The Abrolhos Magmatism as a Trigger for Cenozoic Deformation in Cumuruxatiba Basin, Brazil*

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Abstract

The Cumuruxatiba basin is located in the southern coast State of Bahia in northeastern of Brazil. This basin was formed in distensional setting, with rifting and subsequent thermal phase during Neocomian to Late Cretaceous. During the Cenozoic, the Abrolhos magmatism occurred in the basin with peaks during the Paleocene and Eocene. In this period, there was a kinematic inversion in the basin represented by folds related to reverse faults. Structural restoration of regional 2D seismic sections revealed that most of the deformation was concentrated at the beginning of Cenozoic time with the peak in early Eocene. The post-Eocene has been marked by a decrease of strain rate to the present.

The 3D structural modeling revealed a fold belt (trending E-W to NE-SW) accommodating the deformation between the Royal Charlotte and Sulphur Minerva volcanic highs. The volcanic eruptions resulted in a differential overburden on the borders of the basin acting as the trigger for halokinesis. Consequently, the deformation tends to be higher in the edges of the basin. The volcanic rocks occur mainly as concordant structures (sills) in the syn-tectonic sediments, which showing concomitant deformation.

The isopach maps and diagrams of axis orientation of deformation reveal that most of the folds were activated and reactivated at different times during the Cenozoic. The folds exhibit diverse kinematic patterns over time as response to behavior of adjacent volcanic highs. These interpretations integrated with information on the petroleum system of the basin are important for risk analysis in mapping the prospects for hydrocarbons in Cumuruxatiba basin.

Background and Setting

The Cumuruxatiba basin had its tectonic evolution related to the formation of rifts in the Neocomian progressing to opening of the Atlantic Ocean. The Cumuruxatiba basin had a similar development to neighboring ones of eastern Brazilian margin. However, at the Cenozoic period, the basin was under the influence of basalt flows and diabase intrusions in their stratigraphic sections. The Cenozoic magmatism formed huge magmatic highs (Royal Charllotte, Abrolhos and Sulfur Minerva); the overload of volcanic rocks of higher density probably changed the dynamics of depositional Cenozoic regressive sediments was the trigger for salt tectonics during this period. This work has

analyzed qualitatively and quantitatively the structures formed during the Cenozoic period, represented by fault-related folds in the Cumuruxatiba basin; it provides support to regional geological understanding about salt tectonic related to Abrolhos magmatism and provides information for petroleum exploration, such as: (a) timing of the formation of traps and its deformation over time, (b) salt tectonics control in the regressive sedimentary sequence and formation of stratigraphic traps, and (c) evaluation of possible oil migration pathways.

The study area is located in ultra-deep water (bathymetry above 1500m) on northeast of Brazil at the coast of Bahia state (Figure 1). The study area corresponds to a rectangular polygon of about 1110 km^2. About 50% area was studied with 3D seismic data and four 2D seismic sections covering the entire study. Two wells were used in the calibration of seismic data and structural modeling. All these data are owned by Petrobras; the seismic and borehole data are also included in the collection of the National Petroleum Agency – ANP. In the regional study four 2D seismic section, oriented NNE – SSW, were restored (namely, (011 Az), 250-0206, 250-0207, 250-0208 and 250-0209, hereinafter referred to as 206, 207, 208, and 209, respectively). All sections are in deep water, and they are limited to the north-south by magmatic highs, Royal Charlotte and Abrolhos respectively (Figure 1).The chrono-stratigraphic Cenozoic intervals are subdivided for seismic interpretation into Paleocene, early Eocene, middle Eocene, late Eocene, and post-Eocene in order to characterize the deformation. The 3D model was built from 9 seismic horizons, and several faults were mapped that represent the tectono-stratigraphic framework of the post-salt section of the Cumuruxatiba basin.

