imaged in the area of the Abimael propagator were once continuous and split apart by an embryonic spreading centre (Fig. 21b), then the final plate separation actually post-dates both the rift-drift unconformity and the evaporite deposition.

The Red Sea might be an interesting analogue for the interpretation of pre-breakup salt. There are many similarities with the South Atlantic in terms of tectonic events; the syn-rift phase is interpreted below the massive salt deposition, salt extends toward the volcanic basement, and allochthonous salt is presently advancing toward the abyss in the axial trough (Fig. 21). Based on integration of potential field, seismic refraction and reflection data (e.g., Egloff et al. 1991), and constrained by geological information from exploratory wells (Hughes and Johnson 2005), Mohriak and Leroy (2013) proposed a schematic model for the architecture of the central to southern Red Sea (Fig. 25).

This model suggests that the shelf zone and the deep-water provinces are characterized by large salt diapir structures, and the salt layer advances toward the main trough as allochthonous salt masses. Rifted continental crust

with syn-rift sediments is interpreted below the salt at least in the proximal region and in the platform, and basinward, a volcanic basement may be present below the thick salt mass, as indicated by recent interpretations in the southern Red Sea (e.g., Almalki et al. 2014, 2015b). The axial trough may reach bathymetries exceeding 2000 m in the abyss and the salt masses are beginning to be separated by embryonic or active spreading centres associated with an incipient oceanic crust. This model assumes that the igneous intrusions in the axial trough correspond to a present-day spreading ridge formed about 2 Ma, and the volcanic and igneous crust may be about 7 km in thickness. The axial trough is a starved basin, with only a veneer of siliciclastic sediments covering the volcanic basement. Landward of the axial trough the volcanic basement may correspond to highly intruded continental crust or proto-oceanic crust with seaward-dipping reflectors, thus giving an age for the breakup unconformity older than the Miocene evaporites, with thick salt masses overlying the continental-oceanic crust transition in the marginal zone main trough (Mohriak and Leroy 2013).

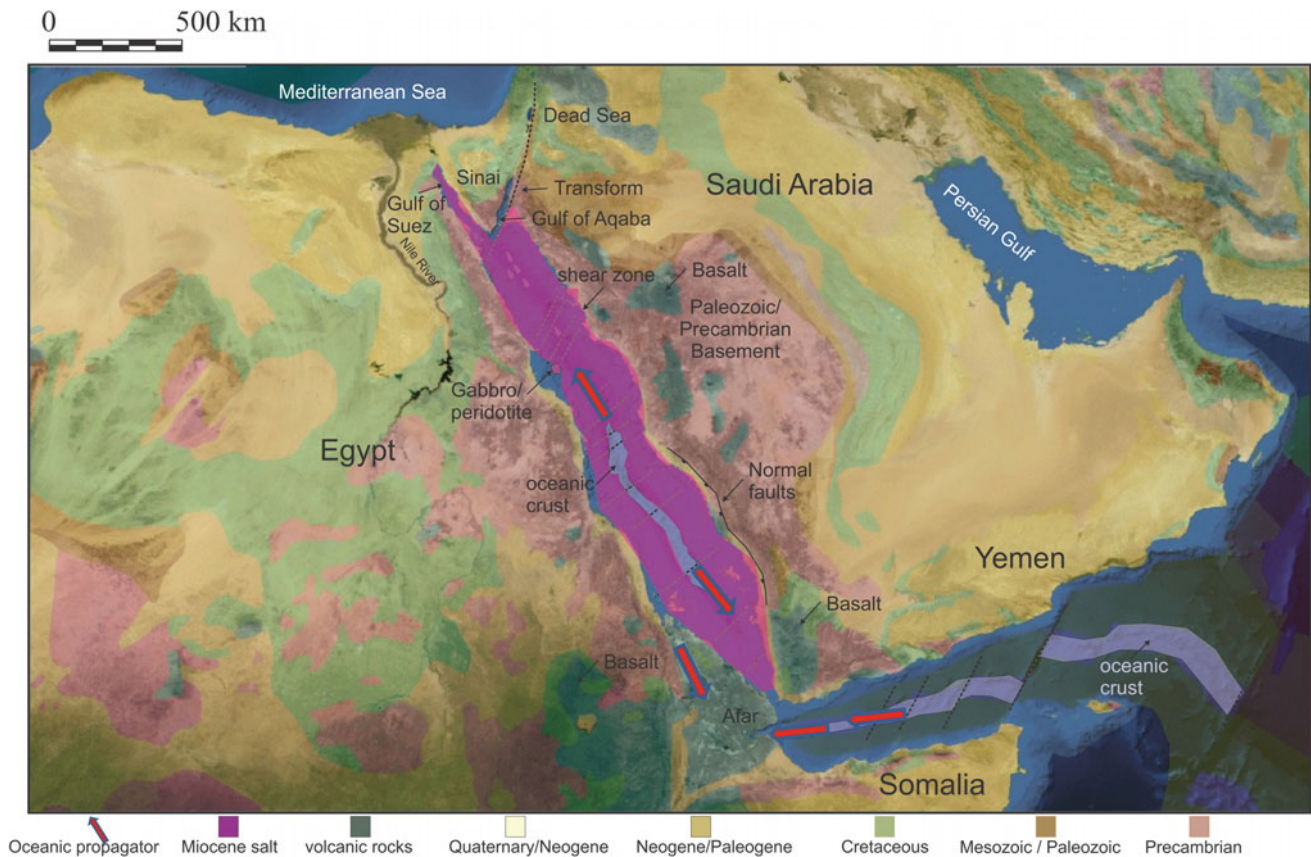
These elements can also be envisaged in the numerical modelling conducted by Allen and Beaumont (2015). In the conceptual model (Fig. 25), the Red Sea is characterized by an onshore rift basin with residual salt covering pre-rift and syn-rift sediments; most of the salt has been mobilized basinward forming large salt diapirs in the platform and in the deep-water region. The deep-water region is characterized by salt layers covering a volcanic basement that rises toward the spreading centre, which is characterized by an abyss in the axial trough. Allochthonous salt is moving toward the abyss



