Albian Rift Systems in the Northeastern Brazilian Margin: An Example of Rifting in Hyper-Extended Continental Crust*

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Abstract

The progress of petroleum exploration toward ultra-deep waters along the Eastern Brazilian coast resulted in the acquisition of seismic reflection data with records as deep as 30 km (18 sec TWT), making possible drilling of exploration wells in the distal portion of Northeastern Brazilian Rifted Margin (NBRM). The interpretation of this dataset allowed not only the visualization of an Albian marine rift system along the NBRM, but also the identification of the boundary between continental and oceanic crusts, and their internal structures. The rheological behavior of the upper and lower continental crusts controlled the geometry of rifted blocks, showing brittle or ductile deformation patterns, from high angle faulted blocks to rotated ones. Along the NBRM, the Albian rifting shows half-grabens with flip-flop and magmatic features such as sills and dykes sometimes related to a broad SDR's domain. Aptian salt diapirs are deformed within some distal Albian grabens suggesting that rifting occurred after the deposition of the Aptian salt. The Albian rift system exhibits wide variation of structural style and amount of associated magmatism.

In the central portion of the NBRM, the Jacuípe and Sergipe-Alagoas basins are characterized by widespread magmatism represented by large intrusions and magmatic flows (SDRs). Further north, the Pernambuco-Paraíba Basin presents a typical half-graben geometry associated with huge igneous features. The Albian age of the distal rift system was confirmed by pillow basalts (identified by resistivity image logging) interbedded with rift sediments. Moreover, samples of the pillow basalts were dated by $^{40}Ar/^{39}Ar$ around 104 Ma, correlated to magmatic bodies that crop out in the onshore Pernambuco-Paraíba Basin, which range from 94-102 Ma ($^{40}Ar/^{39}Ar$). We speculate that structures may be related to deep-water extrusive and intrusive magmatic features mapped in deep reflection seismic sections. Furthermore, organic-rich marine shales were also drilled in the Albian rift system, attesting the presence of source rocks to Upper Cretaceous oil fields recently discovered in the Sergipe-Alagoas Basin. Therefore, the architecture of the Albian rift system plays an important role in understanding the tectonic evolution of the Northeastern Brazilian Rifted Margin and its associated marine petroleum system.

The Northeastern Brazilian Rifted Margin (NBRM): An Odd Puzzle

The Northeast Brazilian Rifted Margin (NBRM) comprises the northern portion of the East Brazilian Margin (EBM) where are located the Jequitinhonha-Almada-Camamu (Ferreira et al., 2013), Sergipe-Alagoas and Pernambuco-Paraíba rift basin sets (Figure 1A). The NBRM is limited southwards in the Jequitinhonha Basin by the Cenozoic Abrolhos magmatic complex, and northwards by the Equatorial Brazilian Margin tip - the Touros structural high in the Potiguar Basin. Unlike the southern part of the EBM, which is well studied due to the recent pre-salt petroleum discoveries in the Campos, Santos and Espírito Santo basins, the distal part of NBRM remains poorly known, despite of the recent discovery of a petroleum province related to Upper Cretaceous turbidites in Sergipe-Alagoas Basin. Recent works (Caixeta et al., 2009, 2012; Ferreira et al., 2011; Ferreira and Caixeta, 2012) have argued the NBRM underwent a quite distinct tectonic evolution of the rest of the EBM.

New seismic reflection data with records as deep as 30 km (18 sec TWT), associated with geological information from some exploration wells in the distal portion of the NBRM, have brought great advances to understanding the tectonic evolution of the EBM. By means of interpretation of deep seismic sections it was observed that some well-established geological concepts about the breakup process in the EBM are outdated. A good example is to use the deposition of Aptian evaporites as a regional mark for ending of the rifting and the beginning of a widespread thermal stage along the entire EBM. This assumption might be useful for the southern portion of the EBM (basically Campos and Santos basins), but definitely can no longer be applied in the NBRM. Thus, the NBRM presents an odd tectonic story within a long-standing breakup model for the splitting up of the South American and African supercontinents.

The Marine Magmatic Albian Rifting: The Missing Piece of the Puzzle

The rifting process along the NBRM can be told in a single story (a common genetic tectonic story) composed by several chapters (poly phase rifting) where the characters (the basins) alternated a final chapter that was unknown (the Albian rifting). Now, this final chapter is played due to advancement of the petroleum exploration frontier toward ultra-deep waters. The earliest rifting in the Northeastern Brazilian coast occurred during Neocomian-Barremian times, with the onshore Reconcavo-Tucano-Jatoba rift system as its best example. During the Neo-Aptian, the NBRM began to develop its current framework through the linkage of isolated large grabens or basin depocenters strongly bounded by basement lineaments (e.g. Vaza-Barris). Some wells record more than 1 km of Aptian rift sediments in the Camamu, Almada and Pernambuco-Paraíba basins. From the Mid-Aptian, the rift architecture changed with the formation of conspicuous hinge faults basinward in Camamu, Almada and Pernambuco-Paraíba basins, while other areas such as Sergipe-Alagoas and Jequitinhonha had progressively less fault activity with initiation of thermal subsidence, known as SAG phase that was widespread until the Neo-Aptian when the Gondwana breakup had taken place. During this period the deposition of evaporites occurred which would mark the beginning of the drift phase. Until the last decade, the tectonic story of the EBM could be briefly told this way.