The Cumuruxatiba basin integrates a set of basinal development on the continental margin of eastern Brazil and characterized as rifted passive Atlantic (Chang et al., 1990). The rift section was formed by normal faults during a phase of extension (rifting and local mechanical subsidence). The post-rift section has sediments corresponding to the transition phase and continental drift. This was initiated by thermal expansion and contraction that caused the subsequent regional thermal subsidence. It is assumed that the flexural overload caused by high sedimentation rates and volcanic overload amplified the subsidence in this phase (Chang et al., 1990). The sedimentary record is formed by Phanerozoic deposits, dating from the Early Cretaceous (Neocomian) to Recent, represented by fluvial-deltaic sediments and lacustrine rift interval, tidal lagoon, and evaporite (restricted marine), transitional and marine sediments of the passive margin.

Cenozoic Magmatism, Salt Tectonics and Fault-related Folds

The post-rift section, the object of present study is controlled by salt tectonics as a result of the onset of thermal subsidence of sedimentary basin and volcanic overload. The listric faults, rollovers and diapiric salt occur mainly in response to high sedimentation rate from Albian to Maastrichtian (Gontijo, 1996). In Cenozoic times, the overload of Abrolhos magmatism associated with thick shale section of Urucutuca Formation resulted in salt-tectonic reactivation of listric faults as reverse faults and drag folds. As a result, highs and troughs that were generated conditioned the distribution of siliciclastic sediments reaching the basin (Gontijo, 1996).

The Cenozoic magmatism is represented by basalts, diabase, and several volcaniclastic rocks, such as hyaloclastites, tuffs, and breccias. These lithologies show the complexity of magmatism, as demonstrated by the associated explosive, subaerial, and subaqueous deposits. The chemical characterization of rocks is tholeiitic to alkaline, and allows interpretation of the degree of partial melting decreasing over time (Conceição et al., 1994). The Abrolhos magmatism occurred between 37 and 59 Ma as several pulses deformed the sedimentary section as

well as the earlier formed volcanic-sedimentary sequences (Conceição et al., 1994). Mohriak (2006) claims that the end of the Abrolhos magmatism is well evidenced in seismic sections by an erosive unconformity that coincides with the boundary between the Eocene and Oligocene. The later pulse of 28.4 Ma was dated from samples of a well located near the Royal Chartlotte magmatic high in northern Cumuruxatiba basin. The Abrolhos magmatism, according Conceição et al. (1994), is classified as a type of hot spot on an intra-plate position. Although its genesis is not explained by the activity of an ascending plume, but by involving the reactivation of fracture zones in oceanic crust and Proterozoic basement shear zones.

The 3D model shows the folds developed by the propagation of faults (fault-propagation folds) as key structures in the Cenozoic deformation (Mitra, 1990; Shaw et al., 2005). They occur along reactivating trends (N-S) listric normal faulting or as new Cenozoic faults (Figure 2) that show curvi-planar geometry. The Cenozoic faults are predominantly oriented EW to NE-SW, perpendicular to oblique to the trend of extensional phase. Some transfer zones were reactivated in Cenozoic. The throw reaches hundreds of meters, providing substantial reverse displacement in some faults. The throws of thrust faults are marked in Albian and Cretaceous top horizons, decreasing until the Paleocene. The Eocene horizon top is not affected by faults and is present only as gentle folds. There is a predominance of a mass transport toward the north. Thus, the structures that show this polarity will henceforth be called as "synthetic." In some sectors of the basin, it is possible to characterize the change of fault polarity like a flip-flop. This change is also accompanied by change of vergence, which sometimes provides the formation of triangular areas (Figure 2).

