Seismic Stratigraphy of the Onshore Portion of Pernambuco Basin: Evidence of Break-Up during Middle Albian for the South Atlantic Rift in Northeast Brazil*

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Abstract

The present study brings new evidence about the age of the rift event alongside the eastern portion of Northeast Brazilian continental margin, which encompasses the Pernambuco, Paraíba and Natal Platform basins, investigating the record of the coastal portion of Pernambuco Basin. This region encompasses the basins northward of Alagoas Basin, linking the distensive marginal domain to the transforming domain of the Equatorial Atlantic Brazilian margin (Figure 1).This region represents the last link between Africa and South America (Rand and Mabesoone, 1982), and along the Brazilian margin, it was influenced by the nature of the sub-domains related to crustal blocks which formed the Borborema Province (Van Schmus et al., 2008; Araujo et al., 2013). This province represents a large set of Archean/Paleoproterozoic and Mesopreterozoic/neoproterozoic terrains, the relations of which were controlled by crustal-scale shear zones (Neves et al., 2000; Araujo, 2013) (Figure 1). Each of those basins is intimately linked to one of the primary subdomains.

The Pernambuco Basin is related to the Pernambuco-Alagoas Massif and is bounded by the Maragogi High (south) and by the Pernambuco Shear Zone (PESZ) (north); the Paraíba Basin is related to the Central domain of Borborema and is bounded by the PESZ and the Patos Shear Zone PASZ (north); the Natal Platform is related to the Northern Domain and is bounded by the PASZ and the Touros High (north) (Barbosa and Lima Filho, 2006) (Figure 1). Additionally, the basins are located between two oceanic plateaus (Pernambuco to the south and Touros to the north), which most likely formed as a result of the interaction between basement lineaments and fracture zones during the extension of the margins (Fainstein and Milliman, 1979; Long et al., 1986). However, the Pernambuco Plateau is often associated with the Santa Helena Hotspot, considering its position between Northeast Brazil and Equatorial Guineau, which occurred approximately 100 m.y. ago (Jackson et al., 2000; Ngako et al., 2006).

In fact, it was previously proposed that the rift breakup in this region occurred during the Albian (Matos, 1999), after its northward propagation from the Alagoas Basin during the Aptian. The marginal region of these basins formed, together with the Benue Trough and Rio Muni-Douala basins, a giant orthogonal structure bounded by large shear zones (Matos, 1999). Additionally, Turner et al. (2008) proposed that the breakup in the region of the Pernambuco Basin occurred approximately 104 m.y. ago.

The first seismic reflection surveys-based investigation along the Brazilian Margin (Asmus and Carvalho, 1978) proposed a general tectono-sedimentary model for this region, which led to the interpretation of a poor petroliferous potential. Subsequently, the region attracted few studies in three decades, resulting in one of the less studied regions of the Brazilian margin. This poor understanding was influenced by certain aspects which were found in the platform regions to the north of the PESZ: (1) high basement with shallow sedimentary cover between 400 and 200 m along the coastal zone of the Paraíba Zone and between 200 and 100 m along the Natal platform coastal zone (Barbosa and Lima Filho, 2006); (2) the age of sedimentary deposits spans from Turonian to Danian-Eocene with a lack of evaporite deposits; (3) in the platform region, the sedimentary cover thickness was estimated at only 1 to 2 km (Fainstein and Milliman, 1979; Barbosa and Lima Filho, 2006); and (4) the platform is narrow, and the shelf break is notably abrupt, creating a regional bypass zone to the oceanic basin (Barbosa and Lima Filho, 2006; Lima Filho and Barbosa, 2010). However, these characteristics are not shared by the Pernambuco Basin and its plateau, which is positioned to the south of the ZCPE (Figure 1).

Since the 1980's, it has been known that the region which encompasses the Pernambuco marginal basin possesses a plateau implanted over continental crust with an expressive sedimentary cover (Fainstein and Milliman, 1979; Alves and Costa, 1986; Mello et al., 1988). However, the lack of wells in the offshore portion and geophysical surveys caused a delay in exploration activities. The region only received attention in recent years, and the exploratory programs that are being developed will reveal the real petroliferous potential of the Pernambuco Basin.

This study was based on reanalyzing the only deep well, drilled in the coastal zone of Pernambuco Basin and the only three seismic lines executed in its onshore portion. We proposed a major revision in the stratigraphic column of the basin with the inclusion of two new units in the Aptian-Albian clastic succession. Additionally, we proposed that the rift in that region developed in two phases, and the break-up occurred in the Lower-Middle Albian and the first drift phase in the onshore region is represented by an Upper Albian siliciclastic marine-influenced formation. Further, the stratigraphic relations observed in the seismic data suggested that the magmatism could have started in the Lower Albian and the existence of compressional features points to late stages of transpressive reactivation of Precambrian basement faults.