However, recently some deepwater wells located in Sergipe-Alagoas and Almada basins revealed an Albian rift system with a stratigraphic section very similar along the NBRM, basically dominated by marine pelites. A representative Albian rift section can be described by shale and marls interbedded with limestones and volcanics in the uppermost section. In contrast to the sandy Aptian rift section, which ends the proximal continental rifting, the distal Albian rift shows fine sediments deposited under the influence of widespread shallow marine environment.

Moreover, the Albian rift system displays a wide variability of structural styles and amount of magmatism along the NBRM. In the southern portion of the NBRM, half-graben sets occur with flip-flop geometry, mostly showing synthetic curved normal faults and associated magmatic features (sills and dykes) primarily within the uppermost section. On the other hand, the northern basins (from Jacuípe Basin northwards) are strongly controlled by magmatic flows which form antithetic curved normal faults that sometimes can be simply described as a SDR domain. The growth of the rift section occurs up to the Albian top, whereas the uppermost section of Cenomanian-Turonian age displays a SAG geometry (here named as SAG II) without significant fault control (Figrue 1B).Thus, the Albian rifting took place in the distal margin associated with magmatic rocks dated around 104 Ma ($^{40}Ar/^{39}Ar$) in the Sergipe-Alagoas Basin as well as is clearly characterized by resistivity image logging displaying pillow basalts with associated meso-scale columnar basalt structures (Figure 2). Furthermore, thin section petrographic analysis confirmed that magmatic rocks were formed by submarine flows interbedded with Albian-Cenomanian clastic rift sediments (Figrue 3). According to our model, the conjugate margin to the southern NBRM is the Gabon Basin which is characterized by a flip-flop basin pattern, marked by the Aptian salt level. The southern NBRM-Gabon Basin clearly presents a distal Albian rift basin toward the mid-ocean ridge. The salt is not common within Albian distal basins which might suggest an elevated area in that period of higher heat flow. The cooling that followed the period of heating formed a distal SAG basin during the Albian-Cenomanian, resulting in a favorable environment for organic matter preservation (Figure 4 and Figure 5).

Diachronic Breakup in the NBRM: From the Albian to the Cenomanian

The regional integrated interpretation of the NBRM (Ferreira et al., 2011; Ferreira and Caixeta, 2012) has shown that the rifting process goes on beyond the Aptian, and displays a distinct thermal phase over time. The latest rift pulses were strongly controlled by conspicuous basement lineaments (e.g. Vaza Barris, Pernambuco, Itabuna-Itaju do Colônia) which led and compartmentalized the rift propagation until the Gondwana breakup (Figure 6). In contrast to the southern part of the EBM, the thinning crust process in the NBRM was influenced by several distinct Archean-Proterozoic basement terranes such as São Francisco-Congo Craton, Pernambuco-Alagoas Massif, and Araçuaí and Sergipana fold belts. Such basement diversity reflected in different magmatic and structural styles along of the NBRM due to the wide variation of rheological behaviors during thinning and extension of the crust. The NBRM shows large variation of structural styles from short to hyper-extended margins. The central part displays short margins formed basically by necking zones in the Camamu and Jacuípe basins associated with the São Francisco-Congo Craton basement. At the southern tip, a broad margin was developed in Almada and Jequitinhonha basins, under influence of the Araçuaí fold belt. On the other hand, the northern portion presents a hyper-extended margin associated with widespread magmatism in the Sergipe-Alagoas and Pernambuco-Paraíba basins. There is clear northwards increase of the magmatism related to the breakup. All these evidence reinforces the puzzling breakup process for this part of the EBM. Along the whole distal NBRM the Albian magmatic rift system occurs in response to hyper-extension of crust just before the final breakup (Figure 1B, Figure 5, and Figure 6).

Therefore, the thinning of the crust occurred mainly in the most distal portion of the NBRM due to marine magmatic rifting, while other distal portions of the EBM (e.g. Jequitinhonha Basin to south) and the proximal margin were already under influence of thermal subsidence during the Albian, as attested by the existence of carbonate shelves. During the Neo-Albian-Cenomanian interval, the distal marine rifting shut down, meanwhile the carbonate platforms were being flooded in the proximal margin, when eventually a diachronic breakup took place throughout the NBRM. The Turonian shale, characterized by worldwide organic deposition, definitely marked the end of the tectonic activity related to the Gondwana breakup in the northern part of the EBM, here named as NBRM (Figure 5 and Figure 6).

Post-Breakup Tectonic Reactivations and Continental Uplifts in the NBRM

Several studies based on different techniques such as structural geological mapping, geochronology and thermochronology (Ferreira and Caixeta, 2012) have already addressed tectonic and magmatic events in the basement and onshore rift basins of the Northeastern Brazilian coast during Albian-Turonian interval (Figure 7). Thermochronology studies showed heating/cooling events in onshore basins and adjacent basement among 100-80 Ma (Morais Neto et. al., 2009), yet this period is still just described as a drift phase formed basically by thermal subsidence without significant rifting. Such events can be easily correlated to reverse faults and harpoon structures observed in deep-water seismic sections throughout the NBRM (Ferreira and Caixeta, 2012), resulted from the tardy breakup processes during Cenomanian-Turonian times. In the proximal margin, this period also was marked by reactivation and uplifting of pre-existing hinge faults and footwalls across the entire NBRM. In addition, post-breakup tectonic reactivations primarily occurred during the Neo-Cretaceous and Cenozoic, as characterized by regional erosional surfaces. Such tardy or post-breakup reactivations reshaped the structural style of the NBRM resulted in: (i) uplift of the Aptian rift section, (ii) development of late inversion/flower structure, and (iii) broad proximal erosion of Albian carbonate platforms.