In the northern part of Cumuruxatiba basin there is a predominance of folds with vergence and mass transport to the south, forming an antithetical triangular zone oriented E-W in the western portion. In the central portion, the faults are synthetic with mass transport to the south. In the east, the trend changes to NE-SW, with the resumption of antithetical set and mass transportation (fold vergence) to the north. There is no contact or intersection of faults resulting from the change of polarity. The folds respond to this variation, forming cells in the folds along the main strike belt. In some horizons, folds are totally disconnected in the strike direction. A triangular zone forms a corridor of E-W direction and changes to NE-SW in the distal portion of 3D model (Figure 2). On the other hand, in the southern part of Cumuruxatiba basin, there is the predominance of folds with vergence and mass transport to the north, presenting similar structures. The central portion of Cumuruxatiba basin is characterized by harpoon structures that resulted from reactivation during the Cenozoic of N-S extensional listric faults. The folds show good development on the tips of normal faults toward the north. The tips of normal faults are reactivated as plane curves that accommodate fault-propagation folds (Figures 2).

Salt tectonics is the main process associated with the formation of faults and folds in the Cumuruxatiba basin. The movements of salt were due to variations in loading that initiated the formation of structures during the Paleocene. The trigger for salt tectonics was associated with flows or eruptions from Abrolhos magmatism (Guerra, 1989). This magmatism began in the Paleocene and had main pulses in the Eocene, resulting in regional movement of salt toward center of the basin. This region has large salt diapirs, in some cases associated with detachment folds and pop-ups filling-in the low blocks of thrust fronts. Variations in the geometry of the salt top can be analyzed with the structural restoration of the 3D model. Such variations are illustrated with maps that show two N-S trends, which have developed since the Cretaceous. During the Eocene, E-W and NE-SW diapiric salt trends also developed. The N-S trend is associated with listric faults of the

Albian rifting phase. The E-W and NE-SW salt diapir trends that developed from Eocene onward show strong relation to reverse faults and folds that have developed during the Cenozoic.

In the Paleocene and Cretaceous, the salt diapirs reached few kilometers high in a deep trough in the center of the basin between the two main N-S listric fault trend. From the Eocene, this pattern disappears and diapirs are smaller. Such pattern was controlled by large N-S listric faults, with the escape of salt associated with the growth of the Cretaceous section. Such salt movements occurred until the Paleocene, which marked the end of the extensional phase. Since the Early Cretaceous a NE-SW salt diapiric trend formed; in some places it crosses the N-S diapiric trend. This NE-SW salt trend must be associated with an extensional transfer zone. During the Cenozoic deformation, the main thrust front was related to structures oriented E-W to NE-SW (Figure 2).

The data analysis from four regional 2D sections (e.g., Figure 3) was done to characterize the Cenozoic deformation over a period of time in Cumuruxatiba basin. This analysis also shows the relation between the Abrolhos and Royal Charlotte high magmatic and Cumuruxatiba basin. Deformation started in the Paleocene. The greatest shortening obtained in the restored sections was observed in the Eocene section (here divided into early, middle and late). In post-Eocene, the deformation decreased. Figures 3 and 4 shows in some detail shortening during these time periods. There was a concentration of deformation in the period from 30 to 55 Ma. The section 209 shows linear shortening up to 110 km. In sections 206 and 208, the shortenings are around 70 km (72.3 and 78.5 km, respectively). The strain rate (the amount of longitudinal shortening divided by the time horizon) has significant variation throughout the basin and over time. Strain rate for Paleocene to Early Eocene increases until the peak of deformation in the Cenozoic. The variation of strain rate over time in restored sections presented two peaks of maximum deformation, in the early and late Eocene (34 to 48 Ma) between the period of lower deformation, which corresponds to the middle Eocene. After the Eocene (after 30 Ma), the strain rate gradually decreased until the present. This denotes the cooling associated with the deformation in the Cumuruxatiba basin after the Eocene times.

Figure 4 shows the cumulative shortening of the sections during the Cenozoic and its location in relation to the coastline, from the proximal to distal restored sections. The graph shows a total shortening, ranging from 16 to 33% in sections, with the highest values located in the proximal and distal portion of the basin, respectively. The central part of the Cumuruxatiba basin accommodates less deformation. This portion of the basin indicates less deformation than on the edges of the basin where there occurred the greater influence of salt tectonics.

