Birth and Development of Continental Margin Basins: Analogies from the South Atlantic, North Atlantic, and the Red Sea*

Webster Mohriak[1]

Search and Discovery Article #41502 (2014)
Posted December 22, 2014

*Adapted from 2013-2014 AAPG Foundation Distinguished Lecture.

[1]UERJ - State University of Rio de Janeiro, Rio de Janeiro – Brazil (webmohr@gmail.com)

Abstract

The results of regional deep seismic acquisition in the South Atlantic continental margins have shed new light on the birth and development of sedimentary basins formed during the Gondwana breakup. Recent models of mantle exhumation (as observed in the deep-water Iberian margin) have been applied extensively to the interpretation of several basins in the Eastern Brazilian and West African conjugate margins. However, the tectonic development of these basins is markedly different from the magma-poor margins. In this article, I emphasize the contrasts from the tectono-sedimentary features imaged in deep-penetrating seismic profiles that extend from the platform towards the oceanic crust. These features indicate that the Red Sea constitutes a better analogue for the birth of divergent continental margins.

This article also emphasizes the differences in basins developed along conjugate margins in the South Atlantic. Integration of geological and geophysical methods reveals widespread volcanism in the southernmost segment (Pelotas – Santos basins in Brazil and Namibia in West Africa), probably related to mantle thermal anomalies. The lack of volcanic features in local portions of the margins, particularly in the shallow-water platform regions (e.g., Camamu-Almada and Sergipe-Alagoas basins in northeast Brazil), points that even in these regions the continent-ocean boundary shows evidence of mantle melts and formation of wedges of seaward-dipping reflectors, as in the Jacuípe Basin.

The central segment of the South Atlantic, from Espirito Santo to Santos basins in Brazil, and from Gabon to Angola in West Africa, is characterized by a major salt basin developed from the first marine ingressions in late Aptian. Salt tectonics is responsible for most of the exploratory plays along the margins, with autochthonous and allochthonous salt structures associated with existing and conceptual petroleum accumulations.

An overview of the geological concepts that evolved rapidly during the last three decades emphasizes the challenges of petroleum exploration in ultradeep water provinces of divergent continental margins. This article also shares with the scientific community the methods and results from the application of modern geological and geophysical tools that help in the interpretation of the crustal architecture, rift structures and the salt tectonic elements that are crucial to basin-analysis studies.

Motivation

- The Red Sea is a natural laboratory for continental breakup processes at an embryonic stage, whereas the North and South Atlantic oceans correspond to more developed divergent margins with tectonic plates in advanced stages of drifting.
- Several exploratory plays in the South Atlantic have analogs in the sedimentary basins across conjugate margins (Brazil - West Africa), including
- pre-salt and post-salt reservoirs.
- Risk analysis of petroleum exploration plays involve evaluation of rift architecture and salt tectonics.

Introduction

This work presents an overview of the rift architecture of the South Atlantic and North Atlantic margins and compares their geological evolution with the Red Sea and Gulf of Aden sedimentary basins, from the onshore area towards the offshore distal margin and oceanic crust (Figure 1). Understanding the differences and similarities between the South Atlantic, North Atlantic, and the Red Sea – Gulf of Aden sedimentary basins and their tectonic controls bears important implications for tectonic models and petroleum systems that are active in the early stages of development of rifted continental margins.

Risk analysis of petroleum exploration plays involves evaluation of rift architecture and salt tectonics development through time. Several exploratory plays in the South Atlantic sedimentary basins have clear analogues in the conjugate margins between Brazil and West Africa, including pre-salt microbialites and post-salt turbidite reservoirs. The largest oil fields discovered in the southern hemisphere in the past decade (2000s) are characterized by carbonate microbialites as the main reservoir, with thick evaporite layers forming seals for the traps (Tupi and Iara fields in the Santos Basin). This play type is very similar to the largest discovery worldwide in the past decade, the Kashagan Field in the North Caspian Sea (Figure 2).

The Red Sea 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 (North America – NW Africa margins). Regional deep seismic profiles have been extensively acquired in the North and South Atlantic continental margins in the past decade, particularly along the Brazilian and West African margins (Figure 3). 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. The recent discovery of deep-water pre-salt reservoirs in the South Atlantic salt basins has raised some academic and industry interest in the Red Sea and Gulf of Aden sedimentary basins as analogues for the early evolution of the continental margins.

Since the development of early plate tectonic concepts, this region has been considered as a paradigm for the evolution of continental rift basins that evolved into incipient divergent margins through a gulf stage. The Red Sea is a natural laboratory for continental breakup processes at an embryonic stage of the Wilson cycle, whereas the North and South Atlantic oceans correspond to a more developed system of divergent-margin basins with tectonic plates in advanced stages of drifting (Mohriak and Leroy, 2013).

South Atlantic and North Atlantic Tectonic Models

The rifted continental margins in the South Atlantic (Figure 3) are characterized by several Mesozoic rifts that extend from onshore to offshore Brazil, Uruguay, and Argentina. The Santos, Campos and Espírito Santo basins are the most prolific offshore Brazil basins, with reservoirs ranging in age from Miocene to Early Cretaceous (Rangel and Martins, 1998). These basins are characterized by a thick Late Aptian salt layer that is also observed in the conjugate margin basins offshore of Angola and Gabon (Mohriak and Fainstein, 2012).

The tectono-stratigraphy of these basins is illustrated by a schematic (but insightful) geological section in the Campos Basin, which shows the main stratigraphic sequences (synrift, transitional, and drift) as well as the structural style and petroleum systems (Figure 4). Several changes in the interpretation of this basin have been discussed in the last 20 years, including: the lack of thick depocenters of synrift strata in ultradeep waters, the presence of important carbonate (microbialite) reservoirs in the pre-salt sequence, the possibility of exhumed mantle in the transition to oceanic crust, and different styles of salt tectonics associated with compression and the presence of allochthonous salt tongues (Mohriak et al., 2008; Mohriak et al., 2012).

Several authors have proposed a model for the North 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; Perón-Pinvidic and Manatschal, 2008). A transect based on reconstruction of regional deep seismic profiles (Figure 5) indicates that in these magma-poor basins the 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, 2013).

A direct but questionable application of the Iberian model for the South Atlantic margins (Figure 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 peridotite rocks. The exhumed mantle in the outer high was divided into zones of different densities (degrees of serpentinization) to fit the measured and modeled gravity data (Zalán et al., 2011). This interpretation suggests that the outer high and also the Florianópolis Fracture Zone are characterized by exhumed mantle, as well as the propagator that has been postulated to advance from the northern Pelotas Basin towards the southern Santos Basin (Mohriak, 2001).

The Iberian model shows many important differences in tectonic context and stratigraphy from the South Atlantic margins (Mohriak and Leroy, 2013). The Red Sea and Gulf of Aden can be considered better analogs for the continental breakup that occurred in the South Atlantic by the late Aptian – early Albian, which was probably marked by two major sedimentary provinces: one north of the Tristão da Cunha hotspot, marked by a major salt basin, and one south of the hotspot (Pelotas Basin in southern Brazil, and the basins offshore Uruguay and Argentina) which are marked by large igneous provinces both onshore and offshore, with volcanic rocks of the Paraná-Etendeka province similar to the volcanism in the Afar region, between the Red Sea and the Gulf of Aden (Figure 7).

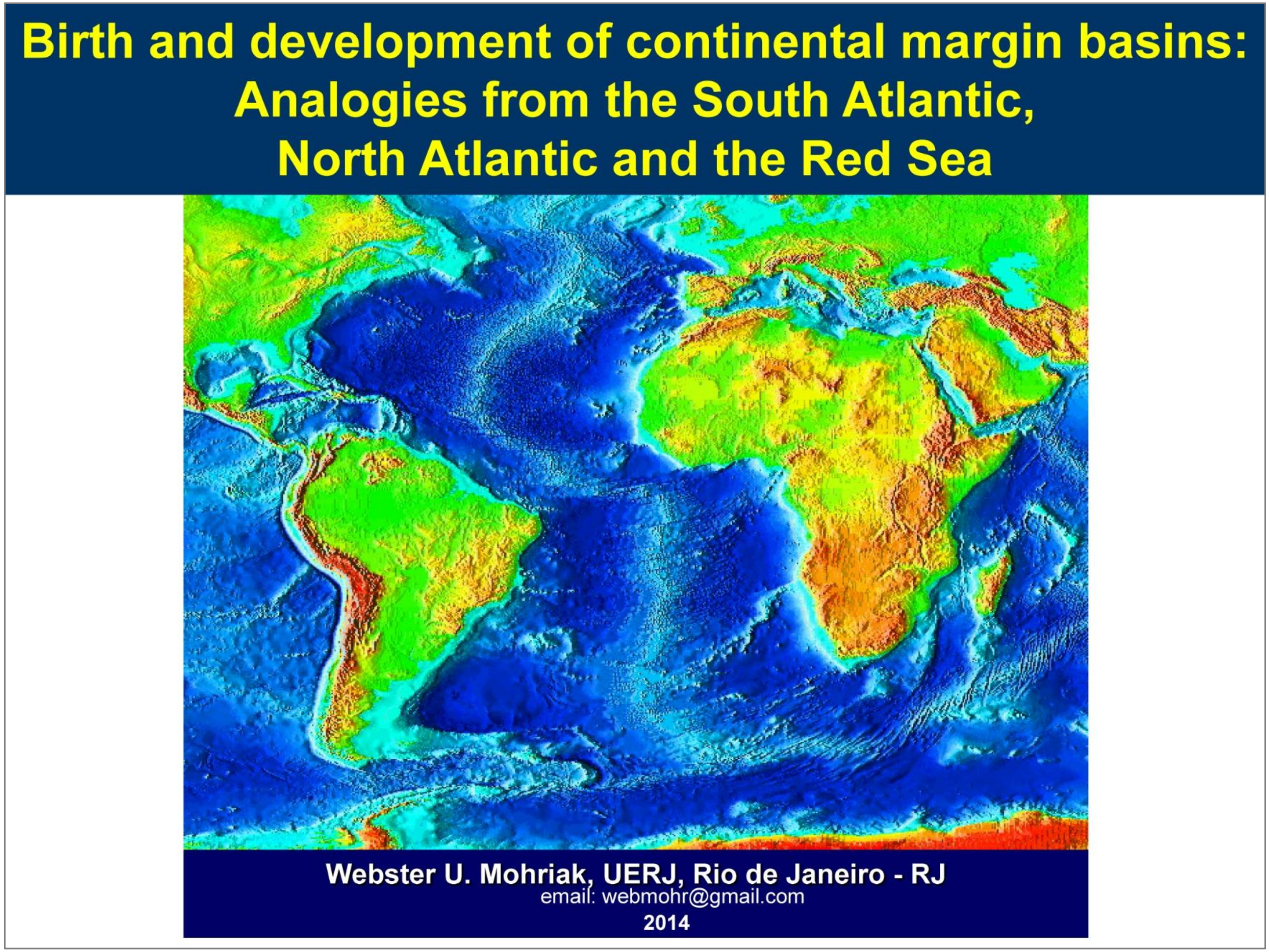

Figure 1. Topo-bathymetric map of the world with the spreading center in the Atlantic Ocean separating the South American and West African plates, with conjugate margins developed in the Mesozoic. The Red Sea and the Gulf of Aden are gulfs formed by separation of the African and Arabian plates by spreading centers developed from Late Tertiary to Recent.

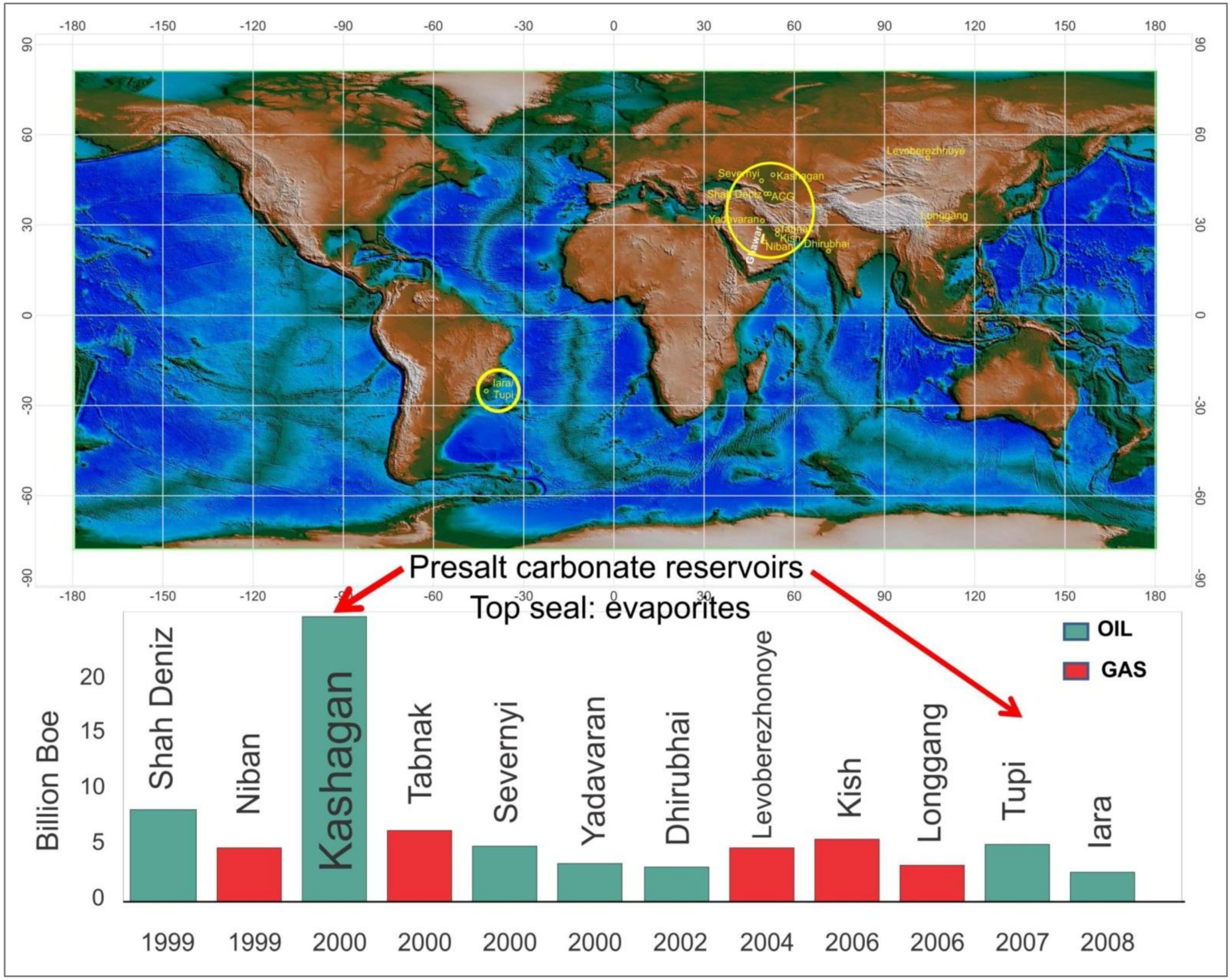

Figure 2. World map with the largest hydrocarbon accumulations by volume of oil in place (VOIP) discovered in the last decade. The cluster of hydrocarbon fields located north of the Arabian Peninsula includes the Persian Gulf and the Caspian Sea. The largest discoveries in the Southern Hemisphere are located in the Santos Basin, offshore Brazil. The Kashagan and the Tupi oil fields are associated with carbonate rocks (microbialites) as reservoirs, and both are sealed by evaporites.