Implications for Geodynamic Models

Most of current geodynamic models of the South Atlantic margin have argued that breakup of Gondwana took place around 112 Ma. Moreover, the end of rifting would have occurred before the deposition of Aptian evaporites when thermal subsidence had formed a widespread SAG phase along the Eastern Brazilian Margin. However, geological and geophysical interpretation of recent data in the northern part of the EBM (NBRM) revealed a more complex tectonic story, reasoned by an Albian magmatic rift pulse in distal margin, consequently placing final breakup after112 Ma (Figure 8). Furthermore, the NBRM presents a volcanic rifted margin showing short domains, formed basically by necking zones alternated with hyper-extended zones with Albian-Cenomanian magmatism confirmed by geochronological dating of magmatic flows interbedded with marine rift sediments. In addition, the amount of magmatism increases northwards, even as the breakup becomes relatively younger toward the Pernambuco-Paraíba Basin. Thus, the breakup leastwise in the northern part of the East Brazilian Margin was undoubtedly a diachronic process that took place during the Albian-Cenomanian interval.

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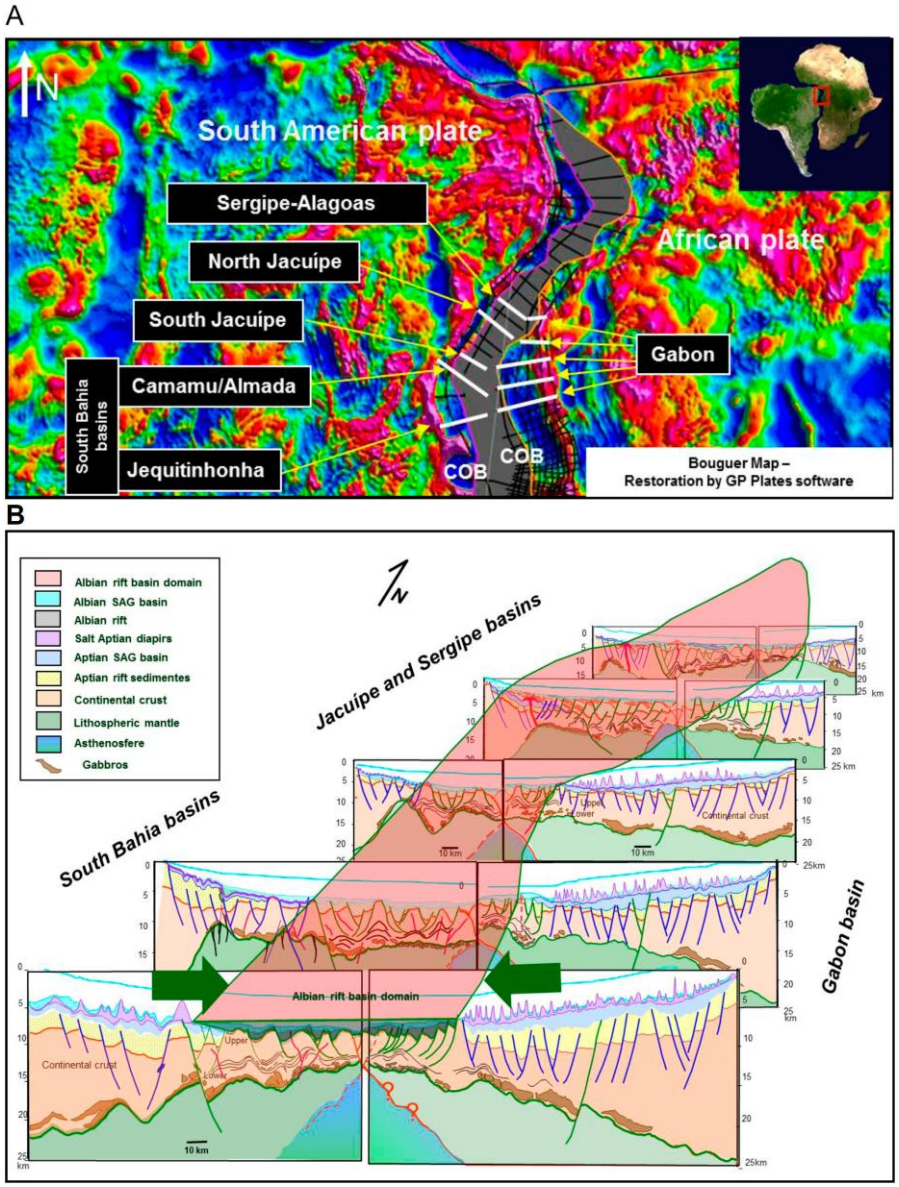

Figure 1. (A) Bouguer map displaying the location of the conjugate transects along the Northeastern Brazilian Margin based on plate restoration. (B) Conjugate crustal transects showing the Albian marine rift systems in distal portion before the first typical oceanic crust was formed. The Albian rift basins developed over hyper-extended continental crust, resulting in younger basins toward the center to the meso-oceanic chain. Source: Caixeta et al. (2012).