The isopach maps show the variation of sediment thickness between two horizons. This variation may reflect sedimentary processes (gravitational flow in edges, clastic wedges deposited by eustatic variation, etc.) and deformational processes (growth syn-sedimentary section associated with listric faults, thinning by uplift in areas of fold hinges, etc.). Often, the thicknesses shown in the maps are the product of a sum of several processes acting simultaneously. In this particular case, the isopach maps are mainly influenced by the activation of reverse faults and folds due to overload of volcaniclastic sediments.

In fold hinge zones of syn-deformation sediments tend to restrict thickness, forming onlaps against the flanks of the folds. Depending on the sedimentation rate, there may be the largest thickness differences between the flanks of the folds. In regions with low sedimentation rate, non-deposition and even erosion may have occurred in the hinges. In the case of deep-water sediments of Cumuruxatiba basin, the

sedimentation rate was low, with erosion in the hinge of some folds. The thinning of the syn-deformation Cenozoic sediments was the main criterion used in this work to indicate activity of fault-related folds over time. It was also possible to obtain relative chronology of movement of structures over time by interaction between different thrust fronts. These criteria were used to observe evolution of fault-related folds during the Cenozoic.

The isopach study of Paleocene and early Eocene sections revealed that major variations in the sediment thickness are related to the beginning of the formation of fault-propagation folds. In the southern portion of the basin, some reverse faults were reactivated as spoon-shaped from the tips of normal listric faults.The structural restoration of each horizon that represents a stratigraphic period yielded strain maps over Cenozoic times. These strain maps obtained from each restored horizon were related to maximum strain vectors in order to show strain behavior over time in the study area. The highest strain values are concentrated in the center and edges of the faults, which are mostly curved. The strain concentration in the center of the fault displacement and extent may be related to the cumulative largest throw, while the terminations are related to dissipation of the strain at the tip. Areas of interaction between two faults, as triangular zones, also show high values of strain. Damage zones are well marked and followed by the fault traces for several kilometers. The orientation of the maximum strain axis since Cretaceous until Paleocene is approximately S10W, coinciding with orientation of 2D regional restored seismic sections. Also noticed is a secondary strain axis with orientation N45E to N80E, in the Paleocene and Cretaceous, respectively. This secondary axis may be related to interference of Cenozoic deformation structures by pre-existing NE-SW orientation that occurs mainly in the northern area.

The restorations made in regional 2D seismic lines present quantitative data of this Cenozoic deformation. The shortening of the total longitudinal sections in this period ranged from 16% to 33%. The lowest values are concentrated in the restored lines located in the center of the basin. About 40% of strain was accumulated between the Paleocene and Early Eocene. In the Eocene and Post-Eocene period occurred about 35% and 15% of total shortening, respectively (Figure 4). The strain rate data indicate that the strain peaks occurred in the early Eocene and late Eocene. A further increase in strain rate was recorded in the latter, and from then on, there was a decrease in the deformation, probably related to the cooling (Figure 5).

The 3D digital modeling revealed E-W folds trends in the northern part of the basin that show a wide variation of strain along the strike. This variation is represented by reverse polarity of the folds and faults (synthetic and antithetic) forming triangular zones. The N-S trend was strong control on inverse kinematics of fault-propagation folds in the Cenozoic. Salt tectonics controls all this deformation, forming also large diapirs. In the final stages of Cenozoic deformation, the salt was concentrated in the center of the basin, possibly in response to overload of magmatic rocks during the Eocene (Figure 5).

Conclusion

The Abrolhos magmatism was the main factor in the initiation and propagation of salt tectonics that occurred in the basin during the Cenozoic. These salt movements resulted in a kinematic inversion forming fault-related folds that occurred in several pulses in a complex pattern due to the location of Royal Charlotte and Sulphur Minerva magmatic highs, in north and east of the basin, respectively. This work has great importance and applicability to petroleum exploration. There is already an active petroleum system with Albian source rock (oil

fields discovered in shallow water). In that way, knowing the timing of fold development is fundamental to the understanding of structural traps for hiperpicnites sandstones deposited in regressive section (Urucutuca Formation) during Late Cretaceous and Cenozoic times.