Geological Setting

The Pernambuco Basin is bounded by the Maragogi High (north) and the Pernambuco Shear Zone (PESZ) (south) (Figure 1). It presents a very narrow coastal zone, ranging from 12 to just 5 km in certain places. The basin presents an area of 1000 km^2 in its onshore portion and approximately 27,000 km^2 in the offshore domains. The primary structures observed in the coastal zone correspond to faults related to the Precambrian basement lineaments with a E-W or NE-SW direction. These faults controlled the basin opening and acted as transfer and shear faults. A second trend is composed of faults with a SE-NW direction, which correspond primarily to normal faults that formed when the basin opened. Secondarily, we have folds and normal faults which most likely are related to late reactivation pulses. These late tectonic pulses most likely extended to Neogene times, as observed in other basins in Northeast Brazil. The Pernambuco Basin could be divided into three main domains (Maia, 2012; Oliveira, 2013): (1) The interior basin, which was formed as a narrow rift - parallel to the Atlantic rift axis and almost parallel to the littoral line - and resembles a ramp whose shallow part is in the south and deepest portion is in the north, ending against the PESZ; (2) The outer high - which is named Maracatu High - has an elongated form, presents a N-S orientation, and separates the interior basin from the offshore domains. The nature of this structure is unknown, but can most likely be associated with the extension of the Alagoas hinge zone (Karner and Driscoll, 1999). This high was affected by the pre-existent NE Precambrian faults, which caused a segmentation of this large structure; (3) The Plateau region, which is positioned over the stretched portion of continental crust and extends to an isobath of ~3000 m. The plateau region is formed by at least four main lows and a secondary hinge that crosses the plateau longitudinally, with an almost N-S trend (Oliveira, 2014).

The coastal zone is localized over the western portion of the narrow interior basin, which was largely affected by an Albian magmatic event (Figure 1). The magmatic pulse produced a large number of intrusions (sills and dikes), lava spills and an expressive content of pyroclastic rocks (Lima Filho, 1998; Maia, 2012). The igneous rocks were included in the Ipojuca Magmatic Suite (IMS) (Sial et al., 1988; Lima Filho, 1998; Nascimento, 2003), which contains basalts, rhyolites, trachytes, andesites, ignimbrites and one occurrence of an alkaly feldspar granite (Cabo Granite). Moreover, we have a large number of pyroclastic rocks - tuffs, lahars, ash falls and surge flows (Maia, 2012; Maia et al., 2012). The origin of the magmatism was associated with the Ascension Plume (Sial, 1976; Long et al., 1986; Sial et al., 1988), but the relation with the Santa Helena hotspot is the most probable cause (Cordani, 1970; Wilson, 1992; Jackson et al., 2000; Ngako et al., 2006).

The previous stratigraphic division proposed for the Pernmabuco Basin, primarily based on its onshore record, has considered the existence of three geological units - Cabo (Aptian-Albian), Estiva (Cenomanian-Turonian) and Algodoais (Post Turonian-Paleogene?) - in addition to the Neogene and Quaternary deposits (Alheiros, 1989; Lima Filho, 1998, Lima and Pedrão, 1989). In this sensu, the Cabo Formation encompasses all the siliciclastic deposits formed during the Aptian-Albian period, which was supposedly formed as products of alluvial systems (Alheiros and Ferreira, 1989; Lima Filho, 1998, Nóbrega and Lima Filho, 2003). The carbonate deposits of the Estiva Formation were interpreted as the result of a shallow carbonate platform, as established during the Cenomanian-Turonian transgressions (Lima Filho, 1998). The Algodoais Formation was proposed by Lima Filho (1998) as post-rift fluvial deposits that covered the Aptian-Albian to Turonian deposits and reworked volcanic rocks of the IMS. Most of those previous works were based in the analysis of the only deep stratigraphic well drilled in the onshore portion of the basin, the 2 CP-01-PE well (Figure 1, Figure 2 and Figure 3), which was drilled by Petrobras Oil Company in 1983. This well, located on the Cupe Beach in the south portion of the coastal zone, crossed 3000 m of sedimentary rocks and did not reach the basement.

A problem recurring in the evaluation of the basin stratigraphic succession is poor understanding regarding the influence of the pyroclastics' expressive contribution to the Albian deposits (Maia, 2012). In most previous works, pyroclastic rocks were described as ordinary sedimentary rocks. The difficulty in recognizing pyroclastics is mainly caused by alterations of the outcropping rocks.

Materials and Methods

This study was based on reanalyzing the record of the 2 CP-01-PE well, considering well logs, chemical analysis of cores, biostratigraphy and petrography (Figure 3). Three 2D seismic lines were studied and presented with depth in time (TWT) (Figure 4 and Figure 4). The interpretations from the subsurface data were integrated with the investigations performed through field work campaigns, which made possible a more complete stratigraphic interpretation (Figure 6). A map of the residual gravity anomaly for the coastal zone was obtained. The database was formed using 1920 terrestrial gravity stations, with an average spacing of 3 x 3 km. The calculated Bouguer anomaly was resampled with a grid of 720 x 720 m and a Gaussian filter was applied to obtain the residual Bouguer anomaly map (Figure 2).

Results

Geophysical Data

The gravimetric map was chosen to highlight the structural features in the onshore region. First, it is possible to observe the strong impression of the Pernambuco Shear Zone (PESZ), which forms the northern limit of the inner basin (Figure 2). The map exhibits a NE trend in the continent and near the coastline; it assumes an E-W direction. The west border of the inner basin presents a concave form. The main faults inferred present two distinct trends, one E-W and another NE-SW, as previously observed. Yet there is another SE-NW trend, which is more expressive in the southern portion. The inner basin could be divided into two main negative anomalies, corresponding to the mains lows - the Piedade Graben in the north and the Cupe Graben to the south (Lima Filho, 1998). The southern region of this inner rift, which ends against the Maragogi High, present a more complex behavior, with two small highs controlled by SE-NW faults - the Tamandaré and Serrambi Highs.The field work revealed that these highs controlled the local deposition during basin evolution. Over those highs, there are no Aptian-related deposits of the Cabo Formation. We named the graben between these highs the Sirinhaén Graben (Figure 2). In the center of the inner basin, dividing the Piedade and Cupe main grabens, there is the Cabo de Santo Agostinho High. In fact, the positive anomaly in this point is caused by the presence of volcanic rocks intruded into the sedimentary succession. In that region, on the coastline, there is an occurrence of an alkali feldspar granite (Cabo Granite). In a general view, the inner basin of the Pernambuco Basin could be treated as a notably narrow rift that developed as a ramp, which slopes from the south to the north, where it ends against the PESZ.