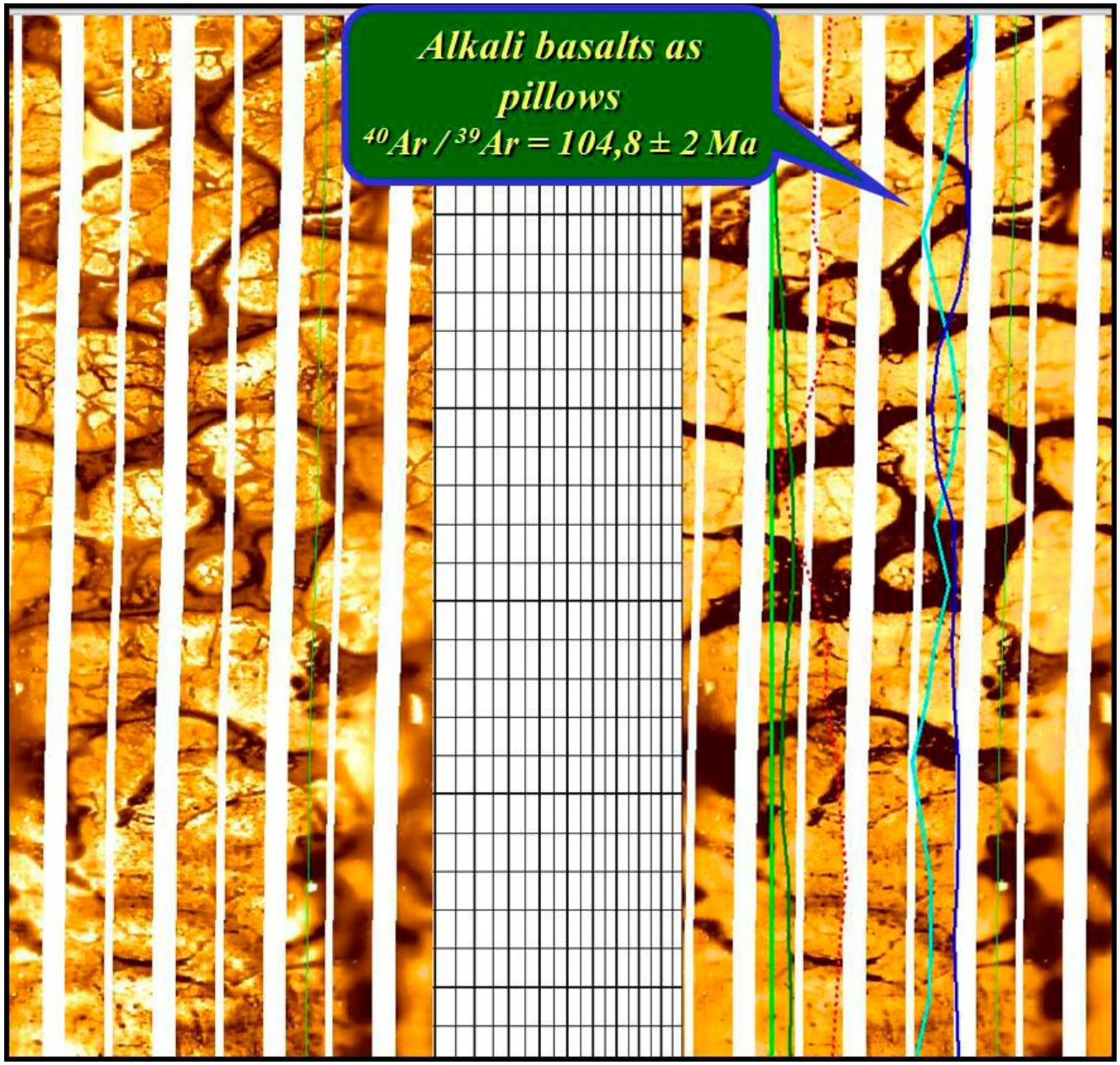

Figure 2. Alkali basalt interbedded with marine pelites in uppermost section of the Albian rift dated as 104 Ma (^{40}Ar-^{39}Ar) showing meso-scale pillow lavas interpreted from resistive image logging of a well located in Sergipe-Alagoas Basin.