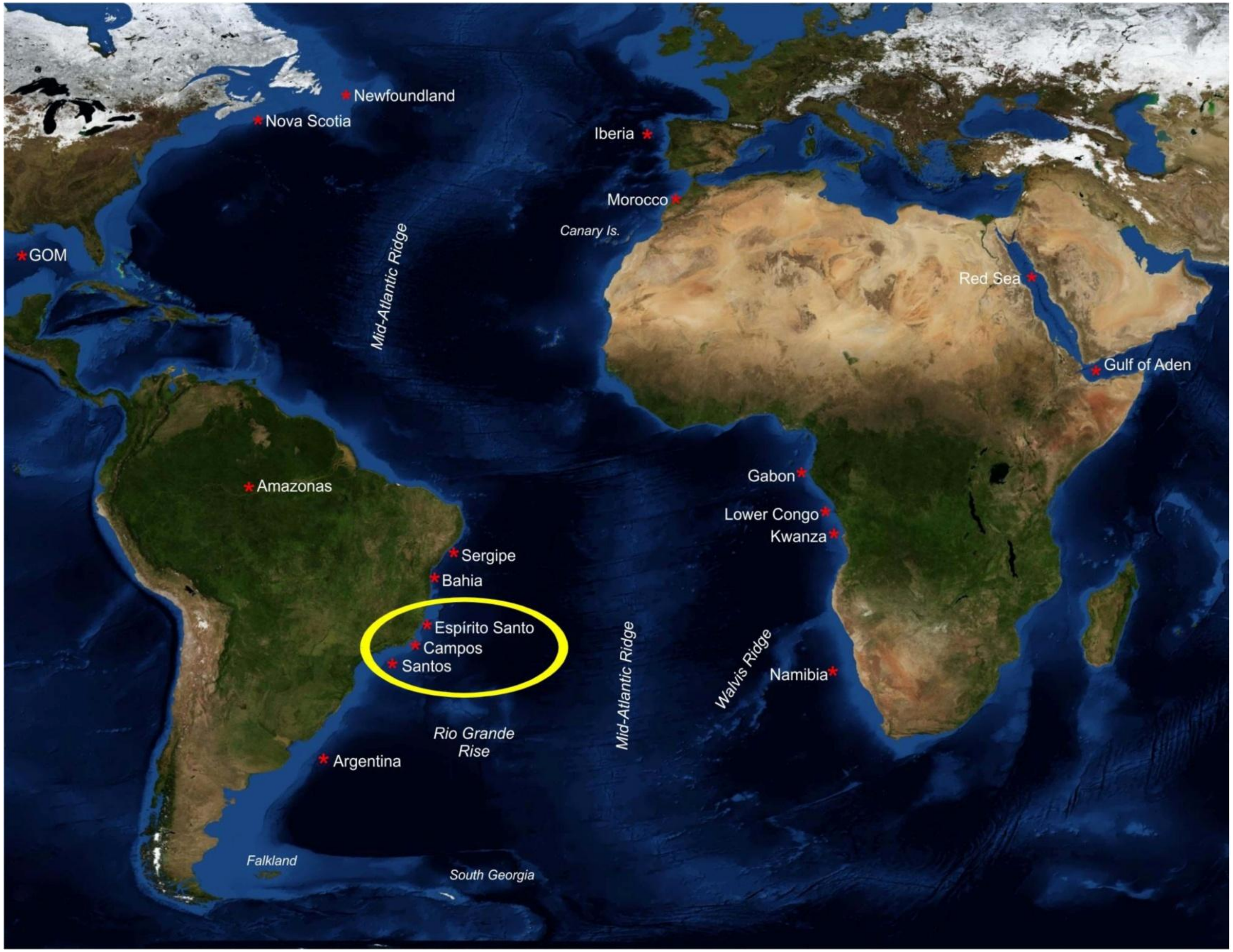

Figure 3. World satellite map showing archetypal sedimentary basins in the Atlantic Ocean. Newfoundland and Iberia are magma-poor basins characterized by mantle exhumation during continental breakup; the Santos, Campos and Espírito Santo basins are salt basins with rich synrift lacustrine source rocks.

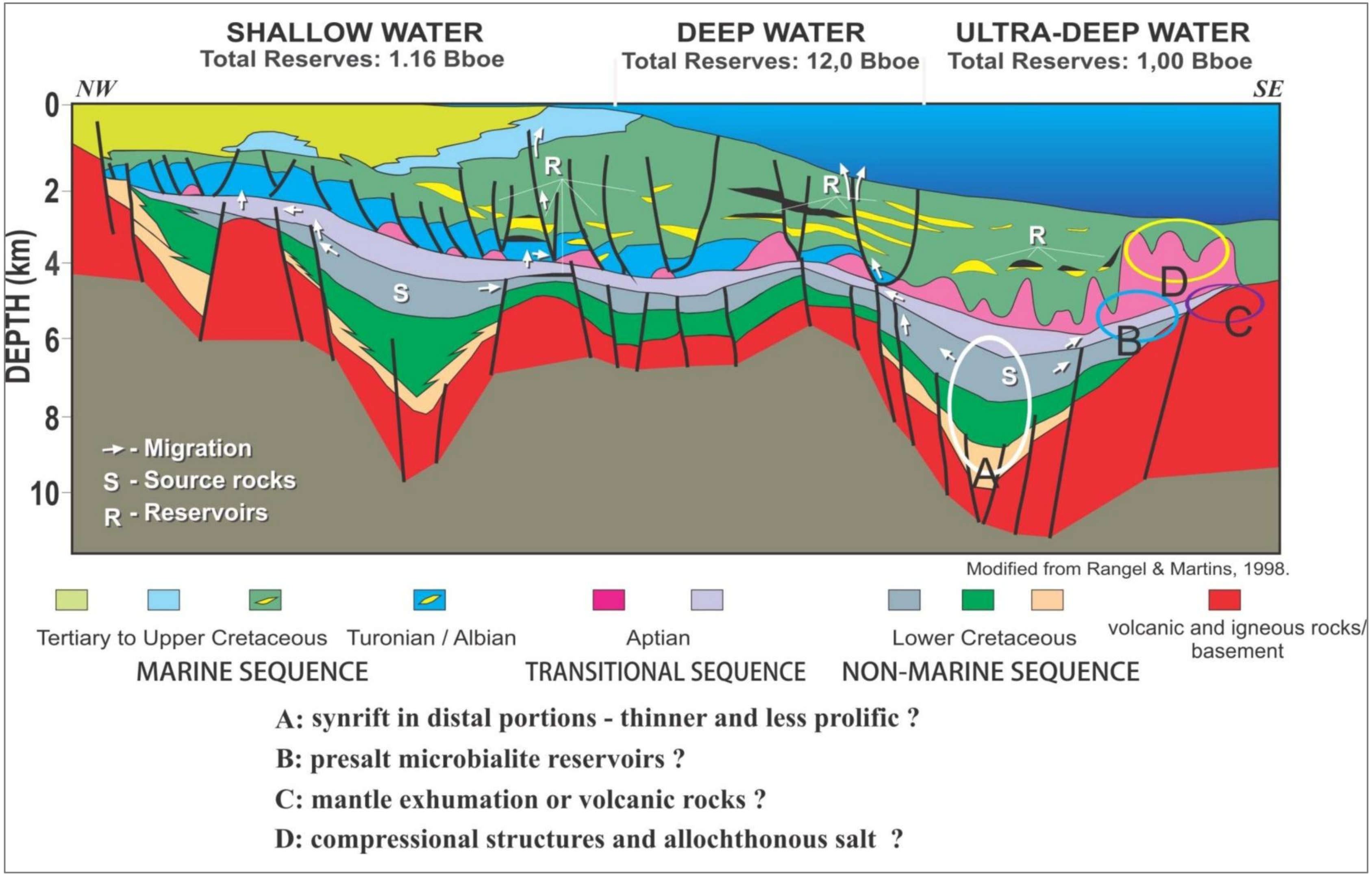

Figure 4. Schematic (but insightful) geological section of the Campos Basin, showing the synrift (nonmarine), transitional (evaporitic) and drift (marine) sequences, as well as the pre-salt and post-salt main petroleum systems (modified after Rangel and Martins, 1998). Many changes in geological interpretation have been obtained by applying modern geophysical acquisition and processing of 2D deep seismic data and 3D surveys covering large areas in the salt wall province. Conceptual geodynamic models still remain to be tested in the transition from continental to oceanic crust.

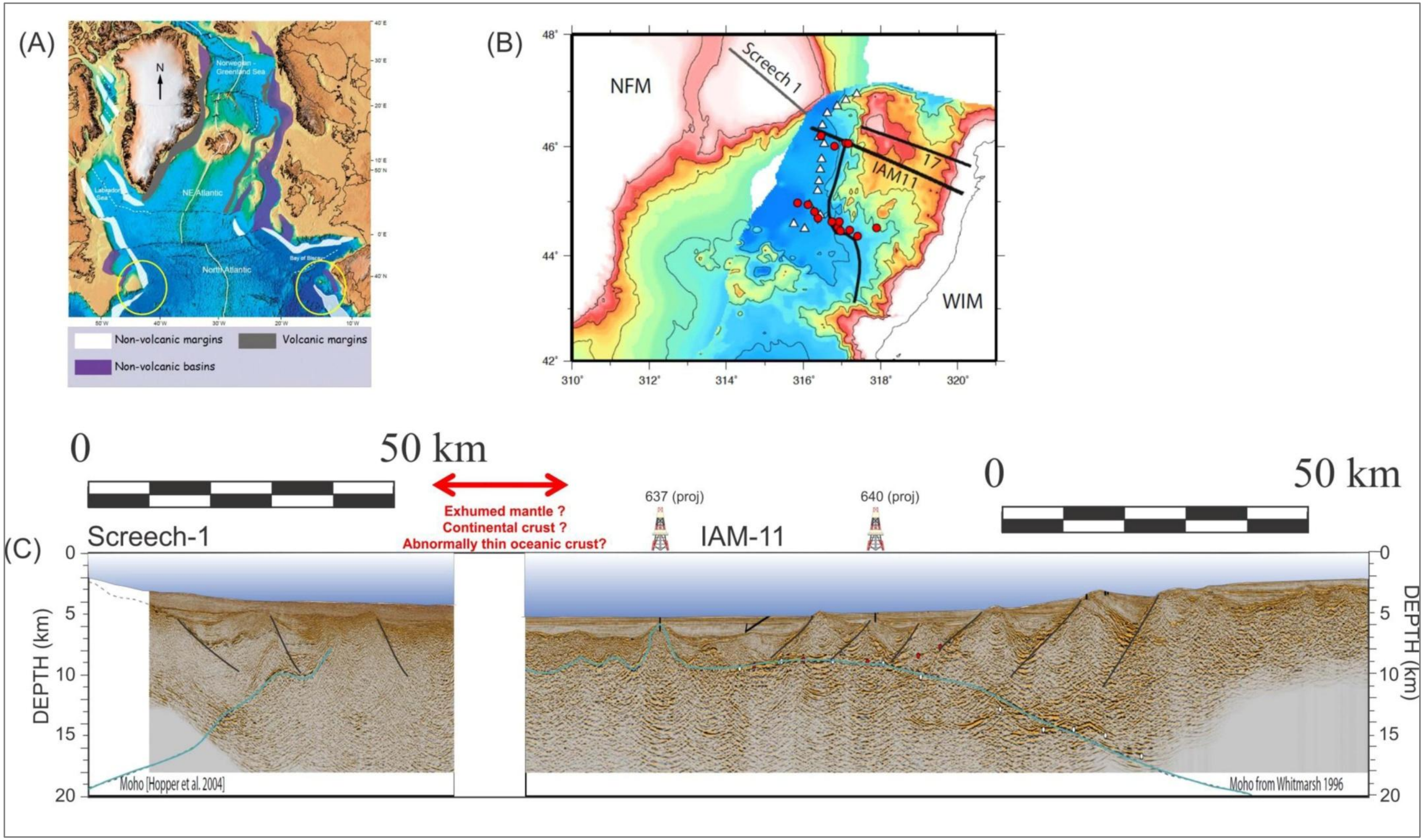

Figure 5. Mantle exhumation model for the Newfoundland and Iberia continental margins (modified after Pérez-Gussinye, 2013). (A) Present-day topo-bathymetric map with circles focusing on the conjugate margins; (B) Reconstruction at breakup with location of seismic profiles Screech-1(Newfoundland) and IAM-11 (Iberia); (C) Seismic profiles from the conjugate margins. The blue line is the Moho discontinuity.