Well 2CP-01-PE

Despite the fact that previous works had proposed that the sedimentary column contained three formations (Lima Filho, 1998),including the carbonate Estiva Formation, recent work presented a major revision, proposing the division of the siliciclastic succession (Aptian-Albian) into at least four different geological formations (Maia, 2012; Maia et al., 2012). Our results, shown below, reinforced the last proposition. As observed in the revaluation of the well 2CP-01-PE (Figure 3), the logs, interpreted with the lithologies, allow the separation of the sedimentary succession into four different units. This interpretation was backed by the seismic interpretation, with the identification of the major unconformities (Figure 4 and Figure 5).

The first formation represents the basal sedimentary deposits, dominated by conglomerates and coarse arcosean sandstones. This formation was kept with the original name, which previously was applied for the whole siliciclastic succession. The gamma ray logs present a more consistent behavior, which forms a plateau. The sonic log also shows a more consistent plateau for the values related to this unit (Figure 3). The well did not reach the basement, at 3000 m, but the geophysical data suggest that the basement is approximately 3200 to 3500 m in this region (Oliveira, 2013). It implies that the beginning of the rift in this region occurred during the middle Aptian. The second unit, named the Suape Formation, gathers the Lower and Middle Albian (Figure 3). The influence of rift pulses are still clear in the base of the unit with conglomerate beds intercalated in the sequence. The upper portion of this formation is mainly dominated by arcosean sandstones. The gamma ray log shows a high-frequency variation between coarse and fining upward pulses, which indicates environmental variations. The resistivity log shows a clear difference of values in relation to the subjacent Cabo Formation. The gamma ray and sonic logs indicate a major cyclicity in the facies between 1000 and 2000 m, most likely caused by an environmental change, from alluvial to fluvial dominated. The age of volcanics that appear in the profile is Upper Albian (between 102 and 105 m.y. old), which means that this unit also presents a syndepositional relation with volcanics and pyroclastics (Maia, 2012). This facies was not considered in the past, so most likely the description of the lithologies in the well section ignored the presence of pyroclastics and most were considered ordinary sedimentary rocks. Only recognizable igneous rocks were assigned. In this unit, an interval of 100 m represents igneous rocks (intrusion?), which shows the intensity of the volcanic influence.

At approximately 350 to 380 m, another unconformity was identified. The gamma ray log clearly shows a different behavior related to this third unit, up to 70 m, where another unconformity separates this unit of the Cenomanian-Turonian carbonates of the Estiva Formation (Lima Filho, 1998). This unit was named Paraíso Formation (Maia, 2012) and is mainly dominated by fine sandstones, less arcosean, shales and mudstones (Figure 6). Biostratigraphic analysis, based on palinomorphs, showed that the two first units are dominated by continental deposition, but the interval related to the Paraíso Formation presents a marine influence. The biostratigraphic analysis found palinoforaminifers and marine dinoflagelates (Maia, 2012). Above the third unconformity, there are carbonate deposits of the Estiva Formation, which spans from Cenomanian to Turonian (Lima e Pedrão, 1989) and possibly reached Santonian in the northern part of the coastal basin (Lima Filho, 1998). We assumed that the Paraíso Formation represents the first unit related to the Drift Phase in the Pernambuco Basin, while the two basal units are linked to two rift phases. Extending the rift into the Albian within this region finds consistency with the tectonic history of the African counterpart basin of Pernmabuco. The Douala/Rio Muni and Niger Basins present a similar evolution and the breakup in this basin was positioned in the Lower to Middle Albian (Meyers et al., 1996). As recently suggested by Turner et al (2008), the breakup in the region of Rio Muni-Alagoas could have occurred approximately 105 m.y. ago, considering the syn-breakup relation of the Ipojuca Magmatic Province. Evidence provided by this study corroborates these propositions concerning the timing of the possible breakup and rift episode cessation into the Albian.

Seismic Data

Analysis of the seismic section 2 (Figure 4) allowed the identification of one unconformity that separates a basal sequence, characterized by discontinuous to chaotic reflectors with high amplitudes. The sequence presents intense faulting with reflectors, indicating tilting of sedimentary deposits due to the rift evolution. Samples from the 2 CP well showed that this sequence corresponds to the conglomerate-dominated Cabo Formation. In the top of this sequence, carbonates and traces of evaporites were found (gypsum and anhydrate) (Maia, 2012). This suggests that sabhka-prone conditions existed under dry climate, which is consistent with other evaporite records in the region (Alagoas Basin) during the Upper Aptian. The second seismic sequence is characterized by continuous reflectors and a parallel configuration, which was identified as the Suape Formation. Some faults clearly have affected both intervals, with faults propagating from the Cabo to the Suape sequence. Abundant features related to sills were observed, characterized by short reflectors with high amplitudes. A number of the sills, observed in the right portion of the section, were crossed by the 2 CP well.This fact helped to adjust the well logs with the seismic section. In the base of the Suape sequence, there is a body that seems to have laterally intruded the deposits. In fact, the reflectors over this body seem to be slightly folded. Above 1 second, in both sides of the structure, there are reflectors that seem to be onlapping the folded beds which form the flanks of the structure. If this intrusion is real, it affected the deposits during the Lower Albian, which suggests that the age of the magmatism is older than the main current proposition.