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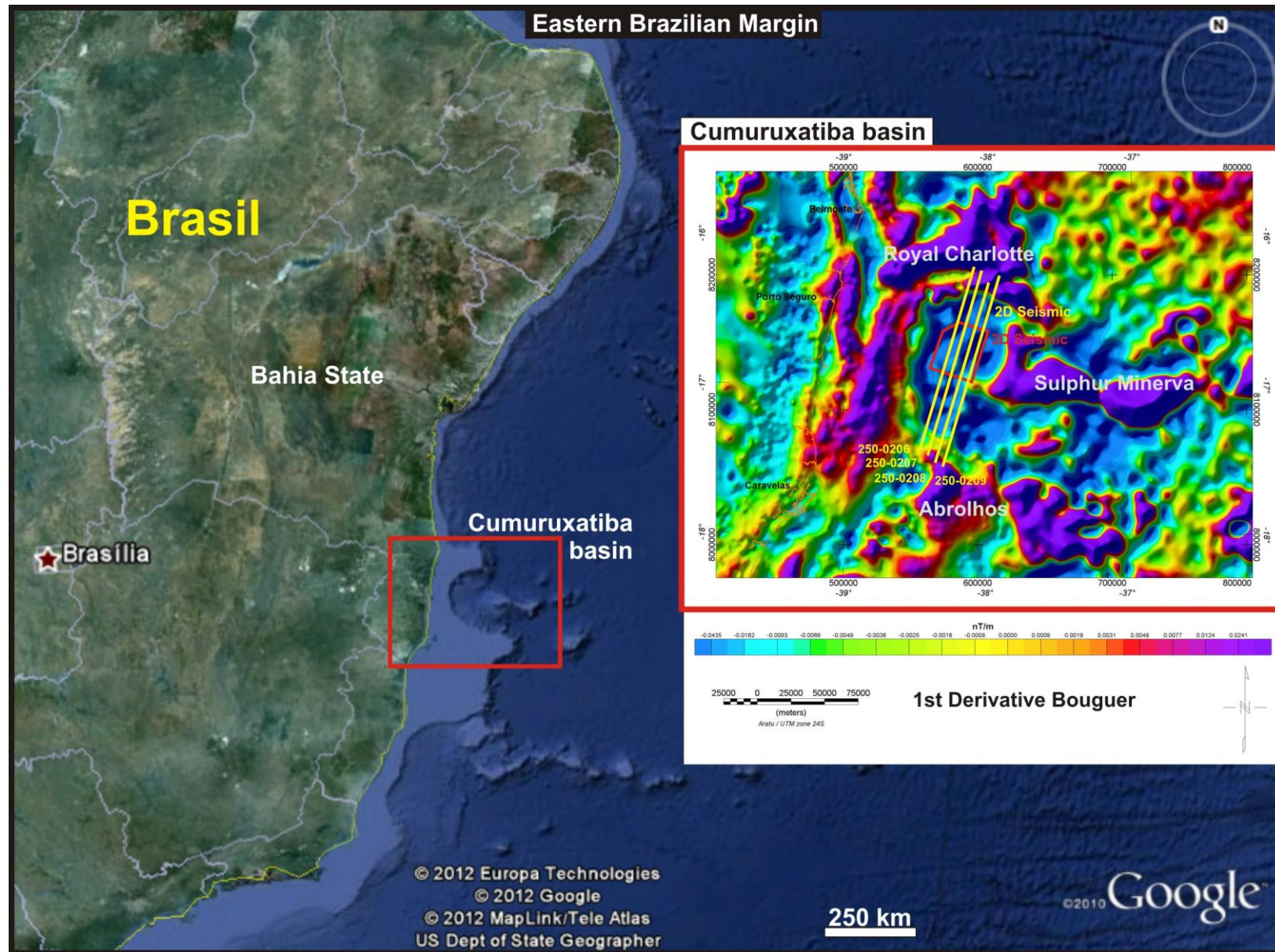
Figure 1. Location map of the Cumuruxatiba basin on the eastern Brazilian Margin. In detail, a Bouguer map that highlights the Cenozoic magmatic highs surrounding the basin. In this map also is presented the layout of the seismic data used (2D lines, yellow; 