**Fig. 28** Schematic geological transect (line X–Y in Fig. 27) across the South Atlantic Ocean showing an incipient oceanic basin that is similar to the Red Sea present-day stage. The salt basin was formed on sectors B and C. Salt is not deposited on the spreading ridge (sector E), but as

observed in the Red Sea, allochthonous salt may advance toward the abyss where the active spreading centre is observed, and evaporites may occur on the incipiently accreted igneous crust (sectors C and D)





**Fig. 29** Satellite image of the African (Nubian) and Arabian plates with a simplified geological map and schematic distribution of salt in the Red Sea, which is registered along the Egypt, Sudan and Eritrea margins in the western plate, with equivalent evaporites along Saudi Arabia and Yemen. Red arrows indicate the propagation of oceanic rifting both in the Gulf of Aden (with well-developed oceanic crust covered by siliciclastic rocks) and in the southern Red Sea (with embryonic spreading centres and a younger breakup unconformity, with the volcanic basement locally covered by evaporites). A single salt basin is observed in the northern Red Sea, whereas in the southern Red

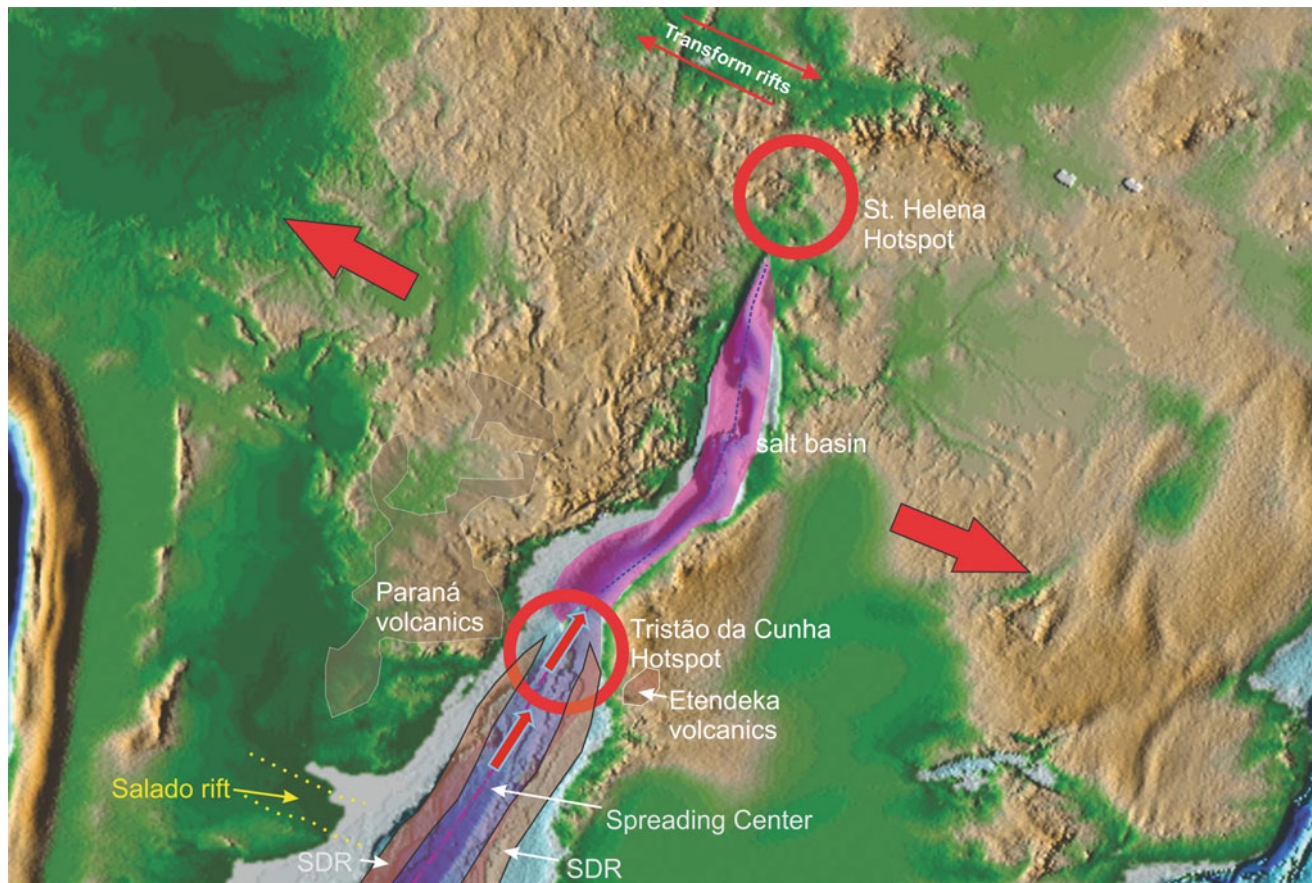
Sea the salt basins have been split apart by the active spreading centre. The salt basin between Africa and Arabia extends for about 2000 km along strike and is limited by the Afar hotspot in the south and by the transform fault at the Gulf of Aqaba in the north. The Gulf of Aden is characterized by older oceanic crust when compared to the Red Sea, and there are no Miocene evaporites in the rift basins along the Somalia–Yemen conjugate margins. North of the Zabargad shear zone there is a limited area of no evaporites in the northern part of the Mabahiss Deep, suggesting an incipient spreading centre with volcanic basement separating the salt masses