The most important observation is that in the center of the section there is a fault that was reactivated as a thrust fault (transpressive) and affected the entire sedimentary succession. The fault could be linked to the large intrusion, which most likely accentuated the early folding caused. The main reactivation could be Late Cretaceous, or Cenozoic. The seismic sections 1 and 3 (Figure 5) allowed the interpretation of the unconformities and sequences showing characteristics consistent with the Line 2 interpretations.
In both sections, it was possible to identify igneous intrusions (sills and dikes). As observed in Line 2 (dip), in lines 1 and 3 (strike) there occur faults that possibly were reactivated as thrust faults, due to transpressive reactivation of the Precambrian basement. This structural aspect is important because these faults have formed folded beds, which can represent good prospects for oil and gas reservoirs.

Field Relations

Field investigation allowed us to identify some relations observed in the seismic sections. It is clear that in the narrow coastal basin the first stratigraphic unit is the Cabo Formation, the deposition of which was controlled by the pre-existing faults of the Precambrian basement (Lima Filho, 1998, Almeida, 2005). This formation is primarily composed of deposits of alluvial systems, with conglomerates formed by rocks of the adjacent basement. Coarse sandstones containing conglomeratic pulses and arcosean, medium to coarse, sandstones are common (Figure 6). In this unit, up until now, no pyroclastic rock was found and the only relations observed with the volcanics are cross-cutting relations, suggesting no contemporary volcanic activity. In at least two places, an unconformity which marks the top of the Cabo Formation was observed. Above this unconformity pyroclastic rocks were found (Figure 6F and Figure 6G). Overlaying the Cabo Formation, these pyroclastic deposits interbedded with sandstones and shaly sandstones representing the Suape Formation. The deposits were formed in a different environment, more influenced by fluvial and shallow lacustrine systems. The Suape Formation is mainly represented by arcosean and argillaceous sandstones and siltstones and is better represented in the south and middle part of the coastal basin. There is no evidence of clasts formed by the basement rocks in outcrops. However, the basal portion of the Suape Formation could present a minor influence of conglomerates (with contribution of the basement), due to the action of the second minor rift pulse, as observed in the 2 CP well. Pyroclastic rocks interbedded with deposits of the Suape formation are represented by; lahars, tuffs, ash fall and volcanic breccia which could be identified (Figure 6H to Figure 6K), despite the alteration of deposits (Maia, 2012; Maia et al., 2012). Additionally, there is an abundant record of magma spills, which formed different rocks as rhyolites, trachytes and basalts. Therefore, this unit maintained a syn-magmatic relation with the Ipojuca formation, showing syn-deposition and cross-cutting relations.

In the seismic sections and logs of the 2 CP well, a third unconformity was identified, separating the Suape Formation from another siliciclastic unit with marine influence. This unit most likely is a sub-outcropping in the coastal basin, with a number of occurrences in the littoral region, in the south and middle portions of the coastal basin. This fact makes good stratigraphic correlations difficult. However, based on some sedimentary and faciologic aspects, we propose that some exposed occurrences could correspond to this unit. In the region of Tamandaré and Serinhaén, there are deposits showing planar beds composed of mudstones, shales and siltstones, which clearly shows a different depositional system, possibly related to tidal flats of a deltaic environment.Those deposits shows siltstones with drapes of green mudstones, quartzose sand sheets with climbing ripples, small cross stratification, parallel laminations and flaser bedding (Figure 6M and Figure 6N). Some surfaces of mudstones with wave marks and herringbone cross stratification suggest a shallow marine or deltaic origin. The beds showed the occurrence of ichnofossils—*Thaenidium*, *Skolithos*, *Planolites* and *Ophiomorpha* (Figure 6O and Figure 6P). Despite the fact that there is no biostratigraphic data for those deposits, we suggested that they correspond to the marine-influenced deposits of the end of the Albian within the Paraíso Formation, as identified in the well (Maia, 2012).

Above the siliciclastic formations of the Aptian-Albian interval, there are the carbonates of the Estiva Formation, the record of which is also a sub-outcropping in the coastal basin, better known through records of wells (Lima Filho, 1998). Additionally, in some points of the coastal region there are deposits of the Barreiras Formation (Miocene) formed by sandstones, mudstones and sandy mudstones that were deposited over coastal basins in Northeast Brazil during the Miocene-Pleistocene period (Alheiros and Lima Filho, 1991; Rosseti et al., 2009). The poor record of this formation in the Pernambuco Basin coastal zone could be attributed to a late erosional phase, possibly caused by one or more localized events of uplift and erosion.

Conclusions

The Pernambuco Basin represents one of the basins of the eastern continental margin of Northeast Brazil which were formed during the last stage of breakup between the African and South American plates. This basin presents three main tectonic domains - a narrow inner basin, which is separated from the offshore region by an outer structural high (Maracatu High), and an external basin developed over continental-stretched crust that formed the Pernambuco Plateau. The rift responsible for the formation of the inner basin began during the Middle Aptian and was active until the Middle Albian. The first rift stage was more expressive and finished during the Upper Aptian, thereby causing an erosional unconformity. The second phase was less intense and finished in the middle Albian. Each phase is related to a distinct tectono-sedimentary sequence, corresponding to the Cabo and Suape formations. Over the Upper Albian unconformity, at the top of the Suape Formation which most likely marks the post-rift onset, a third siliciclastic sequence was formed. This third unit presents a marine influence and most likely marks the first drift deposits. The magmatism which formed the Ipojuca Magmatic Suite has a syn-rift nature and heavily contributed to the sedimentation of the Suape Formation with pyroclastic rocks. The recognition of these tectono-sequences and the unconformities that separate them represents an important contribution to geological knowledge of the basin. Further investigation could provide a correlation of this information with the offshore record.