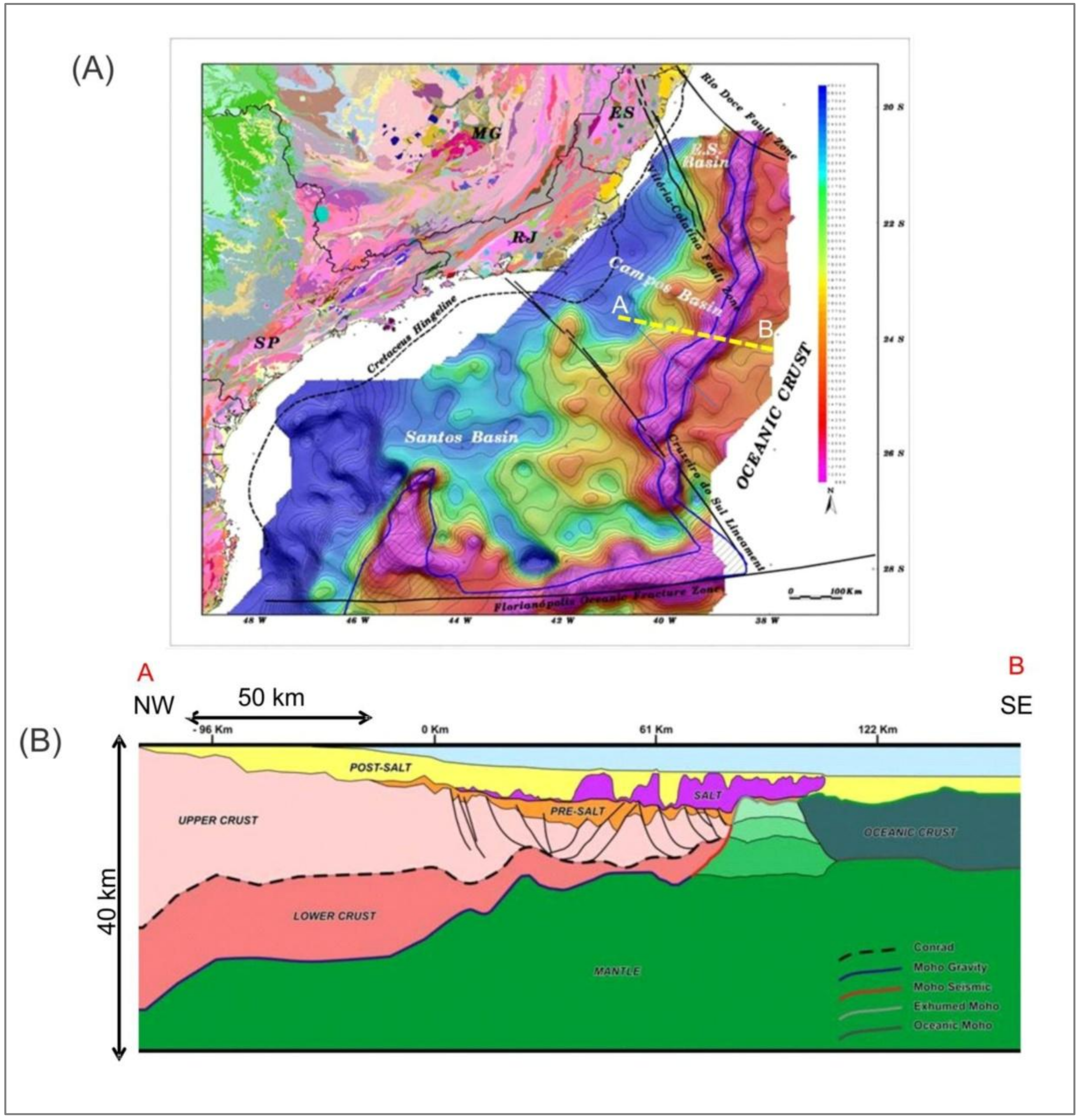

Figure 6. Direct application of the Iberian mantle exhumation model to the Brazilian margin (from Zalán et al., 2011): (A) Moho topography from the Espírito Santo, Campos, Santos, and northern Pelotas Basin; (B) geoseismic transect in the Campos Basin across the outer high and oceanic crust, showing salt overriding serpentinized mantle in deep waters.

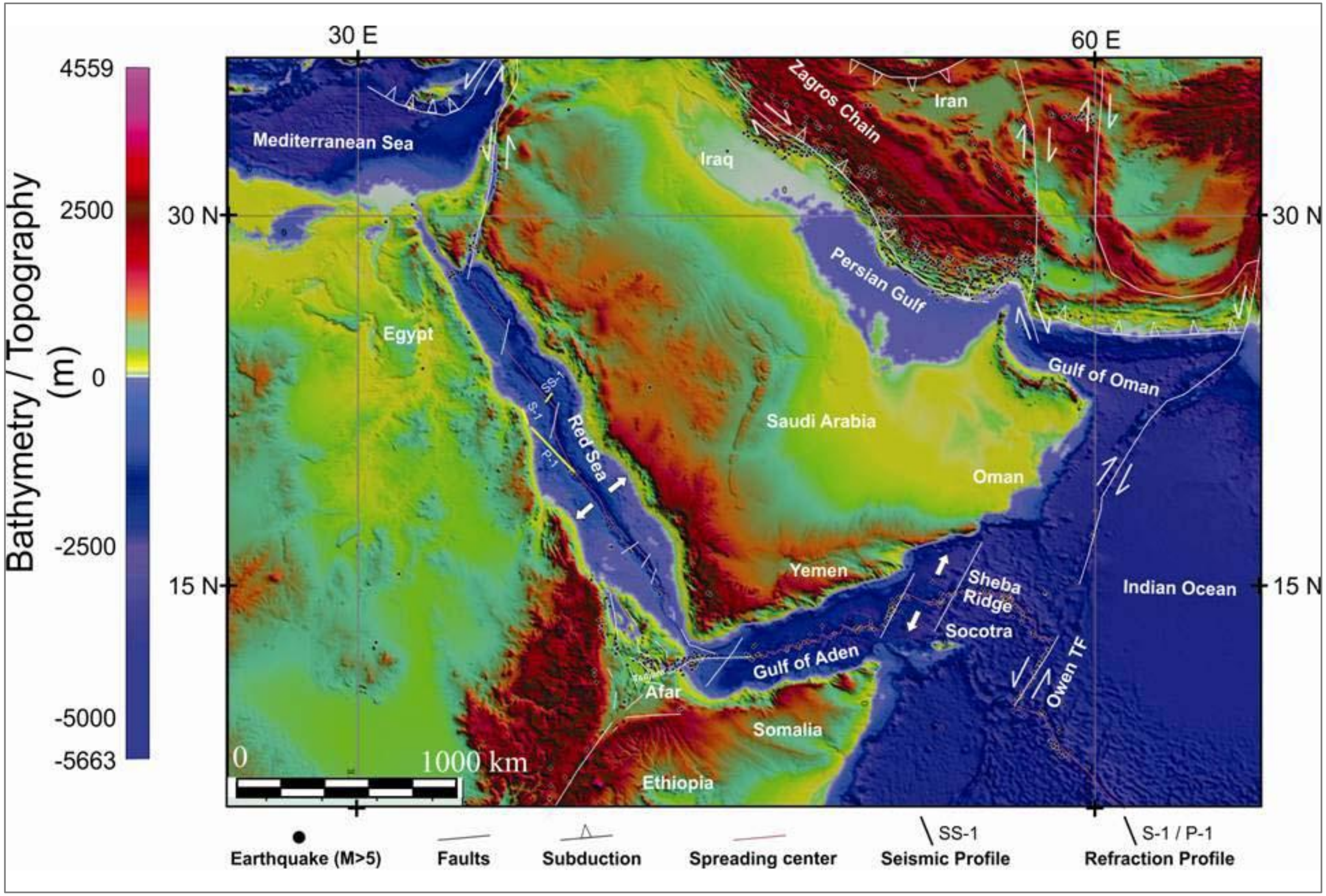

Figure 7. Regional topo-bathymetric map of the African (Nubian) and Arabian plates, with the Red Sea forming an extensive gulf between Saudi Arabia –Yemen and Egypt-Sudan-Eritrea, with an axial trough that is offset by transform faults along a northeast – southwest direction (Gulf of Aqaba trend). The Afar province is located at the southern segment of the Red Sea, connecting with the Gulf of Aden, where the Aden and Sheba ridges are active spreading centers associated with the development of a Late Tertiary oceanic crust. P1 is a seismic refraction profile that was used to constrain the geological transect across the Red Sea, and SS-1 is a seismic section crossing an incipient spreading center in the central Red Sea.

Red Sea and Gulf of Aden Tectonic Models

A schematic geological transect across the central Red Sea (Figure 8) was prepared based on the integration of potential field, seismic refraction and reflection data (eg. Egloff et al., 1991), and further constrained by geological information from exploratory wells (Hughes and Johnson, 2005). This transect suggests that the shelf zone and deep water provinces are characterized by large salt diapir structures, and the salt layer advances towards the main trough as allochthonous salt masses. The axial trough may reach bathymetries exceeding 2000 m and the salt masses are beginning to be separated by embryonic or active spreading centers associated with an incipient oceanic crust. This model assumes that the igneous intrusions in the axial trough correspond to spreading ridges formed about 2 Ma, and the volcanic and igneous crust may be about 7 km thick. The axial trough is a starved basin, with only a veneer of siliciclastic sediments covering the volcanic basement.

Several authors have proposed different geodynamic models for the development of the Red Sea (e.g., Bosworth et al., 2005). The geological transects in the southern Red Sea (Figure 9) show two end-member models of continental breakup and formation of oceanic crust. Model 1 suggests continental breakup by pure shear extension and formation of oceanic crust in the axial trough, which might be filled with Upper Tertiary sediments (Lowell and Genik, 1972). This model (Figure 10-1) is indicated by the interpretation of high-angle normal faults affecting the continental crust; it assumes that salt was deposited on continental crust but is presently advancing towards oceanic crust in the main trough, and the axial trough might be covered by Quaternary and Tertiary siliciclastic sediments overlying volcanic rocks.

Model 2 suggests continental breakup by detachment faults that lead to mantle exhumation by hyperextension of the lithosphere (Ghebreab, 1998). This model (Figure 10-2) is indicated by low-angle normal faults and detachments affecting the continental crust; it assumes that the upper mantle is exposed in the axial trough. The extensional process would be associated with dyke swarms along the conjugate margins and would result in asymmetric conjugate margins. The interpretation of the rift architecture and salt tectonics in the central Red Sea is based on the analysis of regional geoseismic profiles extending across the proximal and distal rift basins, and by a seismic section crossing the axial trough (Figure 11). The proximal profile (Figure 12) is characterized by salt evacuation and development of large turtle structures. The synrift sequences may be divided into early (Wajh Formation) and late (Burqan Formation) phases of rifting, overlain by a possible sag basin (Kiel and Jabal Kibrit formations). The Mansiyah evaporites show indications of basinward flow forming large diapirs in the platform and deep-water.

The distal profile in the central Red Sea extends from the platform towards the main trough and axial trough. This profile does not show bathymetric depressions similar to the depressions in the southern Red Sea, where the axial trough is characterized by a magnetic-anomaly zebra pattern associated with organized spreading in the oceanic crust. Two hypotheses have been analyzed for the interpretation of this profile. Hypothesis 1 (Figure 13) suggests thick salt masses in the axial trough covering tilted rift blocks on the continental crust, which may be affected by extensional faults with large offsets. Salt was deposited during a late synrift phase, before continental breakup, and no oceanic crust has been developed in the basin center. Hypothesis 2 (Figure 14) suggests an alternative interpretation for the distal profile, assuming that the thick salt masses are advancing towards a volcanic basement associated with embryonic spreading centers and are affected by igneous intrusions that will eventually split the salt basins apart. The middle to late Miocene evaporites were deposited in the transition from an early post-rift to an early drift phase, overlying volcanic basement rocks in the distal basin. The salt masses are amalgamated in the main and axial troughs, but are starting to be separated by embryonic spreading centers that have been formed in the past few million years, with intrusive bodies invading the crust and also penetrating the salt layer, which is mainly allochthonous in this portion of the basin. In other areas, the process is more advanced, and the salt masses are totally separated by oceanic ridges and volcanic basement.

The seismic profile across the axial trough in the Thetis Deep (Figure 15-A) shows that the salt basin only occurs in the elevated regions (bathymetry < 750 m), whereas the bathymetric depression forms an abyss deeper than 1500 m, where there is no evidence of salt deposition. The protuberant structural high in the internal zone of the abyss is interpreted to correspond to an active spreading ridge (Mitchell et al., 2010) that was formed about 2 Ma. There is a marked unconformity below a thin veneer of sediments that cover the top of the salt mass (S reflector), and locally we observe undulating features that suggest mini-basins or internal deformation of the stratified evaporites, indicating early halokinesis (Figure 15-B). The salt masses are separated by incipient oceanic crust associated with an active spreading ridge with magma chambers and volcanoes (Mitchell et al., 2010; Ligi et al., 2012).

One important question is whether this type of structure might exist in the South Atlantic salt basin and the implications for timing of breakup, tectonics, sedimentary facies, and petroleum systems.

Comparison of the Distal Salt Basins in the Central Red Sea and Offshore Brazil

Mohriak and Leroy (2013) suggest that the mid-ocean spreading center in the central Red Sea (Thetis Deep) might be compared with the embryonic spreading center in the southern Santos Basin, which is associated with the Abimael propagator in the northern Pelotas Basin (Mohriak, 2001). This feature may be interpreted as an igneous intrusion advancing northwards, which was active during and following salt deposition and initial breakup. After impinging on the salt basin, the propagator aborted when the active spreading center shifted eastwards (Mohriak et al., 2008).

The comparison of the seismic profile in the Thetis Deep (Figure 16-A) with the seismic profile in the Santos Basin (Figure 16-B) indicates that in both cases the salt masses pinch-out towards 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. A comparison of an allochthonous salt tongue in the Espírito Santo Basin (Figure 17-A) with the interpretation of the distal profile in the central Red Sea (Figure 17-B) suggests a much more advanced stage of salt tectonics in the Brazilian margin, with salt advancing towards an oceanic crust basement that was formed by late Aptian – early Albian (Mohriak et al., 2008). The Red Sea profile shows an incipient stage of plate separation and is characterized by amalgamation of salt masses that are only beginning to separate between Egypt and Saudi Arabia, whereas in the Brazilian margin, the allochthonous salt is more than 4000 km from its conjugate-margin salt front in the Kwanza Basin.

