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Seismic and structural characterization of a pre-salt rifted section: the Lagoa Feia Group, Campos Basin, offshore Brazil

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Abstract

The Exploration and development of what it is commonly known the "pre-salt" layer, offshore SE Brazil, is in its infancy but with reservoirs buried below as much as 3000 meter of salt, the pre-salt play presents a multifaceted deep-water scenario that is bringing new challenges to seismic interpretation in offshore Brazilian exploration and production. Reservoirs in this domain are complex, heterogeneous with layered carbonates which makes accurate reservoir characterization very challenging. Our study here deals with the seismic characterization of the stratigraphy of a lacustrine section from the Lagoa Feia Group (Winter et al., 2007) in the Campos Basin, which extends over an area of 100,000 km^2. By using the existing 2D seismic dataset and two deep well logs and core information, we propose a seismic facies analysis and structural characterization of the Lagoa Feia formation. Using some simplified kinematic restoration we show that some of the normal faults affecting the lower units of the Lagoa Feia could be interpreted as pre rift structures *sensu latu* but also as pre-existing structures re-activated during the main passive margin rift activities. Inferences from well core and seismic stratigraphy clearly suggest that the all Lagoa Feia group has a syn rift depositional character. Different pre- syn- and post-rift seismic stratigraphic units, with corresponding bounding surfaces are then defined. Based on their seismic character, four seismic facies representing the main lithological package in the rift section are recognized: border fault deposits; fine grain-dominated re-sedimented deposits; coarse grain-dominated carbonate rich re-sedimented deposits; and an intrusive wipe-out zone affecting all the pre-salt unit. By proposing this seismic classification and interpretation across the pre salt Campos Basin units this work represents an introductory step to a facies classification and structural interpretation applicable at regional level in the internal SE Brazil offshore area.

1 Introduction

The Campos Basin in eastern Brazil comprises an area of 100.000 km2, with more than 2900 drilled wells (Guardado et al., 2000; ANP-BDEP, 2015). Before the recent discoveries of the voluminous pre-salt accumulations, the basin corresponded to more than 90% of Brazil petroleum reserves (Winter et al., 2007). The Lagoa Feia Group, deposited in the rift and sag pre-salt phases, includes lacustrine organic-rich shales, which constitute the source rocks of the basin, and carbonate rocks, which correspond to the main reservoir rocks of the rift section. Despite of the huge number of wells, only a few cores were taken on the rift section of the Lagoa Feia Group. Excluding cored intervals with less than 3 meters, cores of the rift section represent no more than 600 meters across the entire Campos Basin, usually with 10 to 15 continuous meters, taken at the shallow part of the basin. The area has been explored and investigated (Abrahão & Warme, 1990) and recently re-interpreted in detail from a petrologic-sedimentology perspective (Armelenti et al., 2016) and a stratigraphic-seismic point of view (Alvarenga et al., 2016; Goldberg et al, 2017) as re-sedimented gravitational deposits within a rift lacustrine environment . This paper builds on the petrographic, stratigraphic and sedimentological data and interpretation proposed by Armelenti, 2016; Alvarenga et al., 2016; Goldberg et al, 2017 and focuses on the seismic expression of the Lagoa Feia different formations and its structural relationship respect to the syn rift activity. We will discuss the seismic stratigraphy nature of the Lagoa Feia respect to the major normal fault affecting the pre salt system and some rift kinematic scenario for the internal area will be proposed accordingly. By extracting the main seismic reflection parameters (which include geometry, continuity, amplitude, frequency) and analysing some wire-line log data from wells that can be tied to the sub-salt seismic data, we will finally propose some main seismic facies that have regional significance across the Campos Basin for the Lagoa Feia Group.

2 Geological and tectonic settings

The Campos Basin, offshore Brazil, is situated on the south-eastern continental shelf part_of the Brazilian offshore between the Cabo Frio High to the south and the Vitoria High to the north (Fig. 1). Like most of the Brazilian offshore basins, the Campos Basin was formed during the breakup of Gondwana and the drifting apart of South America and Africa in late Jurassic to Early Cretaceous time (Mohriak et al., 2008, Karner, 2000). Following Kumar et al., (1977) and Zalan et al., (2011) the sedimentary wedge in the Campos Basin is at least 4-6 km thick and locally thins out over some basement highs as shown in the regional section from the Campos area obtained from our mapping. During this major tectonic event both the Atlantic margin of Brazil and the west African margin experienced an extended deformation history, first involving deep-seated crustal deformation associated with Barremian-Aptian rifting, and subsequent sea floor spreading and drifting of the Atlantic margins (Mohriak, 2008). Refraction experiments (Zalan et al., 2011; Moulin et al., 2011) suggest that further east the Campos Basin overlies thinned continental crust. Finally following the deep rift structuration during the Cenozoic, deformation of the cover sequences has been mainly driven by gravity tectonics (Demercian et al., 1993, Davison, 2008). Within this tectonic framework, the sedimentary record since the Mesozoic in the Campos Basin has been traditionally (Winter et al., 2007) described in terms of three supersequences (figure 2): (1) Rift Supersequence, (2) Post-Rift Supersequence and (3) Drift Supersequence. In this paper we will abandon this traditional classification based on the new seismic data presented, which clearly suggests some inconsistencies with the current post rift supersequences interpretation.