and is advancing above a volcanic basement adjacent to the present-day spreading centre. In the numerical model (Allen and Beaumont 2015), salt was deposited in a late syn-rift phase, and the salt mobilization resulted in salt flow toward the spreading centre, with allochthonous salt extending over previously formed oceanic crust.

The Mabahiss Deep has been characterized as the northernmost segment of neo-formed oceanic basement in the central to northern Red Sea (Bonatti and Seyler 1987; Guennoc et al. 1990). The distal profile (Fig. 17) suggested initial piercing of the salt basin by igneous structures forming northward of the Mabahiss Deep. The sequence of events presented as schematic diagrams for the Red Sea evolution (Fig. 26) illustrates a possible mechanism of piercing the salt layer by igneous intrusions and

subsequently splitting the margins as an embryonic spreading centre formed southward of the Mabahiss Seamount.

The conceptual model for the breakup process assuming the propagator model (Fig. 27) suggests that as we see today in the Red Sea, a single salt basin might have existed in the South Atlantic by Late Aptian times. The salt basin might have been locally split by oceanic propagators as we observe in the southern Santos Basin, where portions of the salt are separated by newly-formed volcanic basement (Mohriak 2014). The breakup unconformity, which could arguably be associated with the first inception of oceanic crust, predates the salt deposition, thus it was initially formed in other parts of the elongated gulf that extended from offshore southern Brazil to Argentina, where the rifting process was in a more advanced stage of evolution, as indicated by older magnetic



**Fig. 30** Palinspastic reconstruction of the South Atlantic about 120 Ma (Scotese 2002), or probably at the transition from Aptian to Albian about 112 Ma, with schematic distribution of the salt basins and volcanic margins between Brazil and West Africa. Large arrows in South America and West Africa indicate the extensional stresses in the continental crust affecting the Santos, Campos, Espírito Santo and Bahia State Basins in Brazil, and the Namibia, Angola and Gabon conjugate divergent margins. The northern South Atlantic was affected by the Central Atlantic transtensional shear zone that evolved to the transform continental margins after continental breakup in the Albian, with no widespread evaporite deposition in the Late Aptian. The northern limit of the Late Aptian salt basin (magenta colour) is