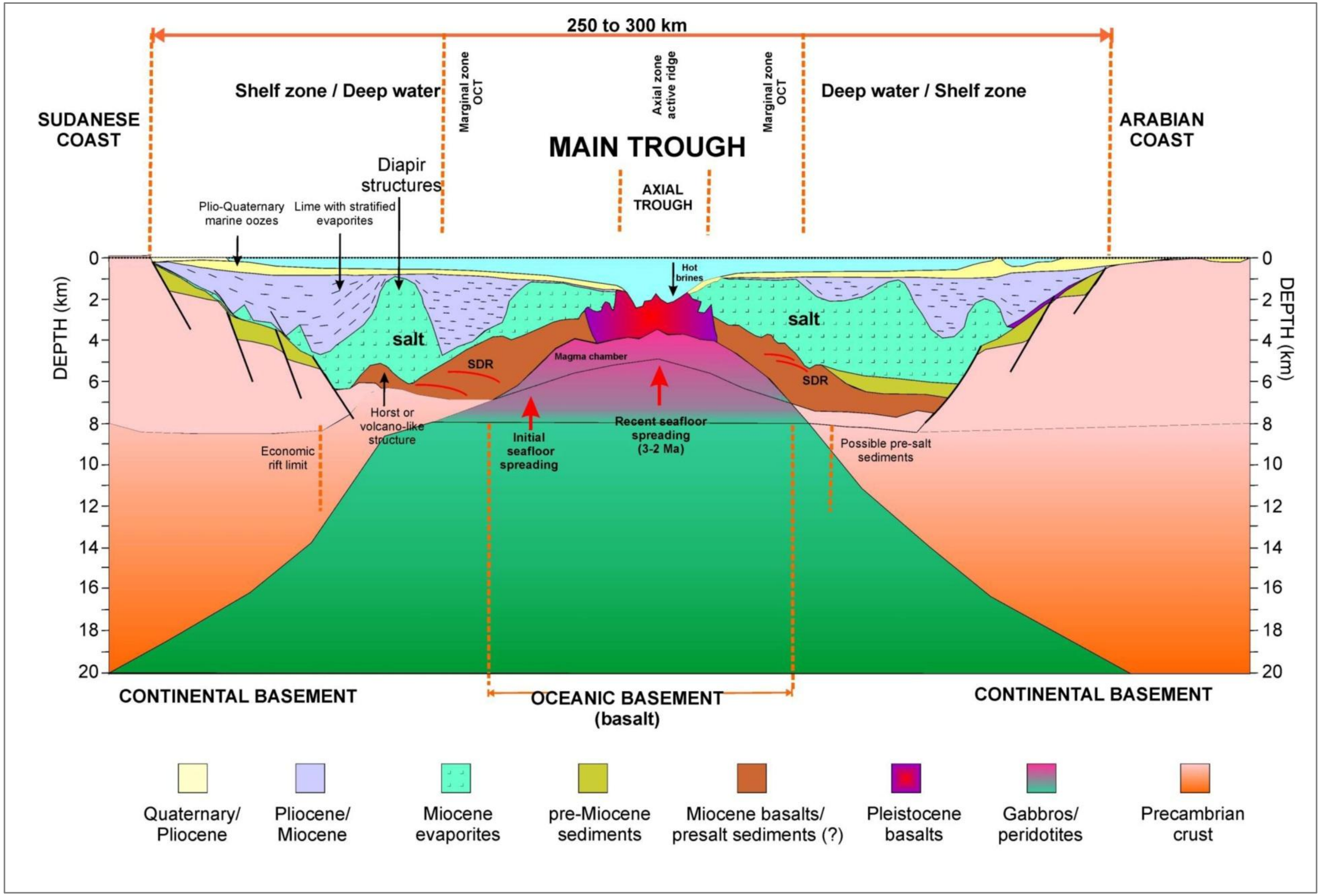

Figure 8. Schematic geological transect across the central Red Sea, based on refraction and reflection seismic data constrained by exploration wells (modified after Mohriak and Leroy, 2013).

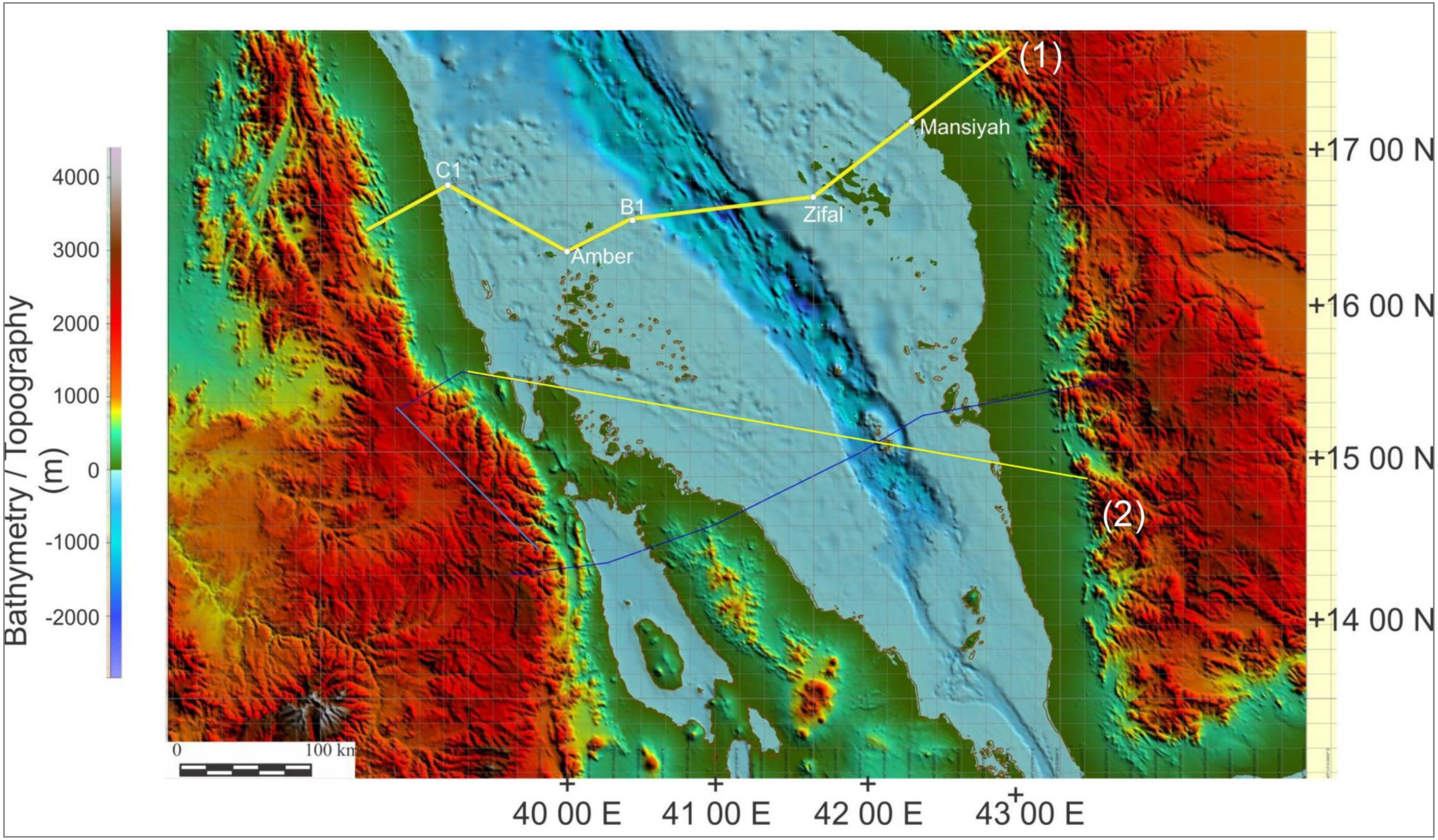

Figure 9. Topo-bathymetric map of the southern Red Sea with location of geological cross-sections from the Eritrean margin to the Arabian margin illustrating the end-member tectonic models: (1) pure shear with oceanic crust in the axial trough; (2) simple shear with exhumed mantle in the conjugate margins adjacent to the axial trough.

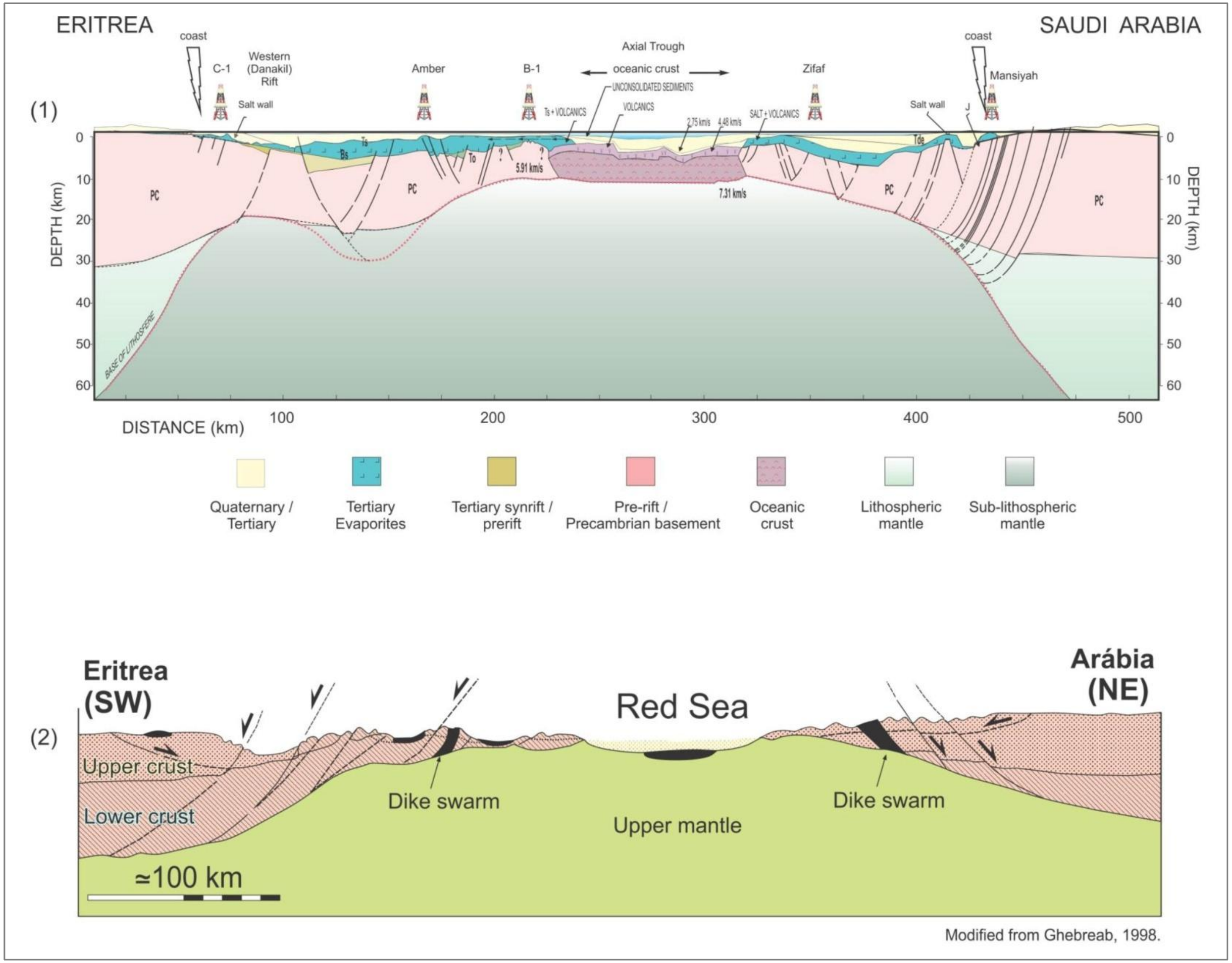

Figure 10. Regional geological transects illustrating end-member models for the tectonic evolution of the southern Red Sea: (1) continental breakup by pure shear extension and development of oceanic crust in the axial trough (modified after Lowell and Genik, 1972); (2) continental breakup by detachment faults and simples shear mechanism resulting in asymmetric margins (modified after Ghebreab, 1998).

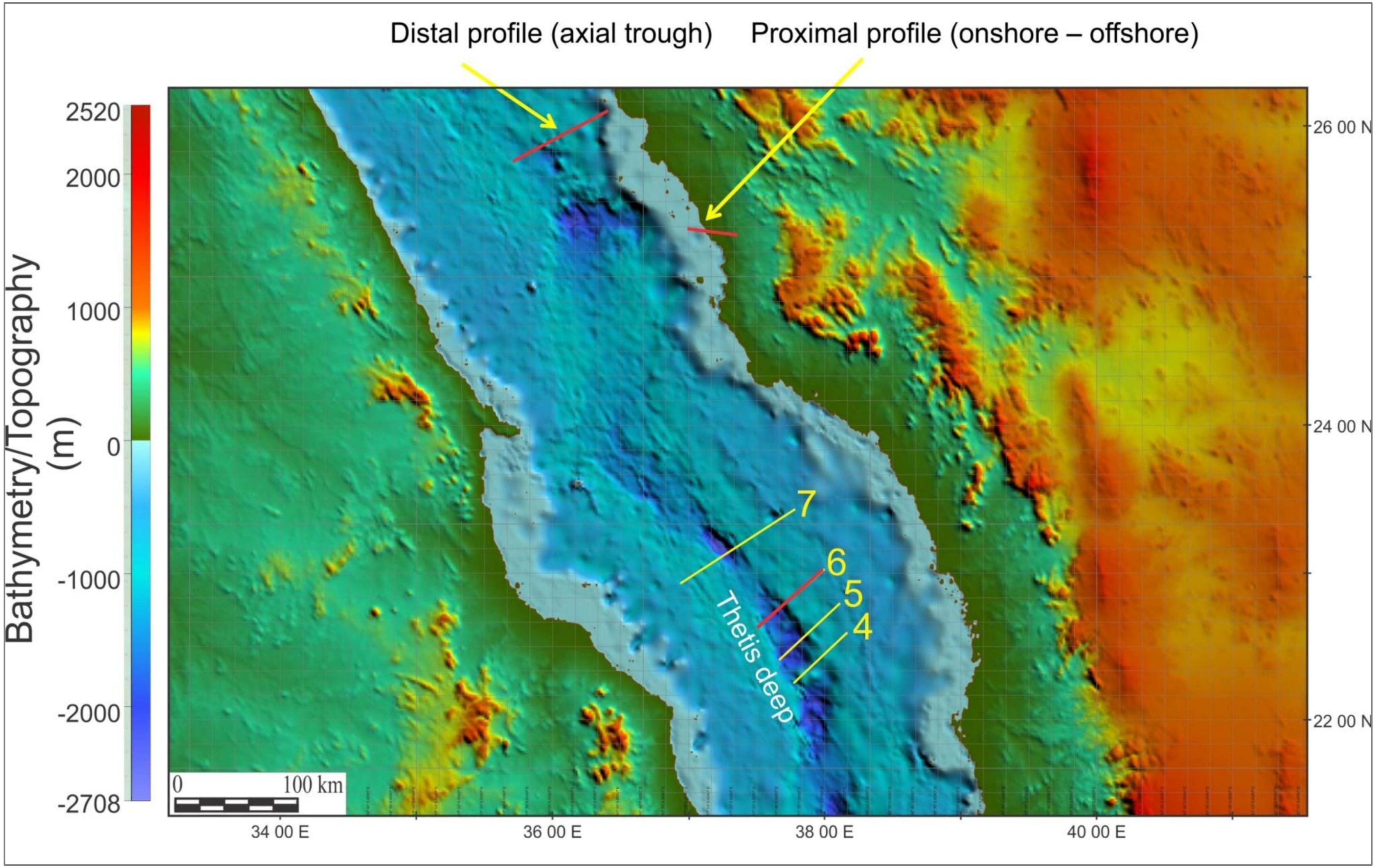

Figure 11. Regional profiles in the central Red Sea: the proximal profile extends from the onshore to the offshore region in the shallow water platform; the distal profile extends from the platform towards the axial trough, in areas where the salt layer is very thick. Line 6 corresponds to a seismic profile in the Thetis Deep, crossing an active spreading center that separates the conjugate-margin salt basins.