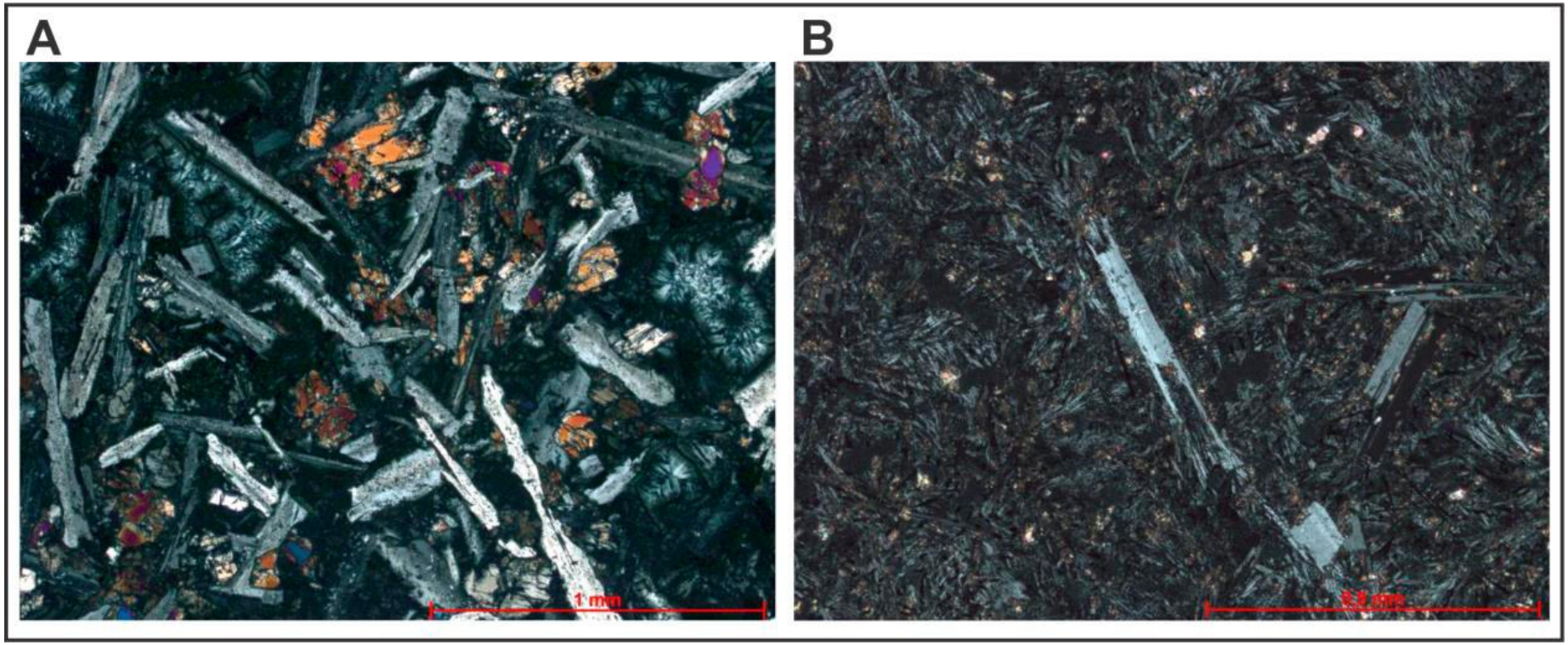

Figure 3. (A) Photomicrography of an Albian magmatic rock drilled in the Sergipe-Alagoas Basin showing a typical intergrowth texture associated with absence of volcanic glass (holocrystalline). (B) Photomicrograph of another Albian magmatic rock displaying swallowtail plagioclase and plumose texture, which is a typical characteristic of a subaqueous environment.

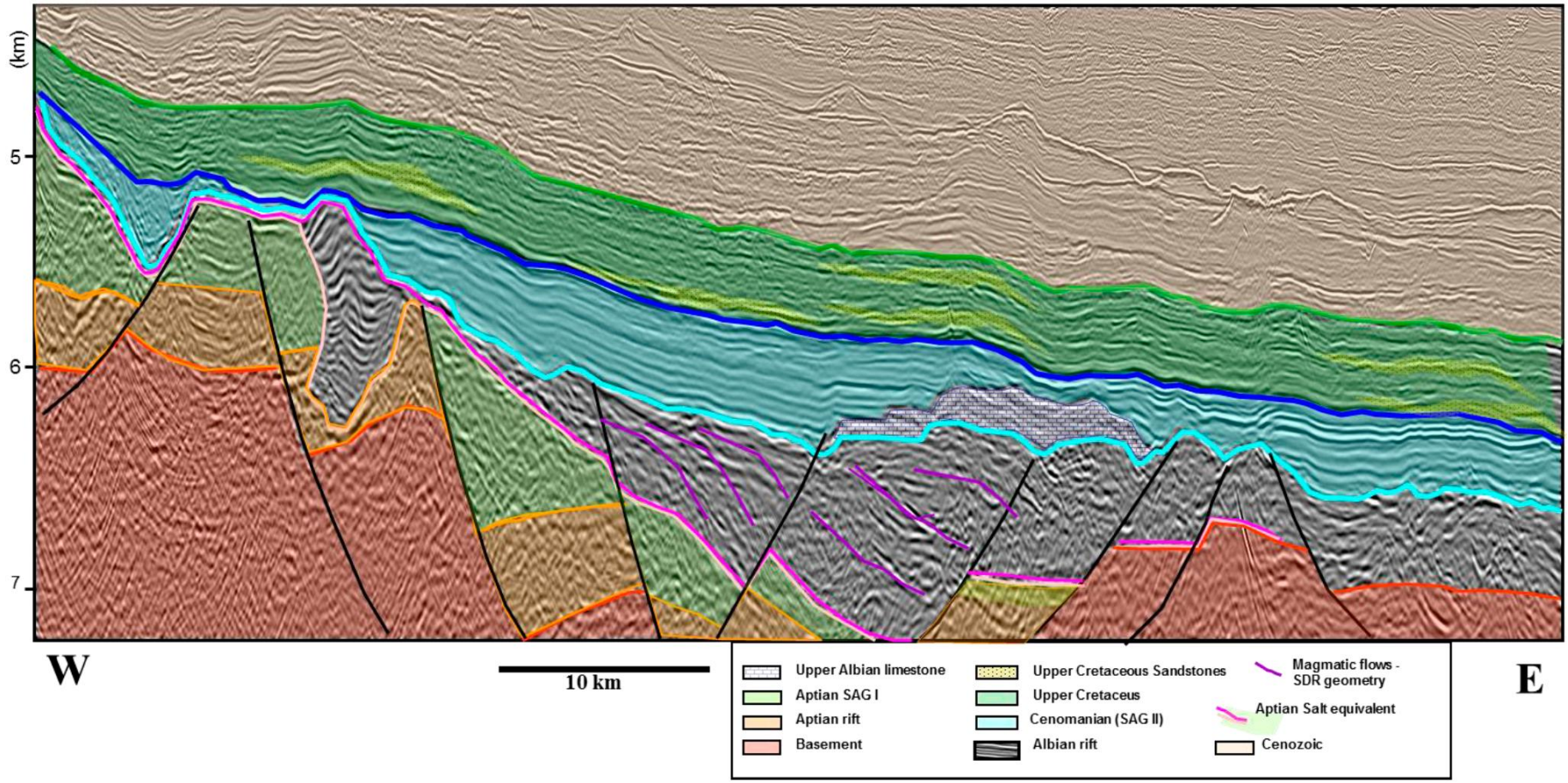

Figure 4. Detail of the Albian rift geometry in Sergipe-Alagoas Basin. Antithetic curved faults control marine Albian rift sedimentation (seaward dipping reflectors) associated with magmatic flows.