3D data area, red). Source of location map: Google Earth.
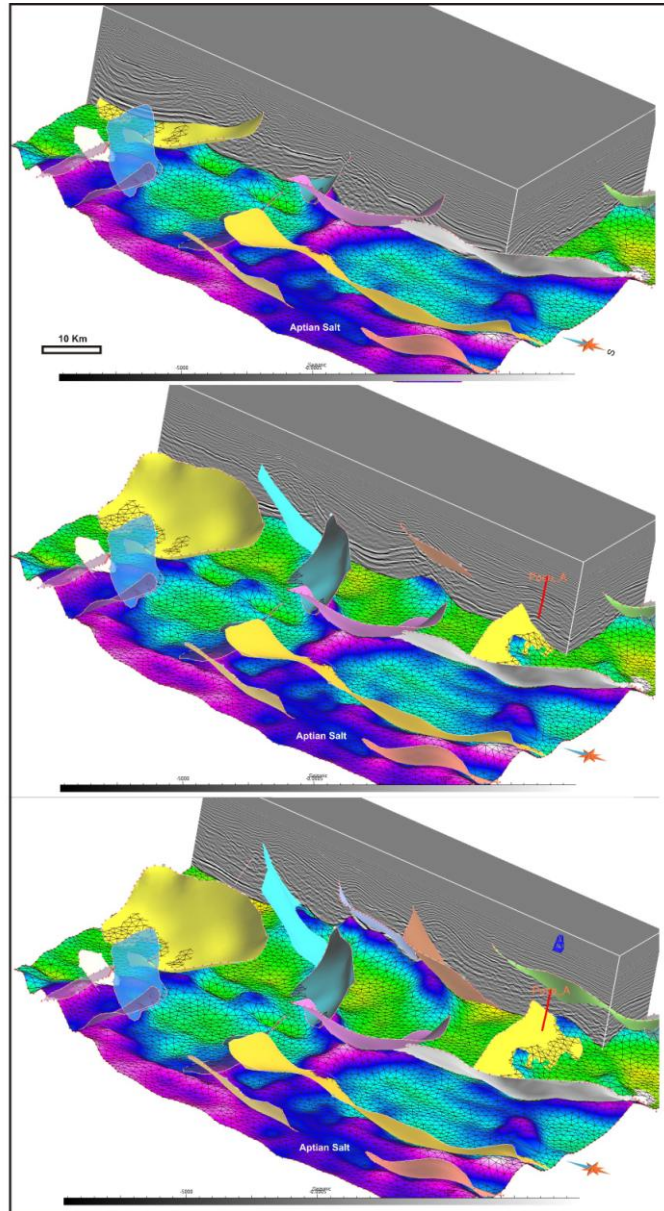
Figure 2. 3D view showing the fault and fold architecture. The Aptian salt forms a detachment surface. Notice the pattern of synthetic faults-related folds to NE-SW and mass transport to south and north. Spoon-shaped faults develop folds at tip of fault.