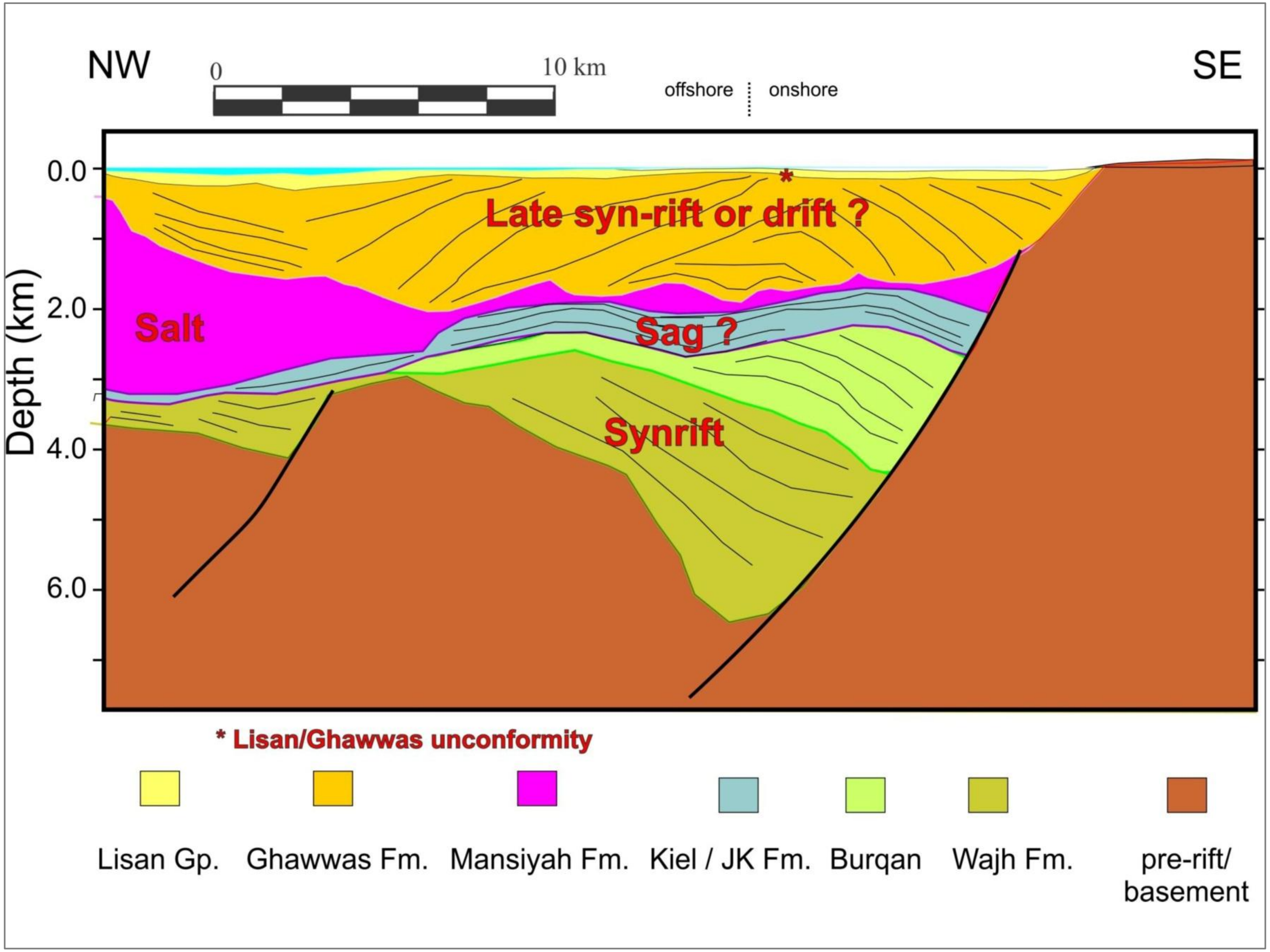

Figure 12. Schematic geoseismic transect in the central Red Sea, illustrating the onshore to offshore stratigraphy and structure of the proximal rift basin.

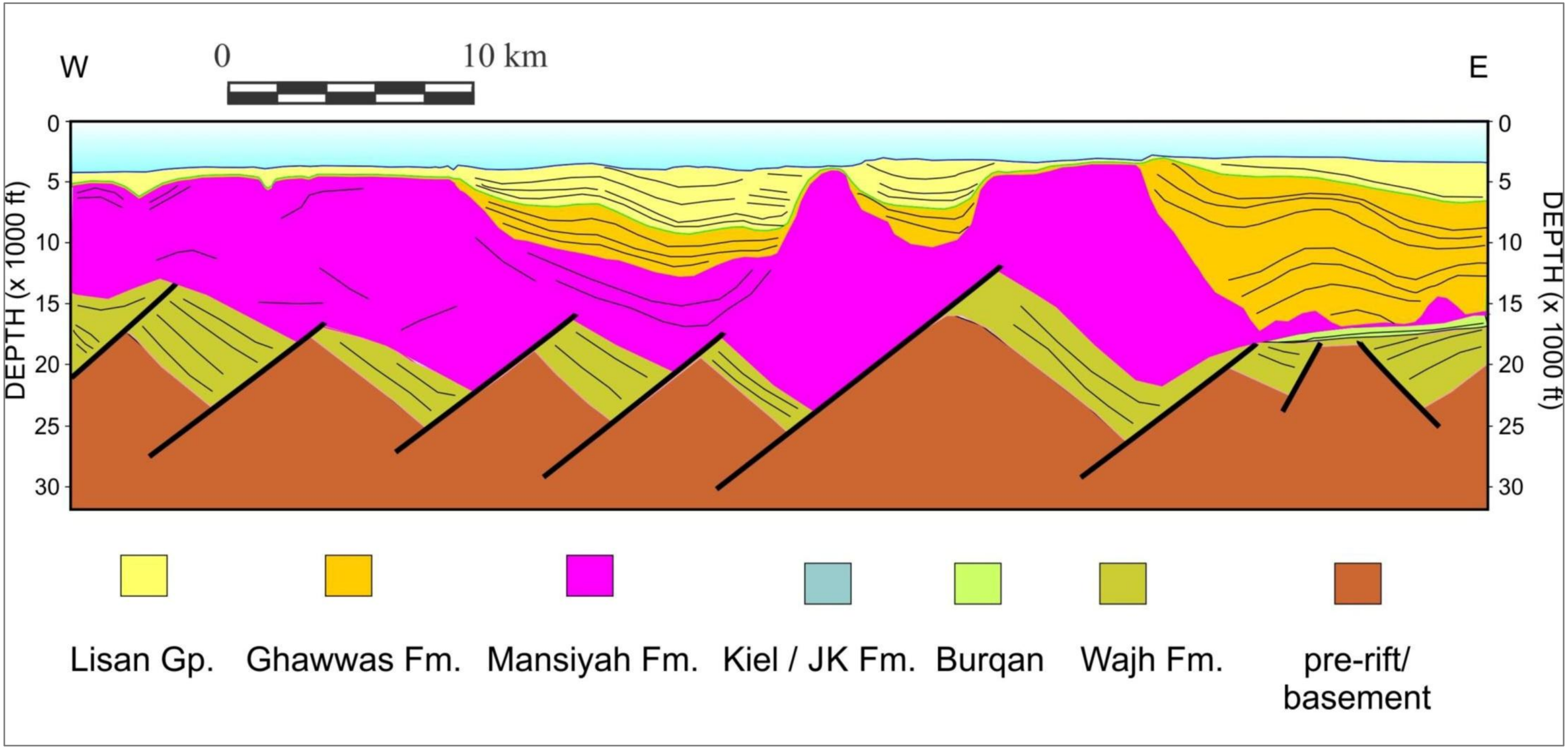

Figure 13. Red Sea geoseismic profile from the platform towards the axial trough. Hypothesis 1: a possible interpretation suggests thick salt masses in the axial trough and tilted rift blocks on the continental crust. Salt was deposited during a late synrift phase, before continental breakup, and no oceanic crust has been developed in the basin center.

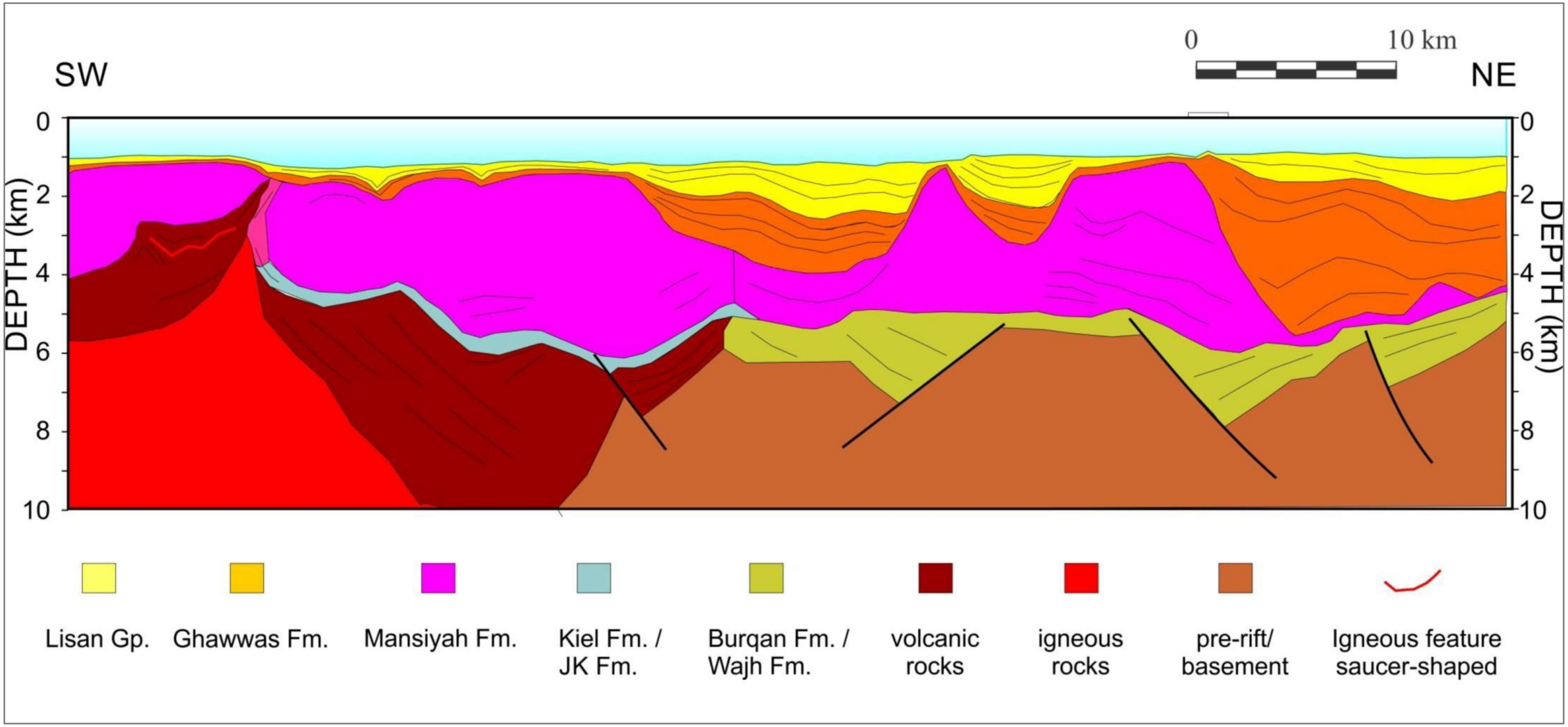

Figure 14. Red Sea geoseismic profile from the platform towards the axial trough. Hypothesis 2: a possible interpretation suggests thick salt masses in the axial trough intruded by igneous rocks and overlying volcanic basement.

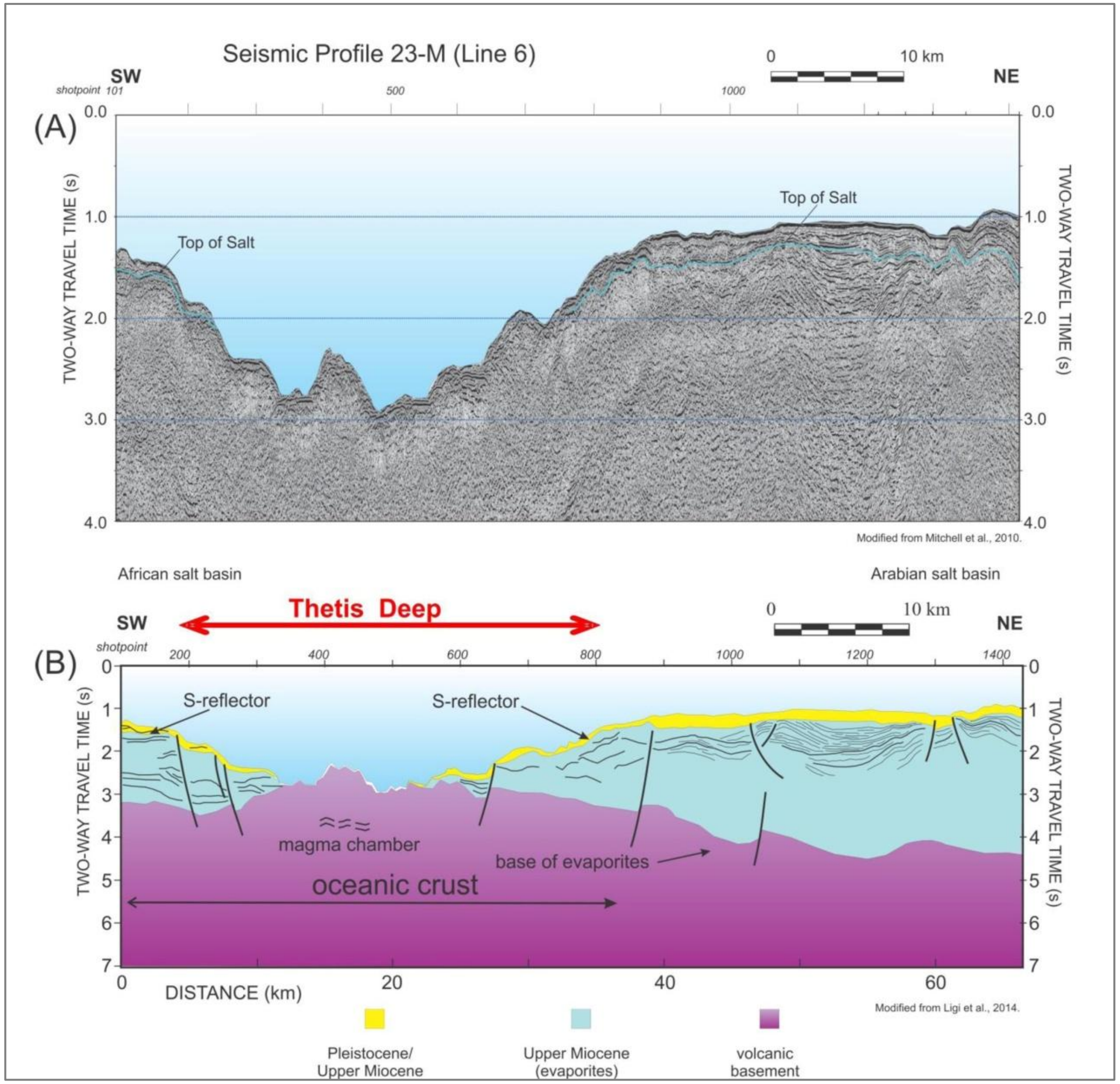

Figure 15. Interpretation of the spreading center and conjugate margins in the Red Sea. (A) Seismic profile (time seismic profile 23-M) corresponding to Line 6 in the Thetis Deep, crossing the spreading center in the axial trough (modified after Mitchell et al., 210). (B) Interpretation of the seismic profile (Line 6) in the embryonic spreading center (modified after Ligi et al., 2012). Salt basins in the conjugate margins are split apart by magma intrusions / diverging plates. The spreading ridge (3-2 Ma) is younger than the allochthonous salt masses that are advancing towards the abyss in the axial trough.