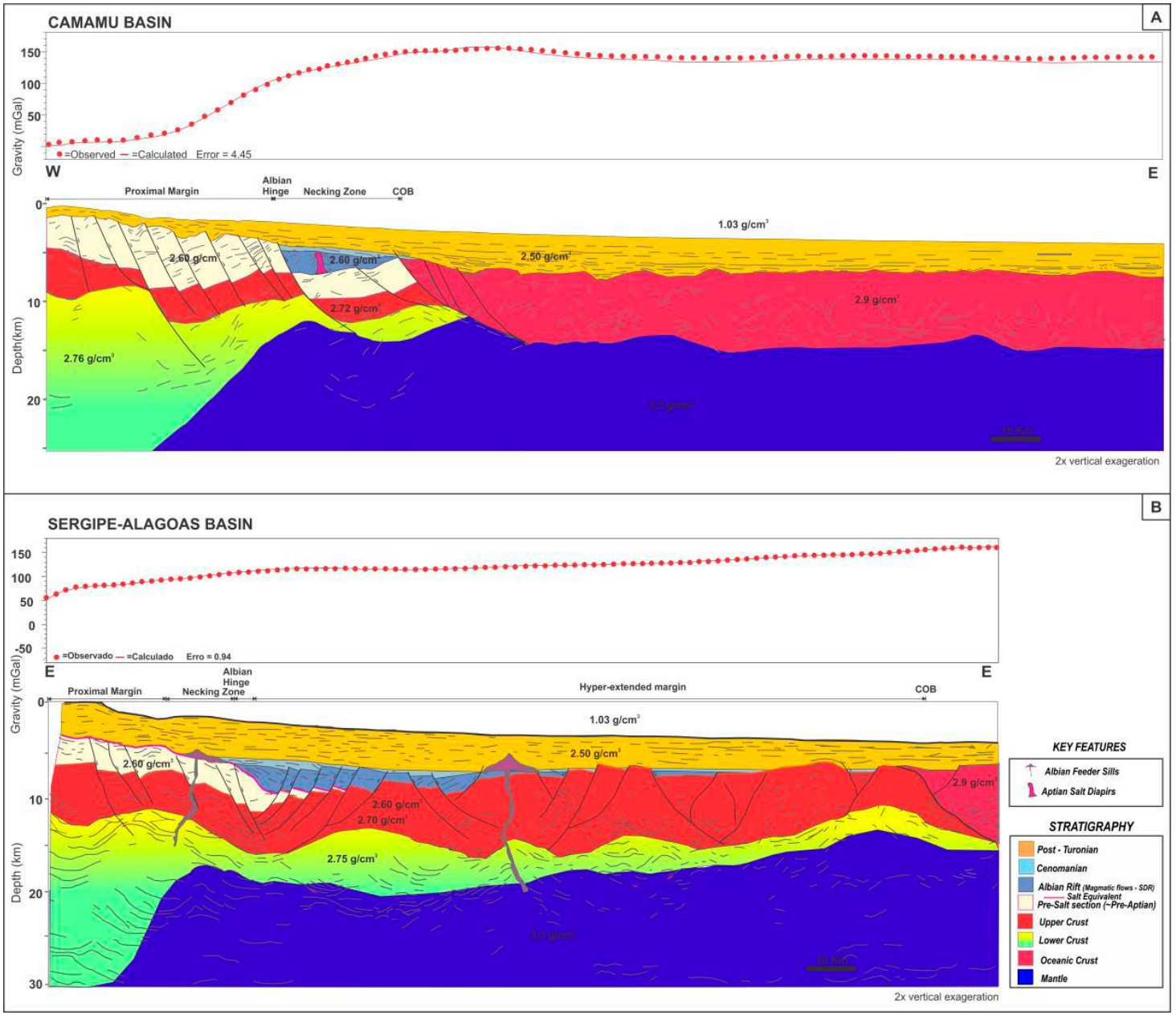

Figure 5. Geological sections located in the (A) Camamu and (B) Sergipe basins showing the tectonic domains across in these margins. Density values printed on each profile were used to adjust the interpretation to the gravimetric curve located above the sections.