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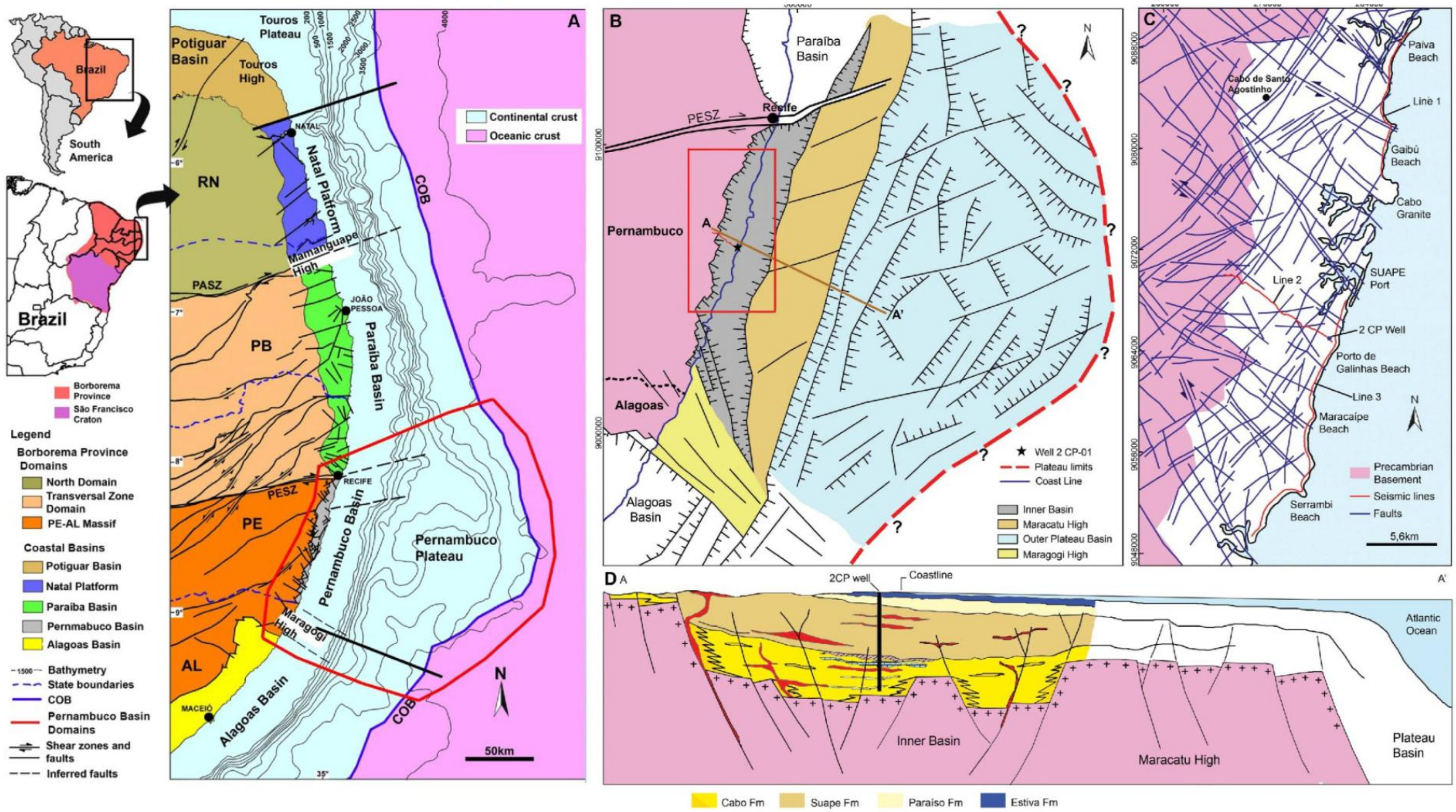

Figure 1. (A) Location of Borborema Province and the basins on the eastern border of Northeast Brazil, whose domains are controlled by large Precambrian shear zones and structural highs. Domains of the Pernambuco Basin marked by a continuous red line. The COB (continent ocean boundary) location is based on previous works (Karner and Driscoll, 1999; Gomes, 2005). (B) Pernambuco Basin main structural domains. (C) Structures mapped in the coastal zone of the basin (red rectangle in map B) and the positions of the 2 CP well and three seismic sections of the onshore region (Lines 1, 2 and 3). (D) Geological section (A-A' located on map A).The stratigraphic column interpretation is based on the results of this study.