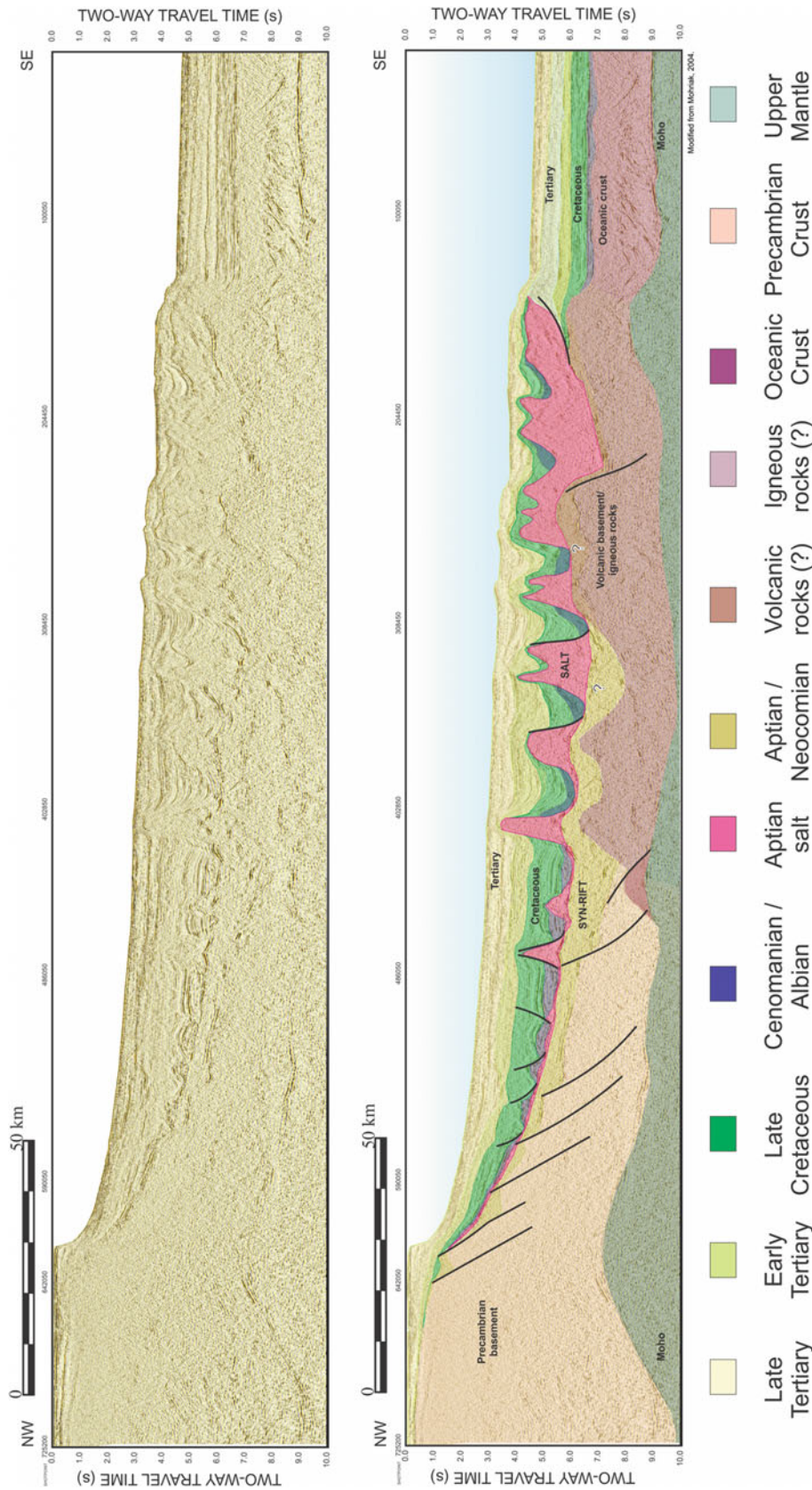
characterized by the transform rifts north of the St. Helena hotspot. The salt basin extends for about 2000 km along strike and is limited to the south by the Tristão da Cunha hotspot and the Florianópolis fracture zone at the southern Santos Basin. The southern South Atlantic is characterized by Early Cretaceous tholeiitic lava flows onshore (Paraná Basin volcanics of the Serra Geral Fm. and Etendeka basalts in Namibia). Offshore these volcanic margins are characterized by seaward-dipping wedges and active oceanic spreading centres that resulted in older oceanic crust and no evaporite deposition in the conjugate margins. Red arrows in the marine gulf between South America and Africa indicate the propagation of oceanic rifting from Argentina toward the Brazilian margin

anomalies and tectonic reconstructions (e.g., Moulin et al. 2010).