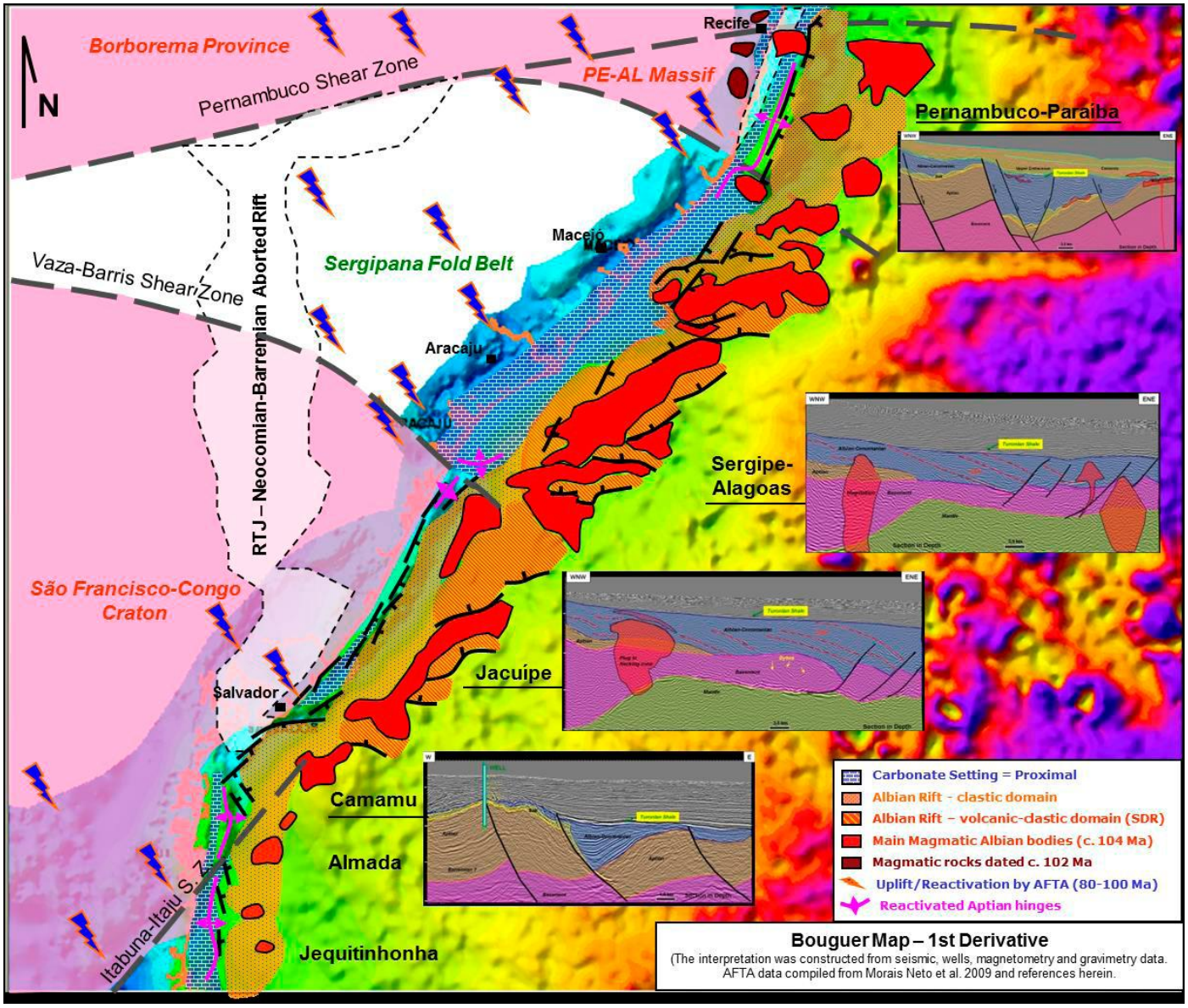

Figure 6. Albian tectonics in the Northeastern Brazilian Rifted Margin (NBRM). The Albian rift system along the NBRM clearly shows an increase of magmatic features northward. Basement lineaments and early proximal hinge faults were reactivated during Albian rifting in the distal portion of the NBRM. Several interpreted seismic sections (black inlets) display the wide variation of Albian rift styles since typical half-grabens to SDR geometry (blue area in the inlet sections) across the NBRM. Source: Ferreira et al. (2011).