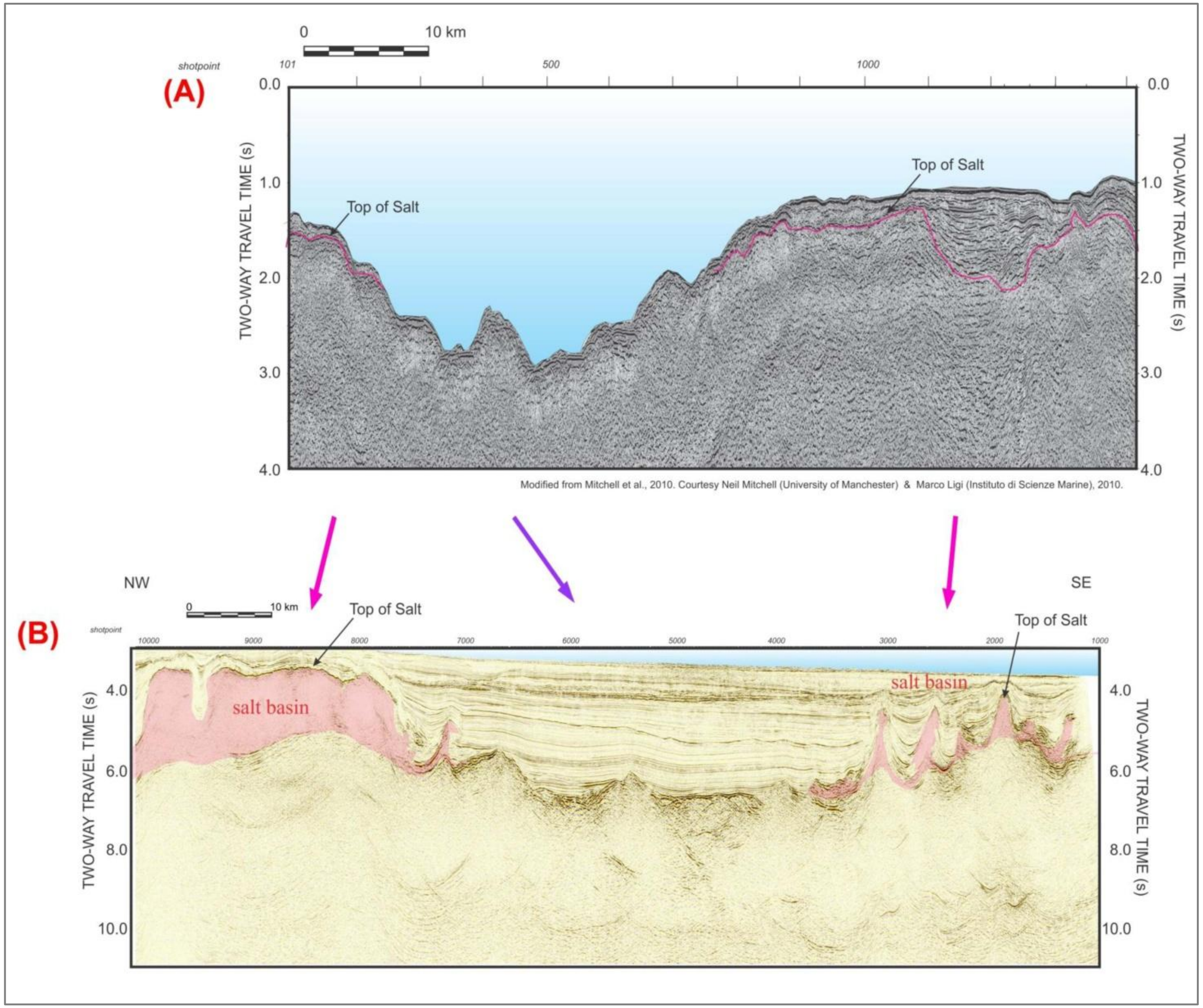

Figure 16. (A) Central Red Sea seismic profile 23-M, with salt masses in the conjugate margins split apart by an embryonic spreading center (modified after Mitchell et al., 2010; courtesy Neil Mitchell and Marco Ligi, 2010); (B) Southern Santos Basin, with salt masses separated by an embryonic spreading center that was subsequently aborted (modified after Mohriak and Leroy, 2013).

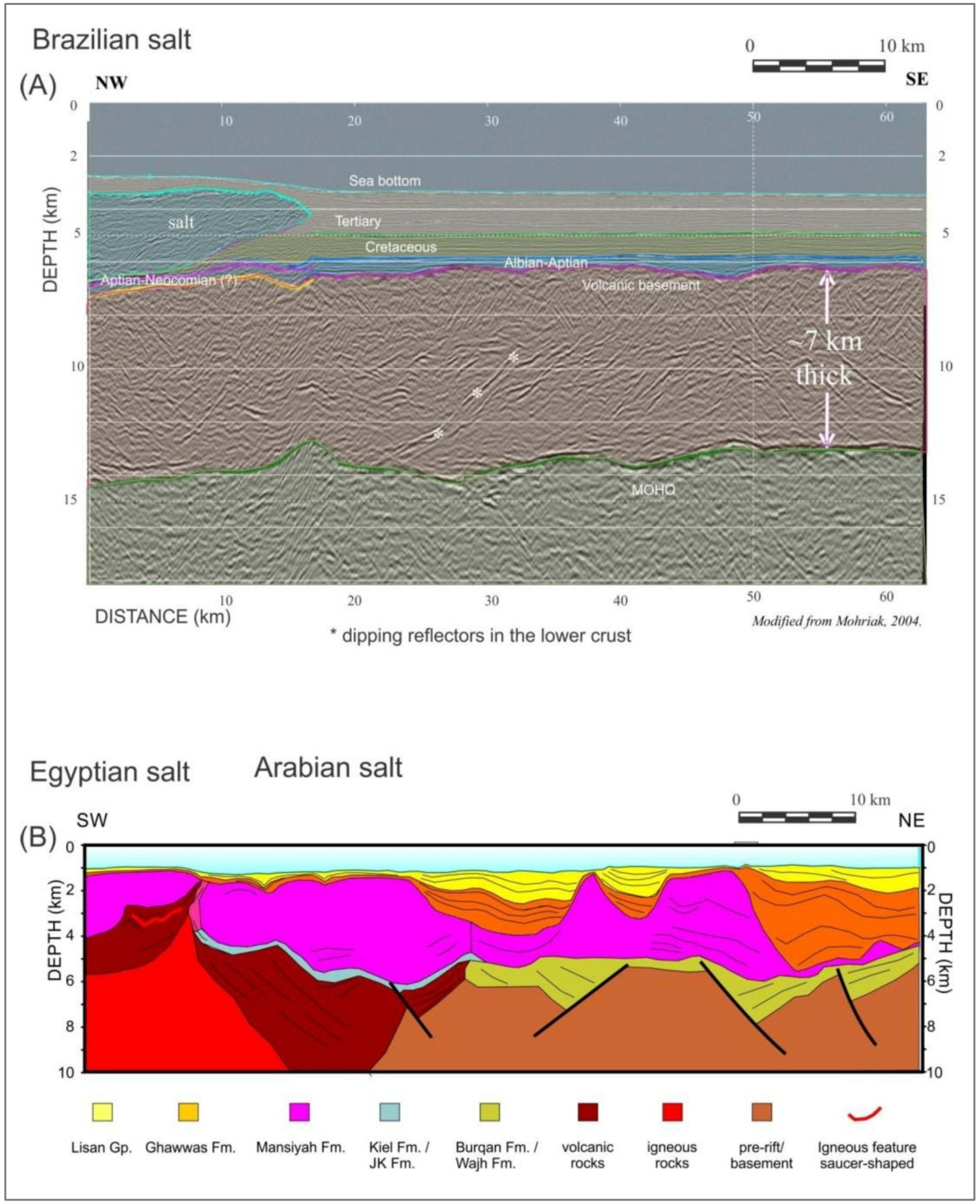

Figure 17. Comparison of an allochthonous salt tongue in a depth-converted seismic profile in the deep water region of the Espírito Santo Basin (A) (modified after Mohriak, 2004), with the hypothesis 2 interpretation of the distal profile in the Red Sea (B).

Analogies with Other Rifted Margins

The seismic profiles across the Sheba Ridge spreading center in the Gulf of Aden suggest that the conjugate margins between Oman and Somalia (Figure 18) are in a more advanced stage of plate separation than the Red Sea (Leroy et al., 2004). Organized oceanic crust with magnetic anomalies can be identified in the conjugate margins, suggesting continental breakup occurred around 17 Ma, and the oceanic ridge is presently advancing westwards towards the Gulf of Djibouti in the Afar region (Mohriak and Leroy, 2013). The seismic transect across the conjugate margins shows rifted continental crust and the continent-ocean transition zone marked by small rift basins and volcanic features, and a large expansion of oceanic crust covered by post-breakup sediments that pinch-out towards the axial trough, where the active Sheba Ridge is imaged (Figure 19).

The plate tectonic reconstruction of the South Atlantic at the gulf stage (around 120 Ma, Scotese, 2002) shows the location of the volcanic margins, south of the Tristão da Cunha hotspot, which are characterized by seaward-dipping reflector wedges in the transition to oceanic crust (Figure 20). The onshore Paraná–Etendeka volcanics are dated around 130 +/- 3 Ma (Almeida et al., 2013), and the salt basins between the eastern Brazilian and West African margins are dated as late Aptian (around 112-115 Ma). The extensive salt basin between Brazil and West Africa was developed between two hot-spots, the southern Tristão da Cunha, which marked the boundary between the Santos and Pelotas basins offshore Brazil, and the northern St. Helena hotspot. The northern segment of the South Atlantic salt basin is characterized by the St. Helena hotspot and the incipient transform rifts that subsequently formed the Equatorial Atlantic sheared margin after continental breakup in the Albian. The southern segment of the South Atlantic is also characterized by onshore-offshore rift basins in Argentina, with axes that trend obliquely to the continental margin (e.g., Salado Basin in Figure 20). There was no significant deposition of evaporites in the volcanic margins and onshore rifts south of the Tristão da Cunha hotspot, which may have acted as a volcanic barrier isolating the Santos Basin from the southern basins (Mohriak, 2001).

The segment of the south Atlantic that is located south of the St. Helena hotspot is marked by narrower rift and salt basins in the Northeastern Brazilian margin (Camamu–Almada, Jacuipe and Sergipe-Alagoas basins), whereas the conjugate margin in West Africa (Gabon) is associated with a wider rift with a large salt basin extending from onshore to offshore (Davison, 2007).

Based on analogies between the South Atlantic, the Red Sea and the Gulf of Aden, Mohriak and Leroy (2013) proposed the schematic palinspastic map with a reconstructed cross-section of the Brazilian and West African continental margins, where the early Cretaceous rifting resulted in proximal and distal basins (Figure 21, sectors B and C). The diagram depicts the South Atlantic at the transition from gulf stage to open ocean stage of the Wilson cycle, showing the distribution of evaporites and rift structures in the conjugate margins that were separated by incipient spreading centers and volcanic crust around Aptian-Albian times. The evidence so far points to magmatic accretion in the distal margin, similar to what is observed in the Red Sea and Gulf of Aden, with development of a late Aptian igneous crust underlying the salt masses in sectors C and D. A 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 towards sector D as allochthonous salt masses (Figure 22), overlying volcanic rocks associated with the inception of an active spreading center that eventually separated the salt basins of the conjugate margins.

Conclusion

- The Red Sea / Gulf of Aden continental margins are a natural laboratory for studies on continental margin breakup processes.
- Several advantages over the Iberian-Newfoundland margins where the breakup occurs in water depths exceeding 5000 m.
- Several analogies with the Atlantic margins: structures, sedimentary facies, volcanism, presence of evaporites in the distal region, embryonic oceanic ridges and crustal architecture.
- Important implications for tectonic models and petroleum systems active in the early stages of basin development.