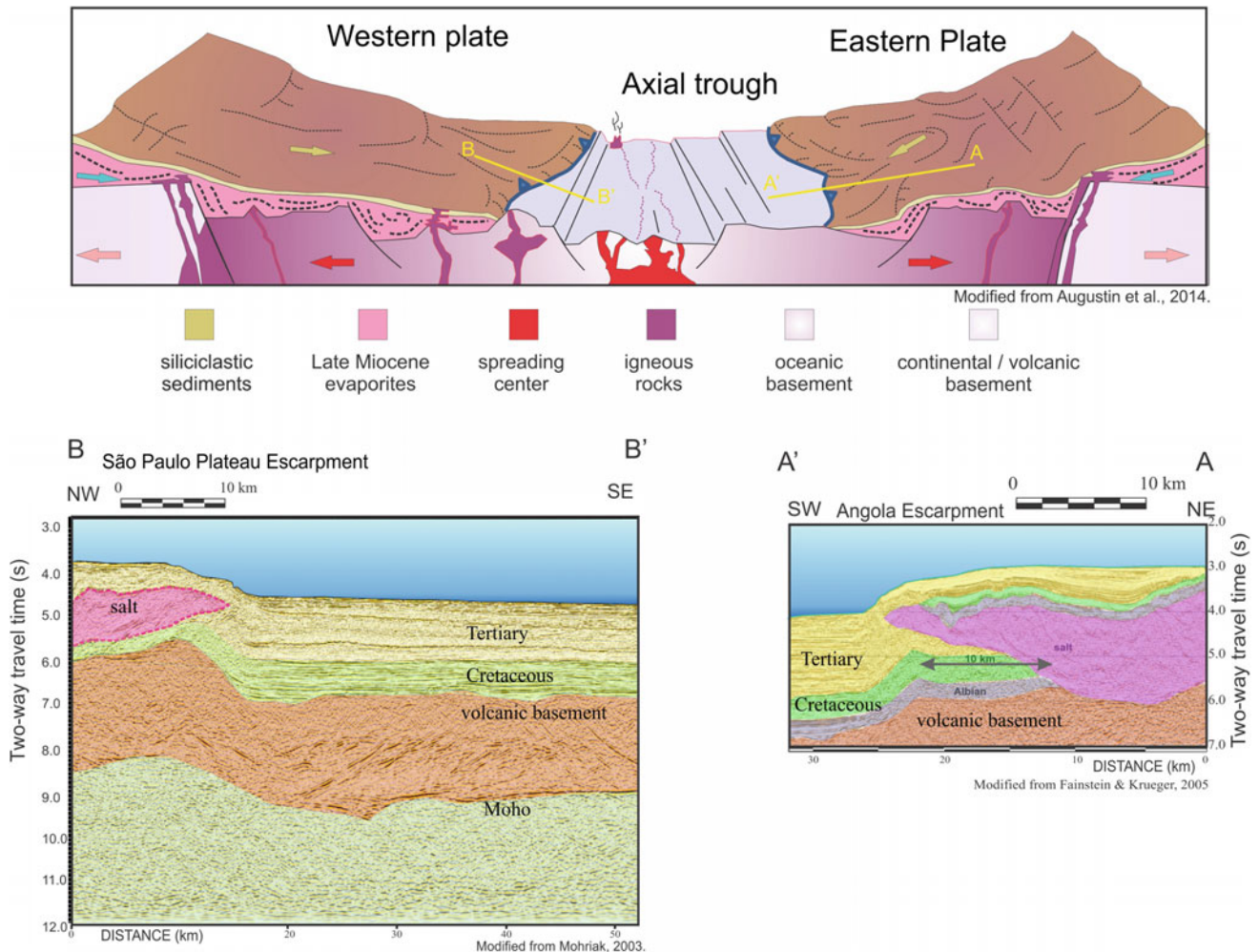
The diachronous nature of the breakup might be envisaged as a propagator advancing from areas with oceanic crust to areas with continental crust still in the rifting process (Fig. 27). The areal distribution of the rocks in this model suggests four types of crust: In the basement region adjacent to the rifted margins the crust has not been thinned (sector A in Fig. 27); the rifted continental crust in the proximal basins might be characterized by shallow lakes and continental sediments (sector B); the distal rifted continental crust might be associated with a gulf that was periodically affected by marine incursions, and basin desiccation resulted in deposition of evaporites overlying syn-rift lacustrine sediments

(sectors B to C); and the distal margin might be associated with mantle exhumation in magma-poor margins such as in Iberia or to a volcanic basement in a transitional crust in magma-rich margins such as in the South Atlantic (sector D). Spreading centres would be formed in different episodes during the rifting process that led to the continental breakup and formation of oceanic crust. The oceanic ridges might start with igneous fingers that pierced through the pre-breakup rift and salt sequence, and subsequently split the salt basin, forming conjugate divergent margins, as observed in the central Red Sea.

Figure 28 schematically shows a cross-section for the South Atlantic at the transition from the gulf to the open ocean stage of the Wilson cycle, showing the distribution of



**Fig. 31** Regional deep seismic profile in the Espírito Santo basin, offshore Brazil (seismic line ES1, Fig. 2), located south of the Abruolhos Volcanic Complex. Top: Uninterpreted seismic line; bottom: Geoseismic profile with a simplified interpretation (based on Mohriak 2003 and Mohriak et al. 2008). A residual salt layer is present in the narrow platform and in the proximal deep-water region. Salt mobilization resulted in large diapirs in the ultradeep-water province, and allochthonous salt is observed overriding a structural high, advancing toward the oceanic crust, forming a bathymetric escarpment. The massive salt walls basinward of the structural high are here interpreted to overlie a volcanic basement, associated with transitional crust highly intruded by igneous rocks, although other interpretations (e.g., Zalán et al. 2011) suggest it might correspond to exhumed mantle rocks (serpentinized peridotites). The oceanic crust at the SE extremity of the profile is clearly marked by a strong Moho reflector at 9.0 s TWT