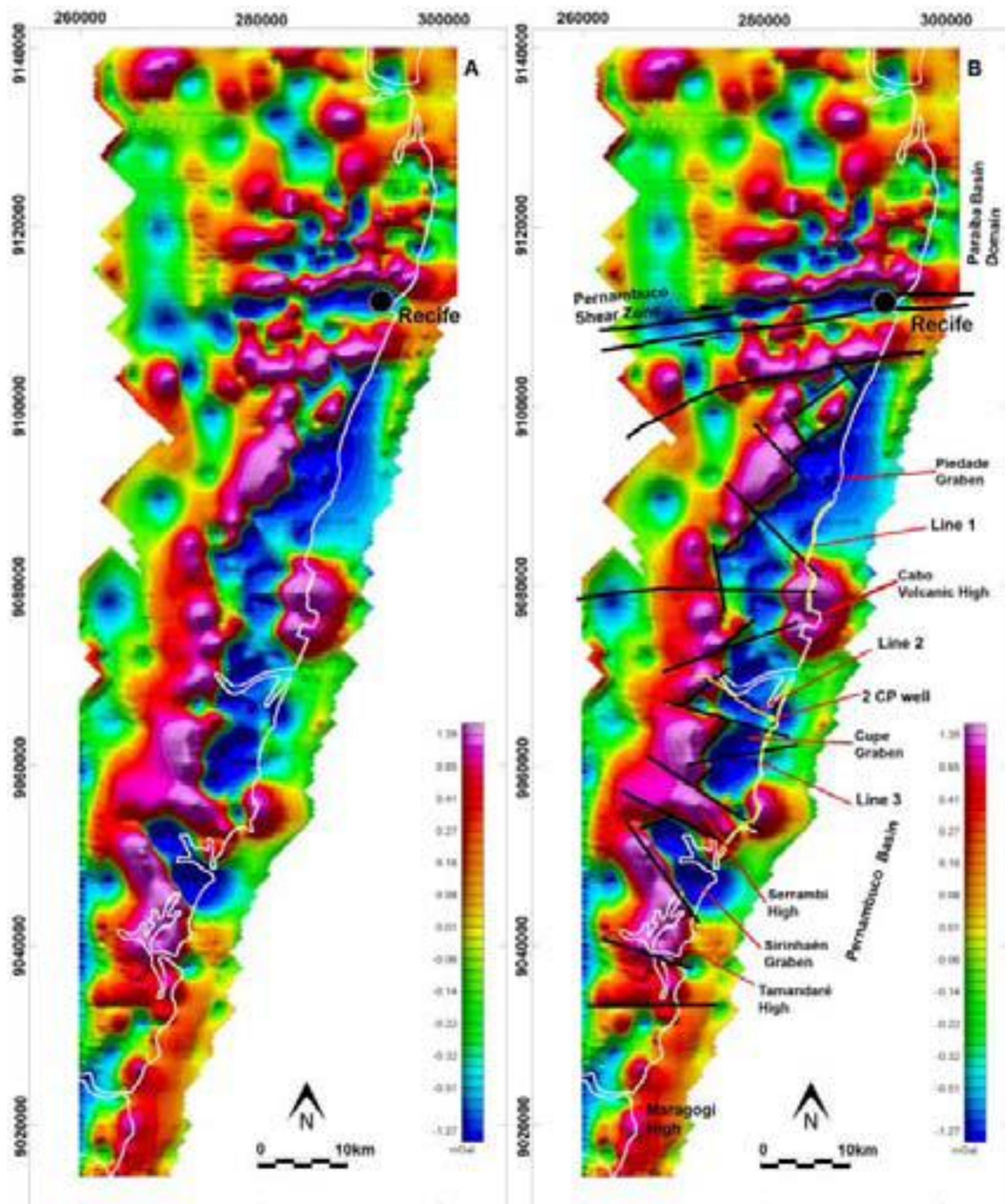

Figure 2. Map of residual gravimetric anomaly of the onshore region of Pernambuco Basin. The west border of the inner basin is shown.

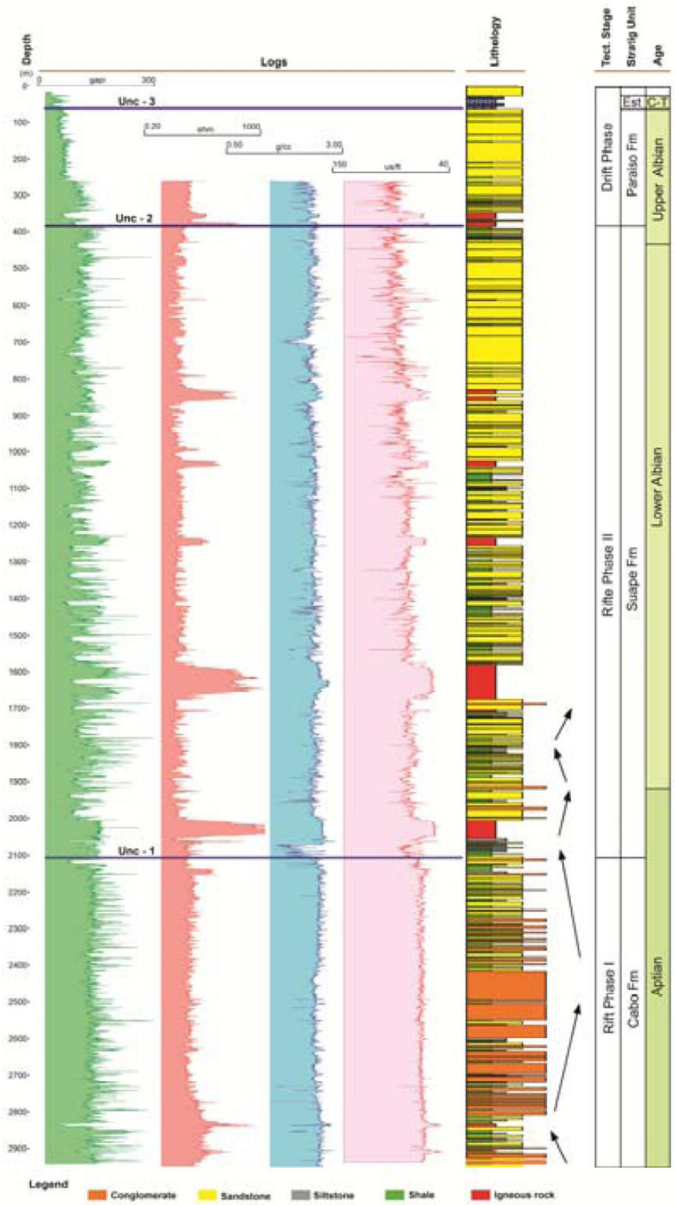

Figure 3. Description of well 2CP-01-PE, including logs and lithology description. The determination of ages is based on the previous analysis from Petrobras. Unc = three main unconformities, which were correlated with the seismic interpretation of the main sedimentary sequences. The arrows indicate possible tectonic pulses, causing coarsening (conglomerates) and fining upward.