Figure 3. Structural restoration in 2D seismic line (250-0208). Note that the formation of folds in Cenozoic period with maximum shortening during Eocene.
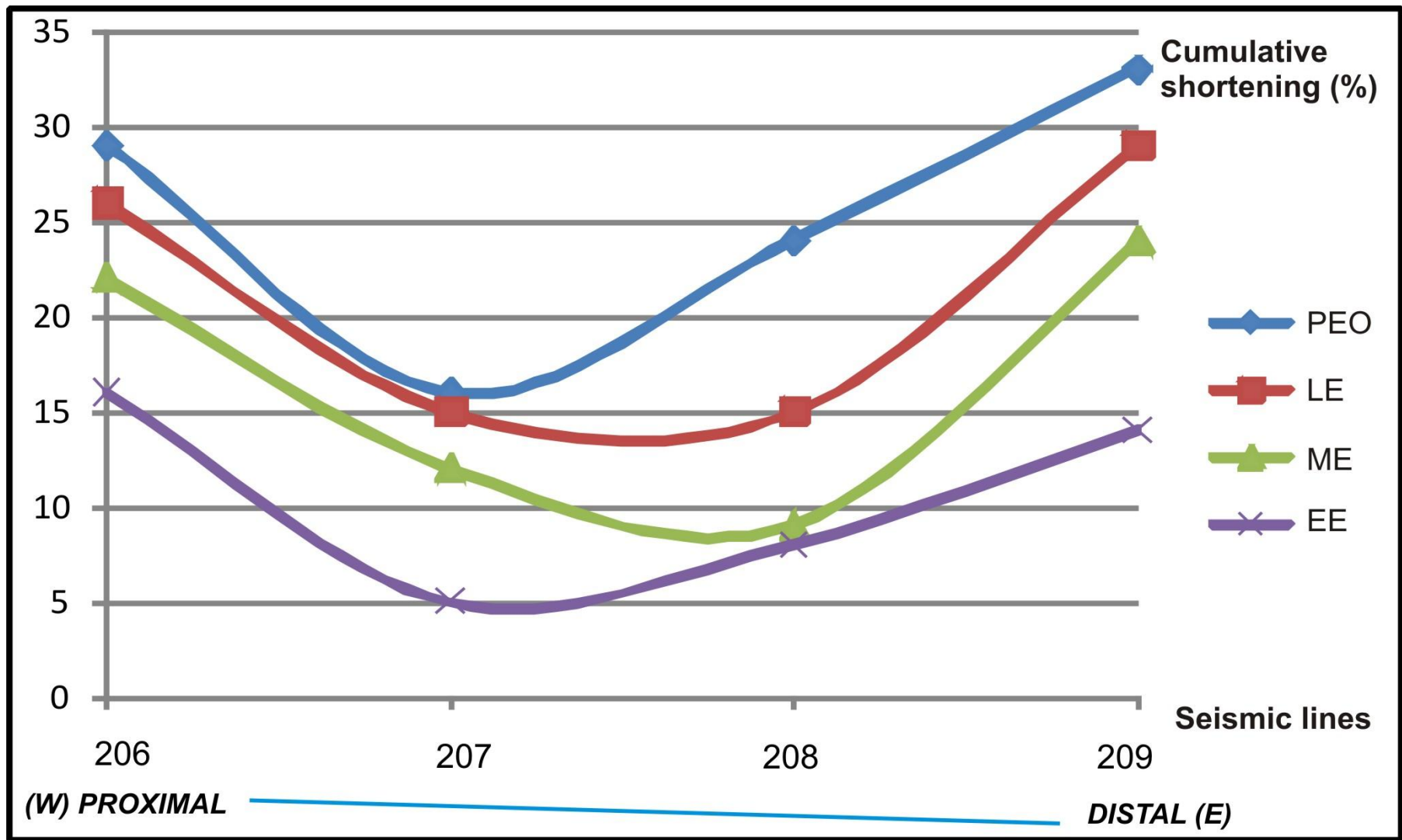
Figure 4. Graph showing the cumulative shortening during the Cenozoic period. The total shortening can be seen in post-Eocene line (PEO). Notice a greater shortening in the proximal (section 206) and distal (section 209) portions of the Cumuruxatiba basin. (PEO) - Post-Eocene; (EE) - early Eocene, (ME) - middle Eocene, (LE) – late Eocene.