**Fig. 32** Top: Schematic model of the Red Sea salt basins with allochthonous masses advancing toward the abyss in the axial trough along thrust faults, overriding volcanic basement highs (Augustin et al. 2014). The Western Plate (Nubian plate in the Red Sea, or South American plate in the South Atlantic reconstruction) may be characterized by an active spreading centre separating the conjugate margin salt basin formed on the Eastern Plate (Arabian plate, or African plate in the South Atlantic reconstruction). Sections B–B' and A'–A in the

upper diagram correspond to the approximate location of seismic profiles along the Brazilian and West African margins. Bottom: Seismic profiles showing a present-day snapshot of the allochthonous salt tongues along the Espírito Santo Basin in Brazil (line B–B', corresponding to distal extremity of profile ES1, see location in Fig. 2 and regional profile in Fig. 31) and Kwanza Basin in West Africa (line A–A'). The distal salt tongue formed bathymetric escarpments in the São Paulo Plateau (left) and offshore Angola (right)

the evaporites and the rift structures in the conjugate margins that were separated by incipient spreading centres and volcanic crust around Aptian–Albian times. The two salt basins are separated by an incipient oceanic basin developed after the Early Cretaceous rifting that resulted in proximal and distal basins (Fig. 28, sectors B and C). Similar to the Red Sea, the model suggests that the evaporites in the distal margin might be advancing toward the embryonic spreading centre and covering a substratum associated with a late syn-rift sedimentation or volcanic basement characterized by SDRs, as recently suggested by Norton et al. (2016). Thus, the distal salt basin might overlie a transitional crust with igneous rocks accreted during the breakup process by Late Aptian times (Fig. 28, sectors C and D). The schematic

transect, based on gravity modelling and seismic interpretation (Blaich et al. 2011; Mohriak and Leroy 2013), indicates that the salt basin extends from sectors B to C and may advance toward sector D as allochthonous salt masses (Fig. 28, sectors C and D), overlying volcanic rocks associated with inception of the active spreading centre that eventually separated the salt basins in the conjugate margins (Fig. 28, sector E, cf. Figure 27).

The salt distribution in the Red Sea is thus characterized by a single salt basin in the north, probably overlying a transitional crust highly intruded by igneous rocks, and by two salt basins in areas where the breakup processes resulted in splitting the salt masses apart (as in the southern Red Sea and more incipiently in the Mabahiss Deep). In these

regions, the axial trough is an abyss with no evaporites, and newly-formed volcanic basement is observed in the regions adjacent to the spreading ridges (Fig. 29). The oceanic propagators that are well developed in regions with oceanic crust might advance toward triple junctions (e.g., Afar) or toward fracture zones (e.g., Zabargad Shear Zone).

In the South Atlantic, the salt distribution is characterized by tectonic limits similar to the Red Sea, involving hotspots and transform fault zones (Mohriak 2014). Several researchers assume that the Tristan da Cunha plume may be associated with the Early Cretaceous flood basalts (Serra Geral Fm. in the Paraná Basin, and Etendeka volcanics in Namibia). Tholeiitic basalts have also been drilled in most wells that penetrated the rift sequences offshore SE Brazil and Namibia, and the Ar–Ar ages for these igneous rocks indicate ages similar to the Paraná–Etendeka lava flows, around  $130 \pm 3$  Ma (Almeida et al. 2013), thus they pre-date the development of the rift basins in the continental margins (Almeida et al. 2013).

The plate tectonic reconstruction of the South Atlantic at the gulf stage (Fig. 30) shows the location of the volcanic margins south of the Tristan da Cunha hotspot, which are characterized by seaward-dipping reflector wedges in the transition zone from continental to oceanic crust (Mello et al. 2013). The southern segment of the South Atlantic (Austral Segment) is interpreted to have opened between anomalies M13 and M4 (139.5 and 130 Ma, respectively) whereas the oceanic spreading in the central segment is believed to have started more than 18 Ma later, at the end of evaporite deposition (Moulin et al. 2010). The southern segment is also characterized by onshore-offshore rift basins in Argentina, dated as Jurassic to Early Cretaceous, with axes that trend oblique to the continental margin (e.g., Salado Basin in Fig. 30). There was no significant deposition of evaporites in the volcanic margins or in the onshore rifts south of the Tristan da Cunha hotspot, which may have acted as a volcanic barrier isolating the Santos Basin from the southern volcanic margin basins (Hinz et al. 1999; Mohriak 2001). A similar role can be envisaged for the Afar plume, which separates the Red Sea from the Gulf of Aden. The salt basins between the eastern Brazilian and West African margins overlie the Early Cretaceous syn-rift succession (Neocomian to Barremian) and also the Aptian sag basin, and might be dated as Late Aptian (around 112–115 Ma), although some authors suggest slightly different ages for the evaporites in Brazil and Africa (e.g., Davison 2007; Karner and Gambôa 2007).