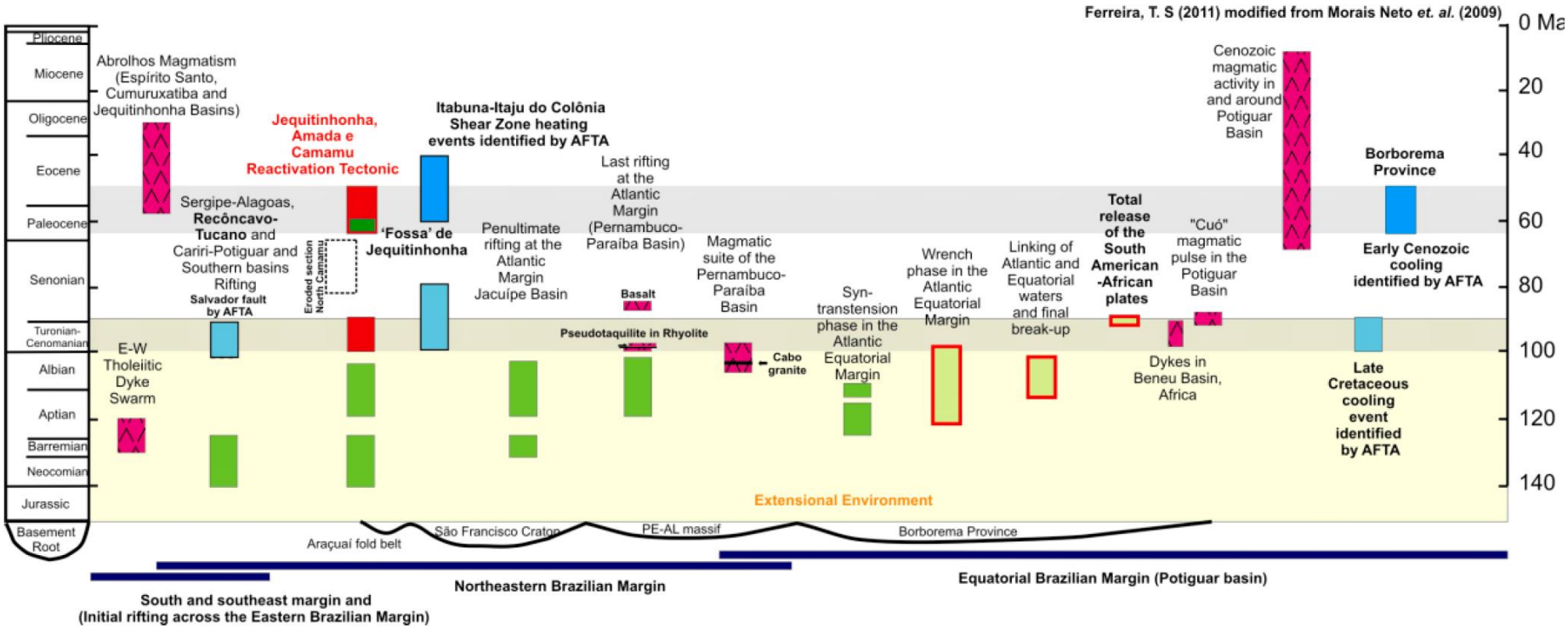

Figure 7. Tectonic and magmatic events reported along the East and Equatorial Brazilian margins by several methodologies. Note that several events are concentrated at two age intervals: 62-50 Ma and 100-90 Ma. In the 62-50 Ma interval Paleogene tectonic reactivation is associated with magmatic pulses (e.g. Abrolhos Magmatism) in offshore basins while adjacent basement and onshore basins were uplifted. Age 90-100 Ma primarily shows reactivations and magmatic pulses related to final breakup of the northeast Brazilian coast. Source: Ferreira et al. (2011).

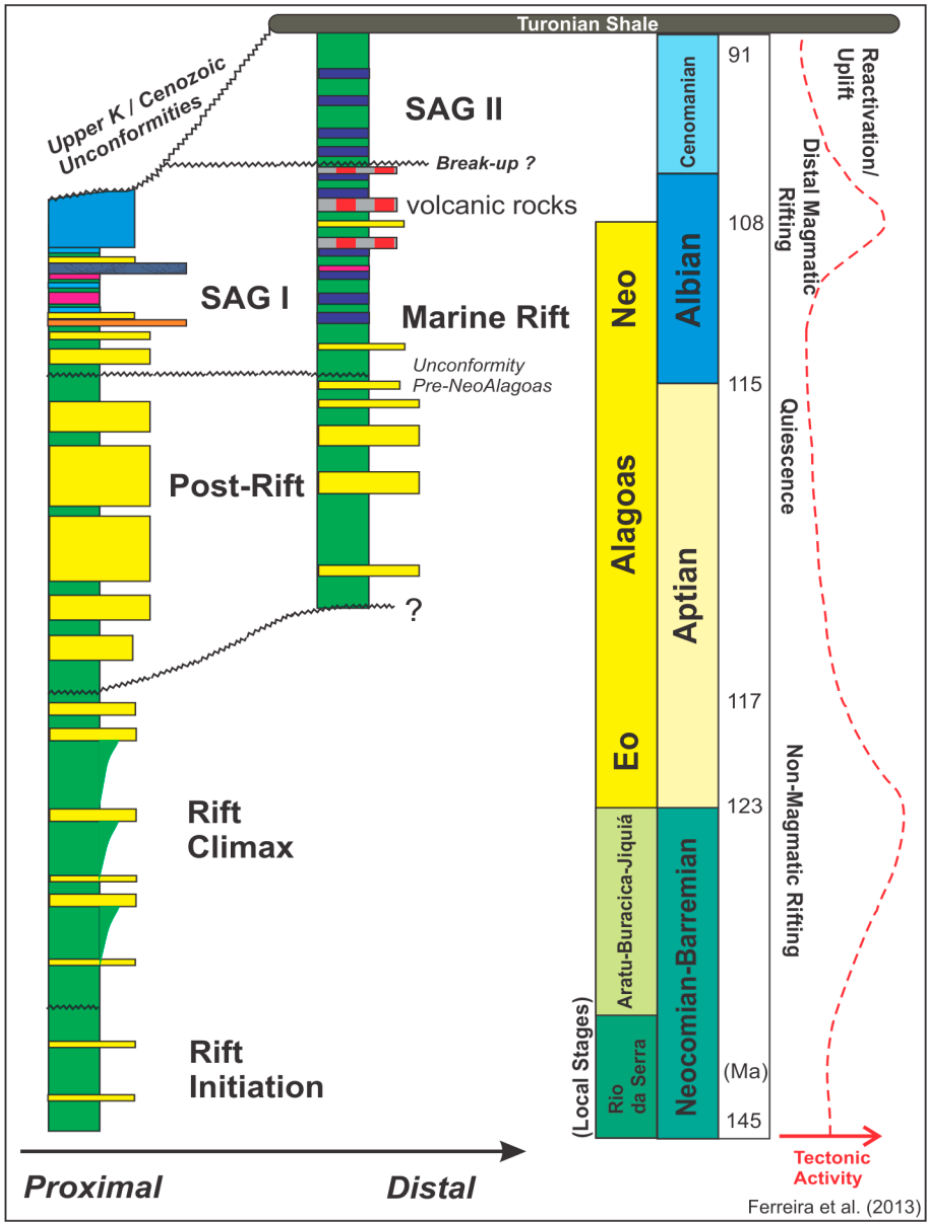

Figure 8. Sketch summarizing the rift pulses that formed the Northeastern Brazilain Rifted Margin (NBRM) over time and its correlation between proximal and distal margins. The Albian marine magmatic rifting only occurred on distal portion of the NBRM, whereas old rift hinges were reactivated and uplifted. Adapted from Ferreira et al. (2013).