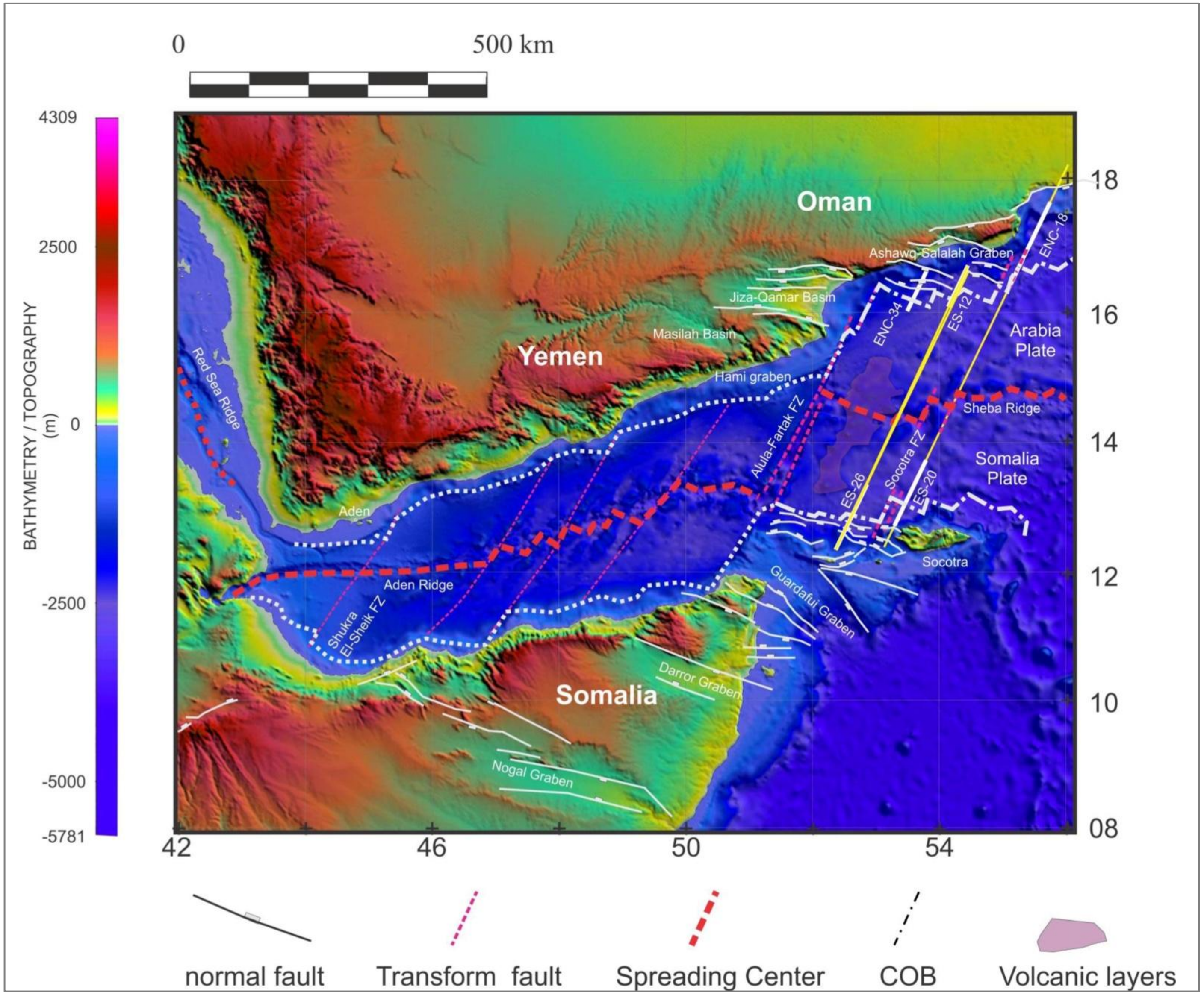

Figure 18. Regional topo-bathymetric of the Gulf of Aden, showing main tectonic features and the location of the seismic transect extending from the Somalia continental margins towards the Oman conjugate margin, crossing the Sheba Ridge. (yellow line defining locations of seismic profiles ES-26 and ES-12).

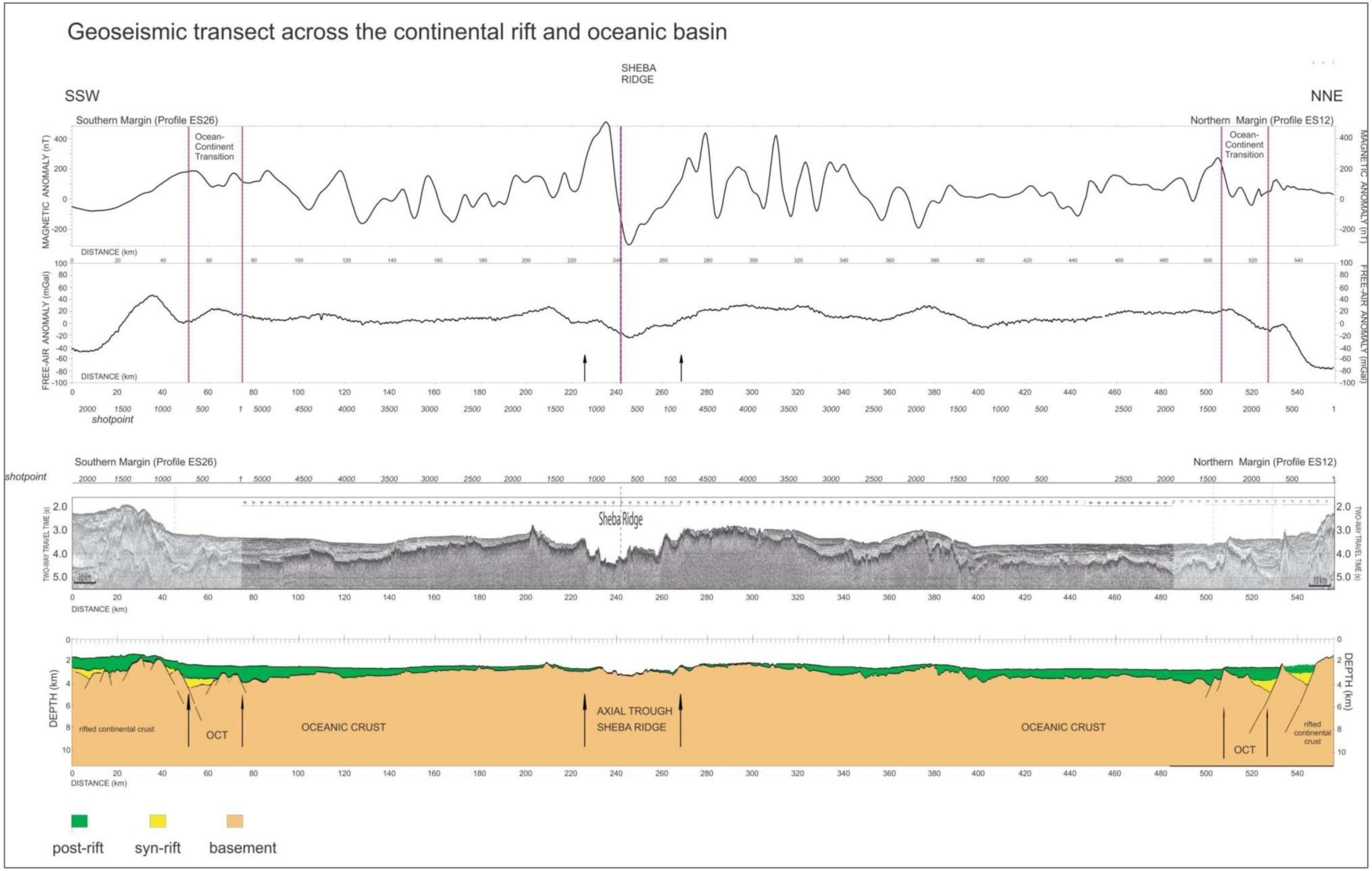

Figure 19. Regional seismic profile from the southern margin of the Gulf of Aden (seismic line ES-26) across the Sheba Ridge and extending towards the Oman continental margin (seismic line ES-12). The free-air and magnetic anomalies are plotted above the seismic profile. The interpretation of the seismic data indicates a large expansion of oceanic crust between the shelf-break and the Sheba Ridge axial trough (modified after Leroy et al., 2004, Mohriak and Leroy, 2013) .

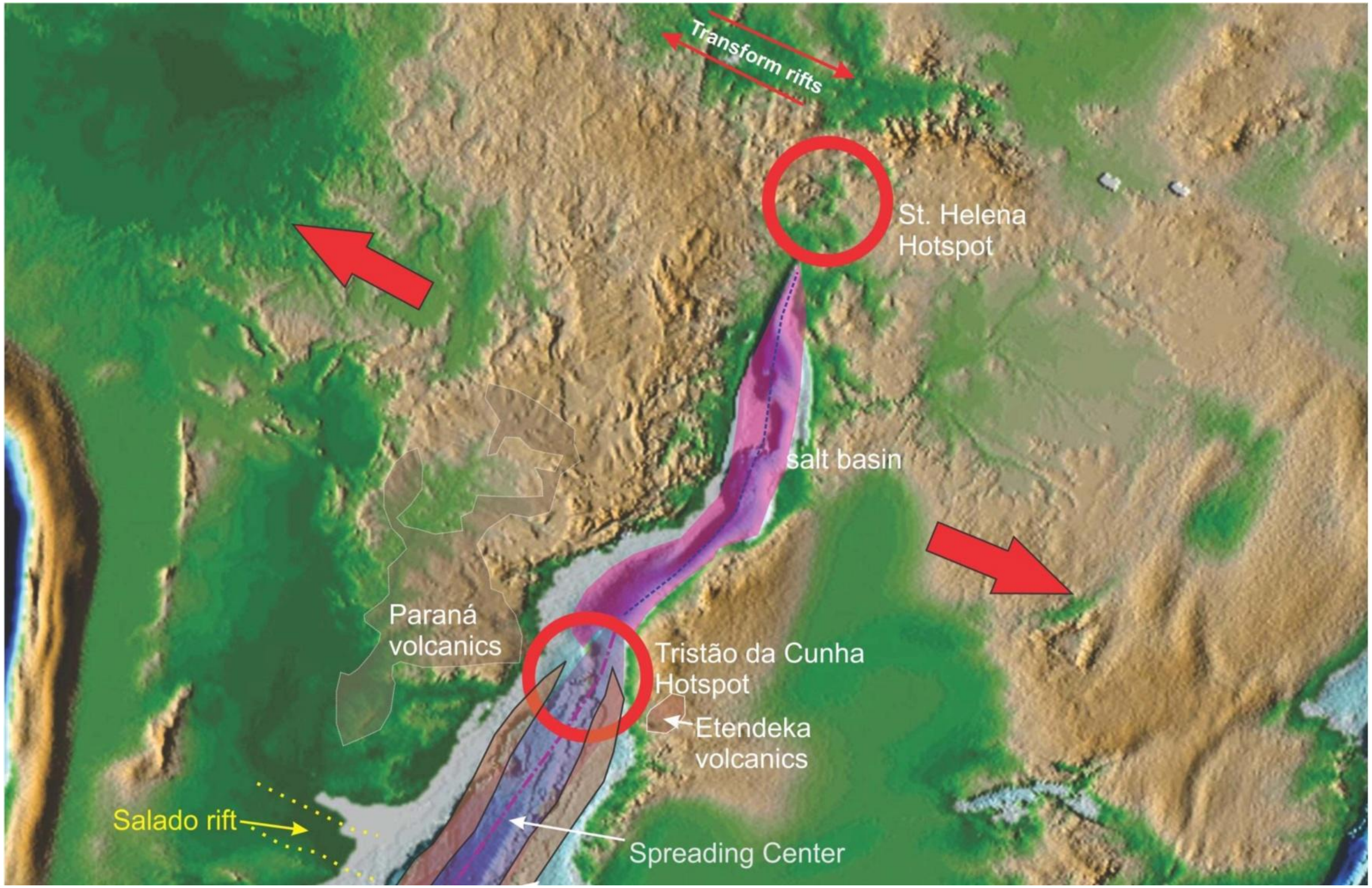

Figure 20. Schematic paleogeographic map showing the distribution of the late Aptian salt basin in the South Atlantic (purple color), overlain on plate tectonic reconstruction circa 120 Ma (Scotese, 2002) that shows the gulf stage before the continental breakup and development of divergent margins with inception of oceanic crust associated with active spreading centers between East Brazil and West Africa. The red arrows indicate the plate motion, and the red circles indicate the approximate position of hotspots. The southern South Atlantic is characterized by tholeiitic lava flows onshore (Paraná Basin and Etendeka basalts, brown color) and volcanic margins with seaward-dipping wedges (tan color) and active oceanic spreading centers (light blue color). The northern South Atlantic was affected by shear zones that developed intracontinental rifts that evolved into transform margins between South America and Northwest Africa in the Albian.

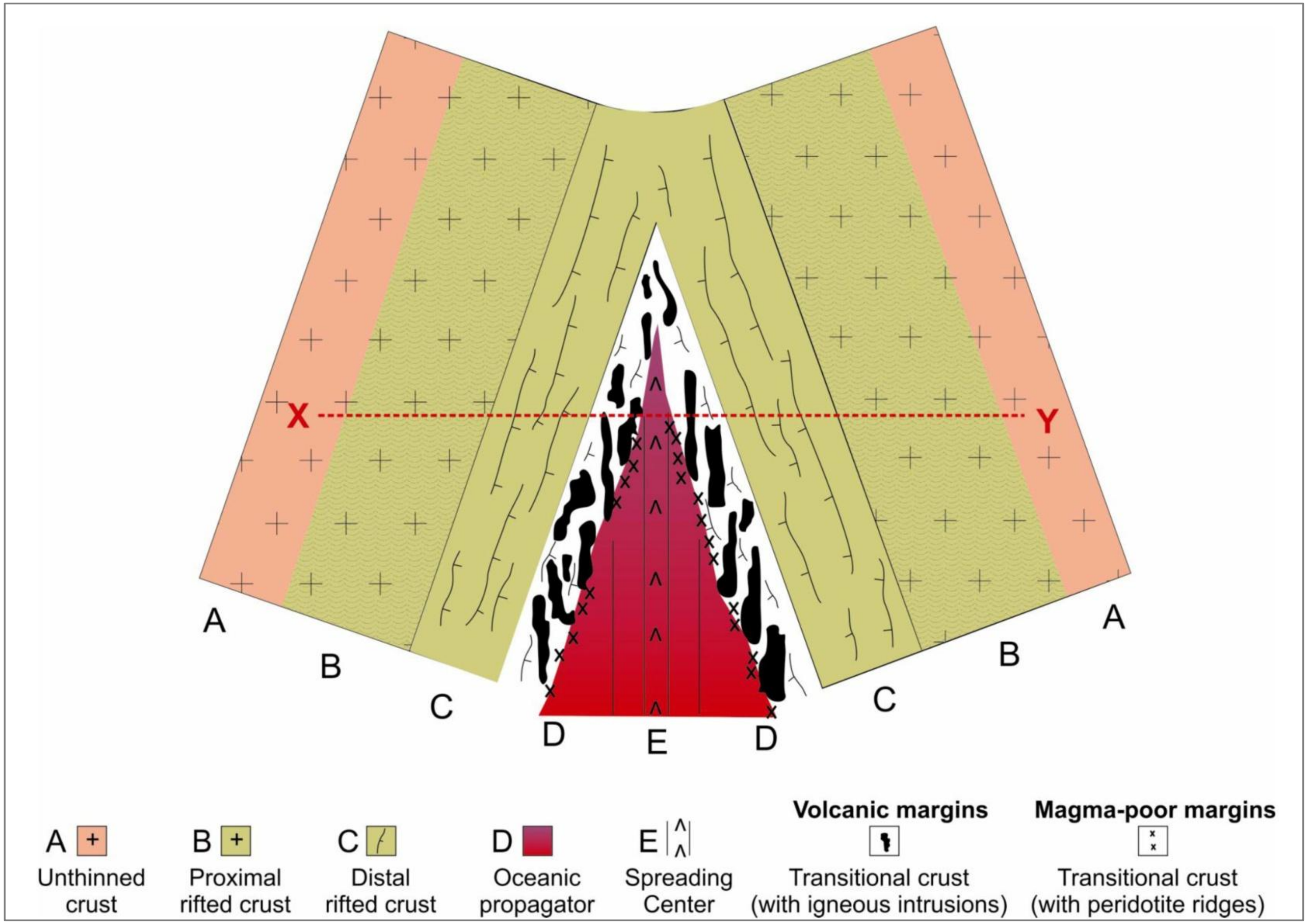

Figure 21. Schematic diagram showing the propagator model and implications for different stages in the same ocean. The region south of the X-Y transect across conjugate margins is characterized by igneous intrusions and extrusions, including seaward-dipping reflector wedges in the transition to oceanic crust and active spreading centers. North of the X-Y transect the propagator is just starting to impinge onto the continental crust, and the rift and salt basins are still affected by continental extension. The transitional crust between the distal rifted crust and the oceanic crust (segment between C and D) may be associated with exhumed mantle (peridotite ridges) in magma-poor margins.