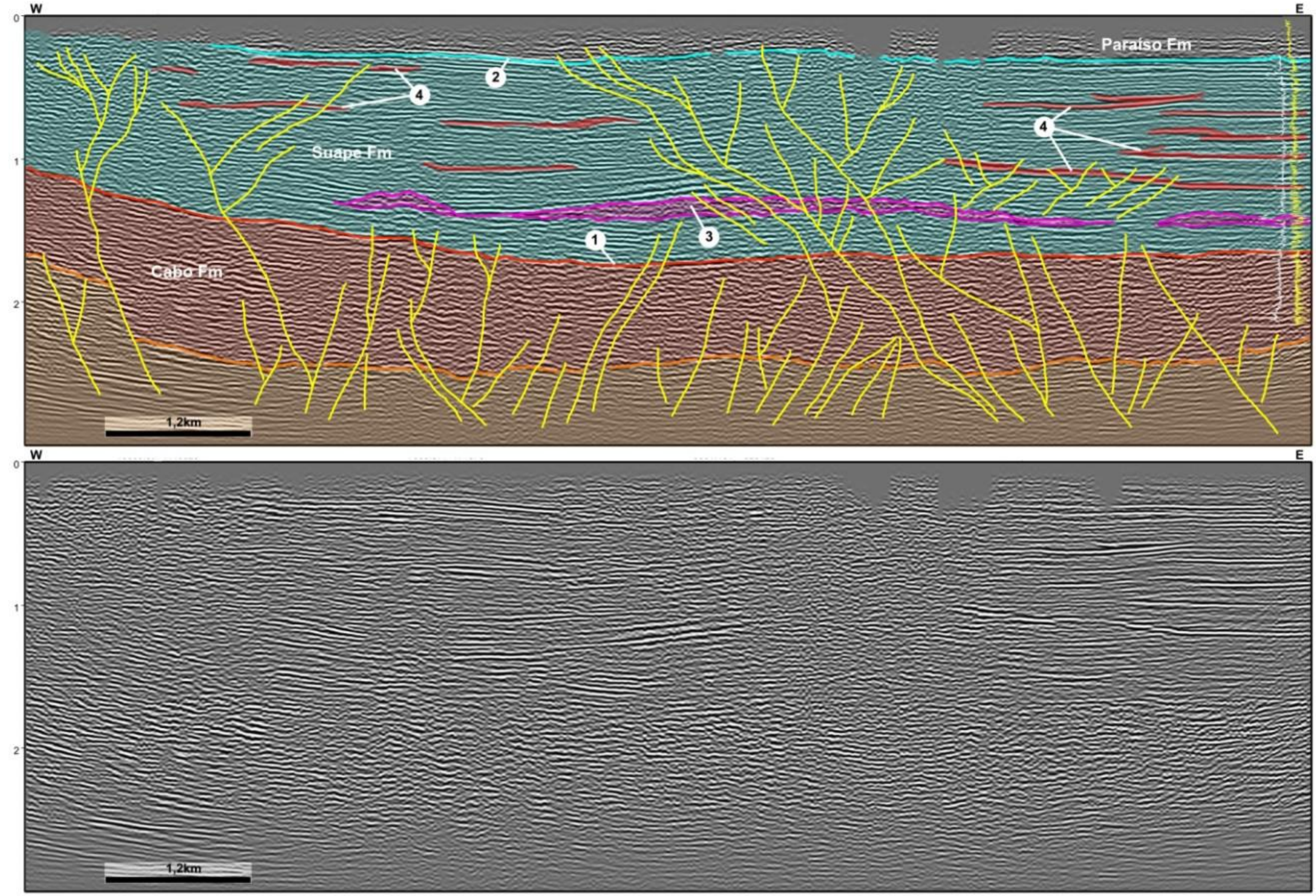

Figure 4. Seismic section 2 interpreted (above) and original (below) (depth in time - twt). Orange horizon - basement. The gamma ray and resistivity logs from the 2CP well are positioned on the right side of the interpreted section. 1 -unconformity at top of the first rift phase; 2 - unconformity at the second rift phase; 3 - most likely igneous intrusion; and 4 - sills and dikes.