The ages for the main tectonic events presented here differ slightly from other reconstructions of the South Atlantic, as for example Scotese (2002) assumes salt deposition at 120 Ma, and Heine et al. (2013) assume that by 115 Ma the salt basins were already separated by an active spreading centre. In this work, we envisage the final

separation only after salt deposition (which probably ended with the marine incursions in the earliest Albian, probably slightly younger than 112 Ma). Most explorationists working in the Brazilian margins envisage the breakup unconformity at the top of the syn-rift tilted blocks, overlain by late syn-rift or sag basin sediments, thus predating the sag and salt deposition (e.g., Winter et al. 2007). This rift-drift unconformity in the Brazilian margin might be related to the inception of oceanic crust in the Austral Segment of the continental margin, considering that the age of the first oceanic crust varied progressively from south to north as indicated by magnetic anomalies, flow lines and tectonic reconstructions (Moulin et al. 2010). However, the final separation between the plates with the salt basins occurred only after salt deposition, as indicated by the aborted spreading centre in the southern Santos Basin, pointing to an age of Late Aptian–Early Albian for final splitting of the Santos-Campos and Kwanza conjugate basins. This corroborates the assumption that the breakup is diachronous and may occur in some parts of the basin coeval with active rifting processes in other parts of the continental margin.

Figure 31 shows a regional deep seismic profile in the Espírito Santo Basin, south of the Abrolhos Volcanic Complex (see location in Fig. 2). The seismic line extends from the continental crust in the platform toward the oceanic crust beyond the salt limit. A conspicuous structural high is observed in the ultradeep-water region, and although there are interpretations of exhumed mantle at this position, the integration with potential field data suggests it corresponds to a volcanic basement high, probably formed around the breakup time, after the rift phase (Mohriak et al. 2008).

In the Espírito Santo profile (Fig. 31), the tectonic processes that led to the development of conjugate divergent margins are much more advanced than in the Red Sea. Figure 32 shows the schematic model of the distal part of the Red Sea salt basin (Augustin et al. 2014) compared with seismic profiles in the distal parts of the South Atlantic salt basins. The Red Sea model corresponds to an analogue of the South Atlantic salt basins at the transition from Aptian to Albian about 112 Ma, and the conjugate margins at present are characterized by allochthonous salt tongues advancing toward oceanic crust (Mohriak 2014). In the South Atlantic, the allochthonous salt bodies have advanced basinward of the basement or volcanic high and are now forming salt tongues that are migrating toward the oceanic crust, resulting in a bathymetric escarpment that is rather similar to the Sigsbee Escarpment in the Gulf of Mexico (Fainstein and Krueger 2005). The salt body at the SE extremity of the Espírito Santo Basin profile (Fig. 32, bottom left) has a thickness of about 3 km. The oceanic crust beyond the salt tongue has a thickness of about 7 km and overlies the oceanic Moho, which is clearly imaged at a depth of about 14 km. This seismic profile corresponds to a snapshot of a

salt basin 115 Ma after salt deposition, with allochthonous salt advancing toward the oldest oceanic crust. The salt tongue in the Angolan margin (Fig. 32, bottom right) might transport Cretaceous strata in a piggy-back style, with about 10 km of Albian to Maastrichtian sequences overlapping above the volcanic basement.

These analogies provide important clues on how salt basins in the South Atlantic might have evolved through time. At present, the allochthonous salt front in Brazil is more than 4000 km from its conjugate margin salt front in the Kwanza Basin, which suggests that salt advanced toward an oceanic crust basement that was formed by the Late Aptian—Early Albian (Mohriak et al. 2008). The tectonic processes are much more advanced in the South Atlantic than in the Red Sea, where only a portion of the salt masses have been split by incipient oceanic spreading in the last 2–3 Ma (Ligi et al. 2012).

## 7 Conclusions

Several changes in the interpretation of the South Atlantic salt basins have been discussed in the last 20 years as a result of intensive exploratory work in the distal margins of these prolific basins. These changes in paradigms and search of new interpretations based on analogies with magma-poor margins include: (1) the lack of thick syn-rift depocentres in ultradeep-water distal sedimentary provinces; (2) the presence of important carbonate (microbialite) reservoirs in the pre-salt sequence; (3) the questionable proposal of exhumed mantle in the transition from continental to oceanic crust; and (4) the characterization of different styles of salt tectonics associated with extensional and compressional events, including the presence of allochthonous salt tongues in the transition from continental to oceanic crust.