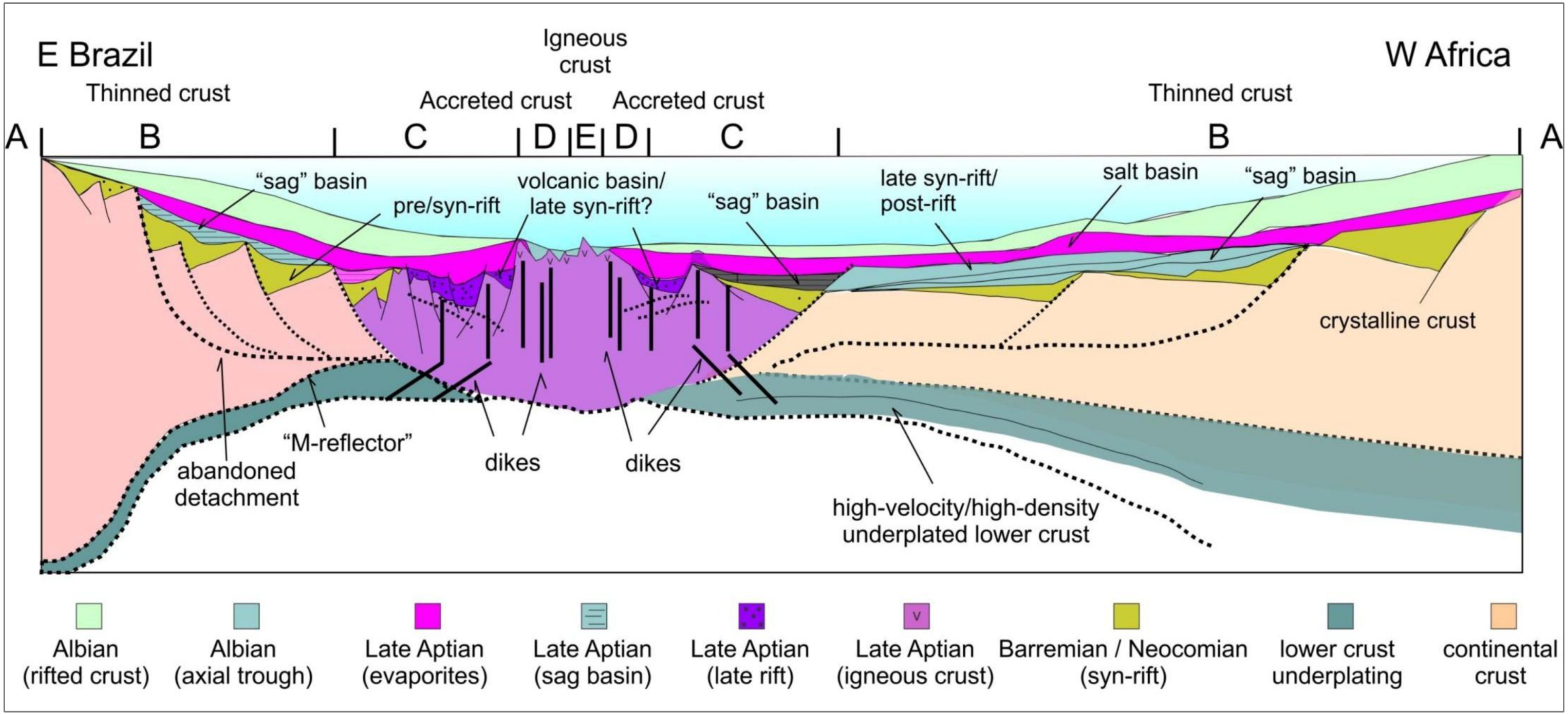

Figure 22. Schematic transect across the South Atlantic Ocean during the incipient oceanic basin (transition from the gulf to the open ocean stage, about 100 Ma) (from Mohriak and Leroy, 2013, modified after Blaich et al., 2011).

References Cited

Almeida, J., F. Dios, W.U. Mohriak, C.M . Valeriano, M. Heilbron, L.G. Eirado, and E. Tomazzoli, 2013, Pre-rift tectonic scenario of the Eo-Cretaceous Gondwana break-up along SE Brazil–SW Africa: Insights from tholeiitic mafic dyke swarms, *in* W.U. Mohriak, A. Danforth, P.J. Post, D.E. Brown, G. C. Tari, M. Nemcok, and S.T. Sinha, eds. Conjugate Divergent Margins: Geological Society, London, Special Publications, v. 369, p.11-40. First published online March 26, 2013, website accessed November 24, 2014 (http://sp.lyellcollection.org/content/369/1/11).

Blaich, O.A., J.I. Faleide, and F. Tsikalas, 2011, Crustal breakup and continent-ocean transition at South Atlantic conjugate margins: Journal of Geophysical Research, v. 116,B01402, 38p.

Boillot, G., S. Grimaud, A. Mauffret, D. Mougenot, J. Kornprobst, J. Mergoil-Daniel, and G. Torrent, 1980, Ocean-continent boundary off the Iberian margin: a serpentinite diapir west of the Galicia Bank: Earth and Planetary Science Letters, v. 48, p.23-34.

Bosworth, W., P. Huchon, and K. McClay, 2005, The Red Sea and Gulf of Aden basins: Journal of African Earth Sciences, v. 43, p. 334-378.

Davison, I., 2007, Geology and tectonics of the South Atlantic Brazilian salt basins, *in* A.C. Ries, R.W.H. Butler, and R.H. Graham, eds., Deformation of the continental crust: the legacy of Mike Coward. Geological Society, London, Special Publications, v. 272, p. 345-359.

Egloff, F., R. Rihm, J. Makris, Y.A. Izzeldin, M. Bobsien, K. Meir, P. Junge, T. Noman, and W. Warsi, 1991, Contrasting structural styles of the eastern and western margins of the southern Red Sea: The 1988 SONNE experiment: Tectonophysics, v. 198, p.329-353.

Ghebreab, W., 1998, Tectonics of the Red Sea region reassessed: Earth-Science Reviews, v. 45, p. 1–44.

Hughes, G., and R.S. Johnson, 2005, Lithostratigraphy of the Red Sea Region: GeoArabia, v. 10/3, p.49-126.

Leroy, S., P. Gente, M. Fournier, E. d'Acremont, P. Patriat, M.O. Beslier, N. Bellahsen, M. Maia, A. Blais, J. Perrot, A. Al-Kathiri, S. Merkouriev, J.M. Fleury, P.Y. Ruellan, C. Lepvrier, and P. Huchon, 2004, From rifting to spreading in the eastern Gulf of Aden: A geophysical survey of a young oceanic basin from margin to margin. Terra Nova, v. 16, p.185–192.

Ligi, M., E. Bonatti, G. Bortoluzzi, A. Cipriani, L. Cocchi, F. Caratori Tontini, E. Carminati, L. Ottolini, and A. Schettino, 2012, Birth of an ocean in the Red Sea: Initial pangs: Geochemistry, Geophysics, Geosystems, v. 13/8, Publication Date: 18 August 2012, website accessed November 26, 2014 (http://onlinelibrary.wiley.com/doi/10.1029/2012GC004155/full).

Lowell, J.D., and G.J. Genik, 1972, Sea-floor spreading and structural evolution of the southern Red Sea. AAPG Bulletin, v. 56, p.247-259.

Mitchell, N.C., M. Ligi, V. Ferrante, E. Bonatti, and E. Rutter, 2010, Submarine salt flows in the central Red Sea: Geological Society of America Bulletin, v.122, p. 701-713.

Mohriak, W.U., 2001, Salt tectonics, volcanic centers, fracture zones and their relationship with the origin and evolution of the South Atlantic Ocean: Geophysical evidence in the Brazilian and West African margins (expanded abstract): 7th International Congress of the Brazilian Geophysical Society, Salvador - Bahia – Brazil, October 28-31, 2001, p. 1594-1597.

Mohriak, W.U., 2004, Recursos energéticos associados à ativação tectônica mesozóico-cenozóica da América do Sul, in V. Mantesso Neto, A. Bartorelli, C.D.R. Carneiro, and B.B. Britoneves, eds., Geologia do continente sul-americano: evolução da obra de Fernando Flávio Marques de Almeida: Beca Produções Culturais Ltda., São Paulo, Chapter XVIII, p. 293-318.

Mohriak, W.U., and R. Fainstein, 2012, Phanerozoic regional geology of the Eastern Brazilian margin, *in* D. Roberts and A. Bally, eds., Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Map: Elsevier B.V., p. 223-282.

Mohriak, W.U., and S. Leroy, 2013, Architecture of rifted continental margins and break-up evolution: insights from the South Atlantic, North Atlantic and Red Sea–Gulf of Aden conjugate margins, *in*, W.U. Mohriak, A. Danforth, P.J. Post, D.E. Brown, G. C. Tari, M. Nemcok, and S.T. Sinha, eds., Conjugate Divergent Margins: Geological Society, London, Special Publications, v. 369, p. 497-535. First published online August 22, 2012, website acceded November 24, 2014 (http://sp.lyellcollection.org/content/369/1/497).

Mohriak, W.U., M. Nemcok, and G. Enciso, 2008, South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil, *in* R.J. Pankhurst, R.A.J. Trouw, B.B. Brito Neves, and M.J. de Wit, eds., West Gondwana pre-Cenozoic correlations across the South Atlantic region: Geological Society, London, Special Publications, v. 294, p. 365-398.

Mohriak, W.U., P. Szatmari, and S. Anjos, 2012, Salt: Geology and tectonics of selected Brazilian basins in their global context, *in* G.I. Alsop, S.G. Archer, A.J. Hartley, N.T. Grant, and R. Hodgkinson, eds., Salt Tectonics, Sediments and Prospectivity: Geological Society, London, Special Publications, v. 363, p. 131-158.

Pérez-Gussinyé, M., 2012, A tectonic model for hyperextension at magma-poor rifted margins: An example from the West Iberia–Newfoundland conjugate margins, *in* Mohriak, W.U., A. Danforth, P.J. Post, D.E. Brown, G.C. Tari, M. Nemcok, and S.T. Sinha, eds., Conjugate Divergent Margins: Geological Society, London, Special Publications, v. 369, p. 403-427. First published online December 21, 2012, website accessed November 24, 2014 (http://sp.lyellcollection.org/content/369/1/403).

Péron-Pinvidic, G., and G. Manatschal, 2008, The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: A new point of view: International Journal of Earth Sciences (Geol. Rundsch.), v.98, p 1581-1597.

Rangel, H.D., and C.C. Martins, 1998, Principais compartimentos exploratórios, Bacia de Campos, *in* Schlumberger, Search November 1998, Searching for Oil and Gas in the Land of Giants: Cenário geológico nas bacias sedimentares no Brasil, Capítulo, v. 2, p. 16-40.

Scotese, C.R., 2002, Paleomap Project. http://www.scotese.com.

Zalán, P.V., M.C.G. Severino, C.A. Rigoti, L.P. Magnavita, J.A.B. de Oliveira, and A.R. Vianna, 2011, An entirely new 3D-view of the crustal and mantle structure of a South Atlantic passive margin – Santos, Campos and Espírito Santo basins, Brazil (extended abstract): AAPG Annual Convention and Exhibition, Houston, April, 2011; Search and Discovery Article #30177 (2011), website accessed November 24, 2014 (http://www.searchanddiscovery.com/pdfz/documents/2011/30177zalan/ndx_zalan.pdf.html).

Acknowledgments

The author wishes to thank several geoscientists at PETROBRAS – Petroleo Brasileiro S.A. for enlightening discussions and participation in previous projects conducted in the 2000s, which focused on the geology of the Red Sea and the analogies with petroleum systems and exploratory plays in the South Atlantic. I am also grateful to many colleagues and students at UERJ – State University of Rio de Janeiro for providing suggestions and improvements for this work. The Red Sea Team at Saudi Aramco provided a unique opportunity to participate in a fieldtrip in the Midyan basin in 2013, and I enjoyed working with the large regional dataset offshore Saudi Arabia. The AAPG Distinguished Lecturer Program is also thanked for their invitation to participate in the 2014 program and present a brief summary of the chapter included in the book "Conjugate Divergent Margins", published by The Geological Society of London in 2013, at several universities and geological societies in the United States and Canada. Several geoscientists from these institutions provided insightful comments after the presentations, which helped in the preparation of this summary.

I am also thankful for the kind invitations to present keynote talks at the 4th Conjugate Margins Conference in Halifax and the 13th African Conference in Houston. Last but not least, I thank the editors from AAPG Datapages Search and Discovery, for their kind invitation to prepare the summary of this presentation and for providing constructive remarks that improved the final version of this work. Finally, I thank Stephanie Wisher for revising the final text and providing helpful comments.