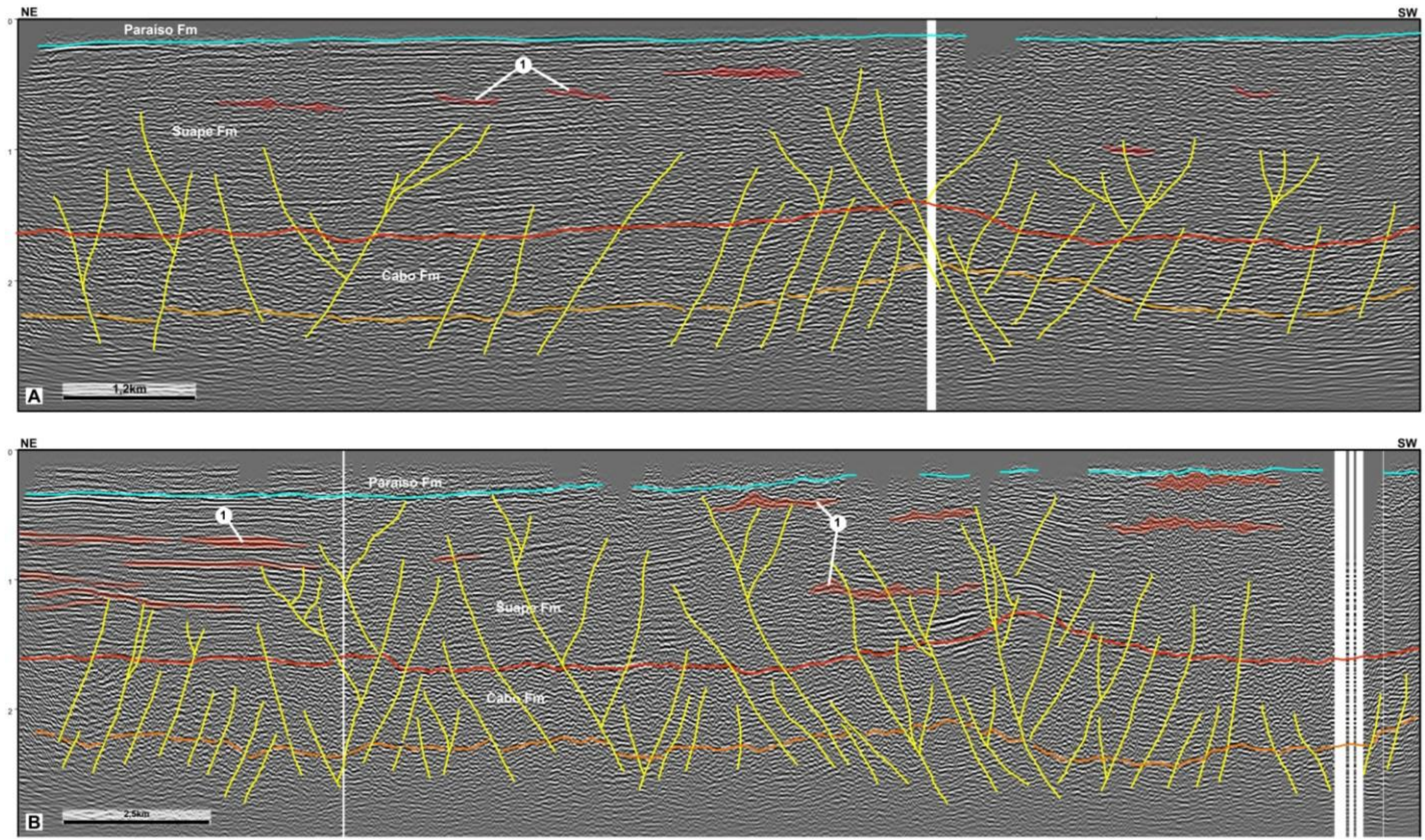

Figure 5. Seismic sections (depth in time - twt). (A) Line 2, interpreted. (B) Line 3, interpreted. 1 - sills and dikes (see the seismic section locations on Figure 1 and Figure 2).

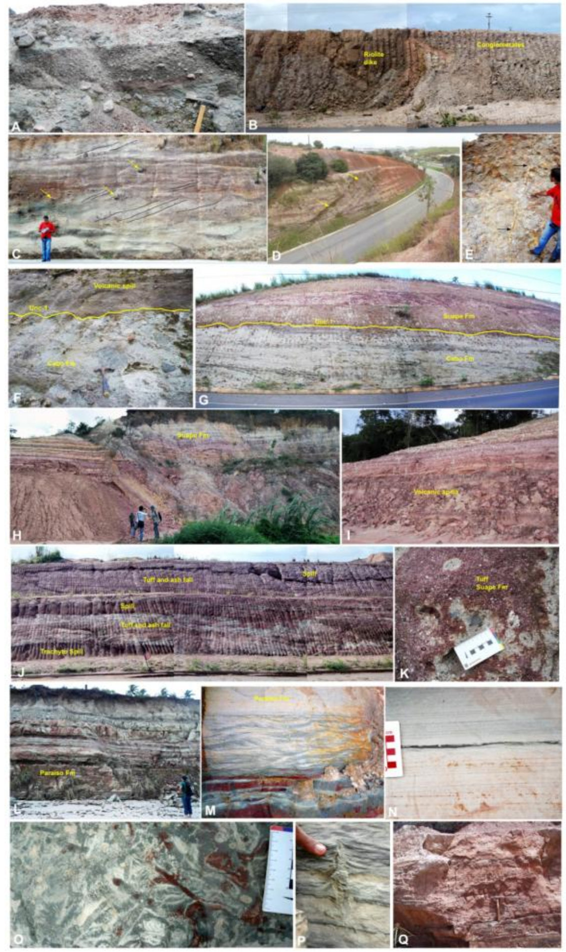

Figure 6. Outcrops photos. Cabo Formation – (A) Conglomerate with coarse arcosean matrix; (B) Conglomerates crosscut by a rhyolite dike; (C) Coarse arcosean sandstone with conglomeratic pulses and blocks from the basement (yellow arrows); (D) Outcrop observed in C crosscut by a trachyte dike (yellow arrows); and (E) Lithified Conglomerate with a transcurrent fault, filled with rhyolite. Suape Formation – (F) Conglomerate of Cabo Formation with the unconformity that separates this unit from the Suape Formation; (G) Conglomerate of Cabo Formation overlain by pyroclastic deposits and interbedded spills of the Suape Formation, pyroclastic and spills beds of the Suape Formation; (I) Spill beds of trachyte and rhyolite which belong to the IMS, interbedded in the Suape Formation; (J) Succession of spills and pyroclastic deposits in the Suape Port region; and (K) Detail of a tuff with clasts of volcanic rocks. Paraíso Formation – (L) Deposits of planar beds of fine sandstones, siltstones and mudstones of Paraíso Formation in the Guadalupe Beach; (M) Flaser bedding and climbing ripples in fine sandstone; (N) Parallel lamination, fine ripples and clay drapes; (O) Silty-mudstone with abundant *Skolitos,Planolites* and *Thaenidium* traces; (P) *Ophiomorpha* burrow; and (Q) Herringbone cross-stratification.