(1) The Rift Supersequence within the Campos Basin corresponds to basalts and minor conglomerates of the Cabiúnas Formation (Hauterivian) and the lower portion of the Lagoa Feia Group defined by the Atafona, Coqueiros and Itabapoana formations (Winter et al., 2007). The Barremian aged Atafona Formation consist of siltstones, sandstones and lacustrine shales with a distinctive talc-stevensite mineralogy, interbedded thin lacustrine limestones; the overlying Coqueiros Formation is of upper Barremian to lower Aptian age (locally resting on the Jiquiá) and has been described as coquinas ("Unit D – Coquinas Sequence" of Rangel & Carminatti, 2000), but is in fact composed of rudstones and grainstones that are not located in a specific stratigraphic interval (see Goldberg et al, 2017). The Itabapoana Formation (alluvial fans/fan deltas proximally and lacustrine/lagoon sediments distally) is also of Barremian to lower Aptian age, laterally equivalent to Atafona and Coqueiros formations (Winter et al., 2007). (2) The Post-Rift Supersequence (Fig 2) comprises the upper part of the Lagoa Feia Group, including the upper Itabapoana Formation, laterally equivalent Gargau (dominantly marls and calcilutites) and Macabu (stromatolitic and laminated microbialites?), and the overlying Retiro Formation, which is characterized by evaporites composed of anhydrite, carnallite and halite/sylvite of Aptian age deposited in marine/lagoonal environment in an arid climate (Winter et al., 2007, Tedeschi et al., 2017). However, all these lithostratigraphic units are not chronostratigraphically and regionally consistent, being in fact related to specific depositional environments that varied substantially along the rift and across the Campos Basin (Stanton & Masini, 2013). Moreover the interpretation of the upper part of the Lagoa Feia Group, including the upper Itabapoana Formation, laterally equivalent Gargau (dominantly marls and calcilutites) and Macabu (stromatolitic and laminated microbialites?) as part of the post rift supersequence has now been questioned (and will be further questioned in this paper). These units can certainly be interpreted as still part of the pre salt syn rift (Goldberg et al., 2017) but have been interpreted by others as a sag formation (Karner & Gamboa, 2007). The halite of the Retiro Formation represents the clear post rift formation unit (Tedeschi et al; 2017) and is remobilized into salt domes and diapirs with amplitudes of up to 3000 meters or more, which cut the overlying stratigraphy (Rangel et al. 1994). The upper portion of the Retiro Formation displays a retrogradational pattern, representing an eustatic sea-level rise (Winter 2007; Davison, 2007). (3) The Drift Supersequence comprises marine sediments of the Macaé and Campos Groups deposited in a regime of thermal subsidence associated with gravity-dominated tectonics (Winter et al., 2007), dominantly evaporite remobilization. The Macaé Group (Lower Albian to Cenomanian) consists dominantly of limestones and marls, while the Campos Group (Turonian to Recent) consists dominantly of siliciclastic sediments, deposited in progressively deeper marine environment (Winter et al., 2007).

3 Description of the Datasets:

The subsurface dataset (acquired through the 1980s to 1990s) consists of a series of 2D seismic surveys with a total of 282 seismic lines (but few of them has been here selected as representative), and 40 wells of which only 13 have well logs and two have core (referred to here as wells A and B, Fig 1). Before describing the main seismic units and their tectonostratigraphic interpretation, it is worth discussing some of the properties of the seismic dataset.