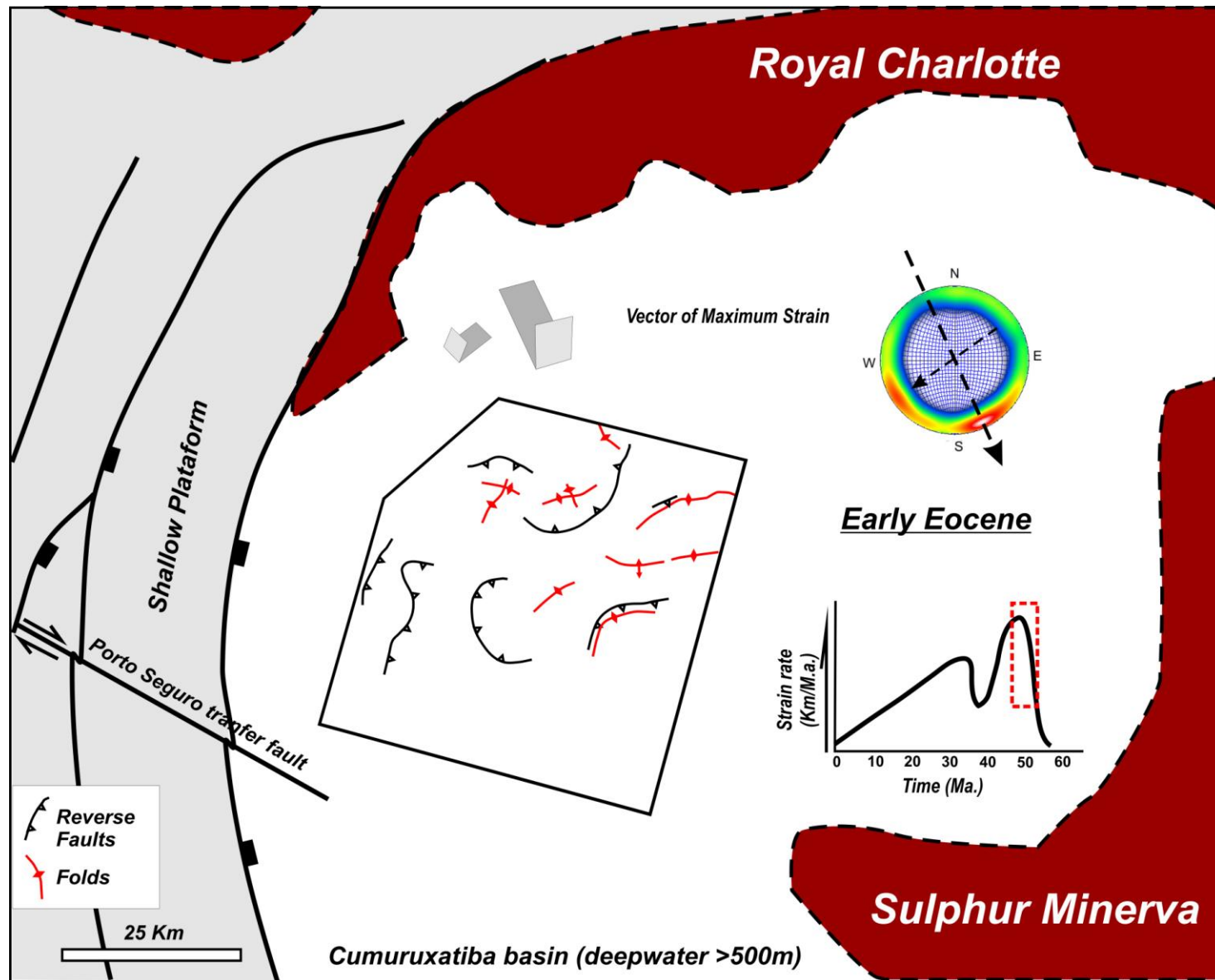
Figure 5. Schematic map showing the structures active during the early Eocene in the modeled area (black polygon) of Cumuruxatiba basin. Note that adjacent magmatic highs acted as triggers for Cenozoic deformation. In the upper right corner, the Wullf stereogram represents the main directions of maximum strain (highlighted by arrows). Below is a chart with the average behavior of strain rate in the basin during the Cenozoic, emphasizing the period shown on the map.