The Iberian model of mantle exhumation, which recently has been extensively applied for the Brazilian and West African basins (Péron-Pinvidic et al. 2013), shows many important differences in tectonic context and stratigraphy from the South Atlantic margins (see Mohriak and Leroy 2013—Table 1). The Iberian model assumes that the separation of extending continental crust is achieved by detachment faults that expose large stretches of mantle peridotites before an oceanic spreading centre is formed. This occurs in areas where volcanic activity is negligible both before the rift and during breakup. This is not the case of the Red Sea during the Neogene and Quaternary periods, which are marked by magmatic activity during the rift and early drift phases. Volcanic rocks related to the rifting process are observed both onshore (for example, in Saudi Arabia and Yemen, and in the Afar province) and offshore (for example, in volcanic islands recently formed near the southern Red Sea axial trough, or as volcanic structures partially covered

by salt in the central to northern Red Sea, for example, in the Mabahiss Deep). Volcanic structures such as wedges of seaward-dipping reflectors, volcanoes and hydrothermal vents have also been characterized in the South Atlantic during the Early Cretaceous rift phase and in the early drift phase.

The Red Sea basins can be considered better analogues for the continental breakup that occurred in the South Atlantic by the Late Aptian—Early Albian, after the magmatic episode that formed the Paraná-Etendeka large igneous province (LIP) and the extensional stresses that formed continental lakes in the rifted margins. Similar to the Gulf of Aden–Red Sea system, the South Atlantic is marked by two major sedimentary provinces, which are separated by the Tristan da Cunha mantle plume. The volcanic rocks of the Paraná-Etendeka LIP may correspond to the initial impact of a mantle plume in the continental crust, and thus are similar to the pre-rift volcanism in the Afar region, between the Red Sea and the Gulf of Aden. The region north of the Tristan da Cunha hotspot is characterized by major salt basins that are extremely prolific in hydrocarbons, and the basins south of the hotspot (Pelotas Basin in southern Brazil, and the basins offshore Uruguay and Argentina), are characterized by large igneous provinces both onshore and offshore, with development of large wedges of seaward-dipping reflectors, with minor oil production both in South America and in Africa. Syn-rift magmatic activity resulting in formation of volcanic basement and large volcanoes is registered both in the Red Sea (as in the Mabahiss Deep) and in the South Atlantic salt basins. Several exploratory wells in the Campos and Santos basins have sampled volcanic rocks in the syn-rift and pre-rift sequences, and seismic interpretation suggests the presence of volcanic layers (even forming incipient wedges of SDRs) or magmatic structures such as saucer-shaped sills and hydrothermal vents.

The analysis of industry and academic seismic profiles in the Red Sea indicates that the known distributions of volcanic structures onshore and offshore are associated with development of an incipient divergent margin, with an axial trough locally characterized by embryonic active spreading centres that correspond with volcanic rocks (tholeiitic basalts). These features have been imaged in the central Red Sea and can be compared to the aborted spreading centres in the South Atlantic salt basins, particularly to the Abimael Ridge in the southern Santos Basin, which apparently propagated from the Pelotas Basin toward the southern Santos Basin, but failed to develop an active and successful spreading ridge that would split the South American and African plates at the western tip of the Florianópolis Fracture Zone. This feature penetrated the southern Santos salt basin and constitutes an important element to calibrate the relative ages of rifting, salt deposition and continental breakup. It is interpreted as an igneous intrusion associated with seaward-dipping reflector wedges in the Pelotas Basin. The

Moho rises rapidly basinward of the salt limit in the deep-water region of the southern Santos Basin, but there is no clear mantle exhumation or salt deposition in the region of the oceanic propagator.

Two end-member hypotheses for salt deposition in the South Atlantic have been discussed; one (A) that assumes that salt was deposited before, and (B) the other after continental breakup. Jackson et al. (2000) discarded hypothesis (A) and favored hypothesis (B), suggesting that the salt basins in the South Atlantic have always been separated by a spreading centre formed before salt deposition, and the salt layer does not extend toward the normal oceanic crust. Using the Red Sea as a present-day analogue, this work suggests that hypothesis (A) may be observed in some parts of the central Red Sea, with spreading ridges splitting a single salt basin and forming conjugate margins with evaporites separated by newly-formed oceanic crust. The breakup unconformity, however, may be interpreted as older than the evaporites, assuming a diachronous propagation of the oceanic rifting. This interpretation would imply that the evaporites advanced over a volcanic basement developed before the formation of the active spreading centres that are splitting the salt layer in regions such as the Mabahiss Deep or the Thetis Deep.

Assuming the model based on the Red Sea observations, the South Atlantic salt basin was split after salt deposition by igneous intrusions and embryonic spreading centres that propagated from regions with oceanic crust already formed (as for example, offshore Argentina). Salt migrated toward the newly formed oceanic crust axial troughs after initial halokinesis, forming allochthonous salt tongues overlying volcanic basement. Oceanic propagators in the South Atlantic and in the Red Sea advanced from oceanic crust toward a mantle plume thermal anomaly and transform fault zones, and the breakup is diachronous along the length of the continental margins. These tectonic models have important implications for understanding the petroleum systems that may be active in the early stages of basin development, particularly for the evaluation of pre-salt stratigraphic successions, source rock and reservoir distribution.

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