1) Most of the seismic data (2D) released for the project (Fig 1) was acquired primarily for the purpose of imaging the supra-salt, post-rift sedimentary units. They represent pre stack time migrated seismic section. As a consequence, most of the seismic processing has been focused on imaging units above the salt while only secondary attention has been paid to the sub-salt units. In Figure 3a, a sample 2D line extracted from the survey is represented in terms of the frequency. It represents a three frequency decomposition Red Green Blue (RGB) blended image (20, 48, 60 Hertz frequencies) using a constant mean frequency/ total bandwidth ratio. The blended image indicates that the highest frequencies over 40 Hertz (whitish colours pointed by the arrows) are clearly associated with the supra-salt unit while the sub-salt units related to the Lagoa Feia Group are restricted to values below the 30 Hertz. Using the check-shot information available within the Lagoa Feia Group (Fig 3), which yield measured velocities varying between 2.1 and 2.7 km/sec, and using the mean frequency distribution described in Figure 3, we can estimate a minimum and maximum tuning thickness that varies between 10 and 50 m. Figure 3b shows the calibration of some reflectors using the well log B which clearly confirms the resolution values of 16-30 m (at best), supporting the frequency analysis.

2) The frequency analysis (Figure 3a) also suggests that the sub-salt seismic quality impaired the use of some seismic attributes to recognize and map the main boundaries between the basement (here named Cabiúnas Formation) and the main sequence. In some cases, due to the very low frequencies, the seismic resolution was well above the required tuning thickness necessary to unravel the main internal variations or lateral continuity of the seismic facies, reducing our ability to interpret the internal architecture of the syn-rift deposit. It is worth noting that several of the available wells were originally drilled with the intention of investigating targets located in the supra-salt sediments. This implies that most of the check-shots do not reach the Lagoa Feia Group and most of the wells do not contain any core information about the lowest pre-salt unit of interest. Only 3 wells stored useful core information across the full dataset and only two could match the entire pre-salt sequence. Therefore most of our seismic texture analysis will be devoted to seismic lines that are tied to those wells (Fig 1).

3) Interval and average velocities for part of the well has been obtained mostly from both the well log sonic log and the check shots released for this research activity. The velocities varies considerably within the Lagoa Feia different formations but an average two main packages have been recognized. The Unit right below the salt unit across the main upper syn-rift unit (defined later as *high tectonic to low tectonic activities system)* show interval velocities varying between 2.7 to 3 km/sec. A second package, with an average velocity of 2.4 to 2.5 km/sec has been instead defined below the main thick re deposited carbonate rich units as suggested by the two interval velocities indicated in figure 3b (white values in figure 3b). The two packages are roughly represented in figure 5b respectively by the two

bold thick lines in light orange and dark grey. Those two average of velocities has been used to calculate the mean depth across the well as in indicated by white numbers in figure 5b.

4. Method

4.1 Seismic facies analysis

In the last thirty years exploration geoscientists has been advancing seismic processing and visualization technology with the aim of recognizing large scale geological features by visual inspection of seismic reflection patterns. These efforts have led to the development of concepts such as *seismic facies*, defined as mappable three-dimensional seismic units composed of groups of reflections whose parameters (amplitude, reflection geometry, continuity and wavelet frequency) differ from the surrounding units (Prather et al., 1998; Posamantier et al., 2003). The concept of seismic facies has often been linked to geologic interpretation as a function of the depositional environment and lithofacies. Once these seismic properties are shown to be systematically associated with specific geological features then they can be defined as seismic facies. The interpretation of seismic facies often first requires the existence of a large-scale framework of seismic sequence analysis defined through the recognition of main sequence boundaries. Within this framework it is then possible to insert genetically-related subunits by using seismic expression calibrated through well log information. The study and use of seismic attributes (post- and pre-stack attributes) have played a fundamental part in this seismic facies analysis process by developing a plethora of temporal, spatial and instantaneous physical attributes (Taner & Sheriff, 1977; Taner et al., 1994; Chopra & Marfurt, 2007, Alves et al. (2014) Marfurt (2015), Marfurt and Alves (2015)), with the aim of enhancing signal properties and specific textures of seismic units. Seismic facies have then been constrained through robust statistical procedure and also through the consistent cross-analysis of well log data. When the geological information is incomplete or non-existent, seismic facies analyses are called non-supervised (Duda et al., 2000) and are performed through unsupervised learning or clustering algorithms (De Matos et al., 2007); When geological information is used to tie the seismic facies to wells then the term supervised seismic facies can be applied. Efforts to define seismic facies have been undertaken within a variety of geological contexts, such as carbonate (Sarg & Schuelke, 2003; Colpaert et al., 2007), deep-water (Prather et al., 1998; Posamantier & Kolla, 2003) and fluvial depositional environments. In this contribution we aim to investigate the qualitative seismic response of several seismic units from a rift lake system of the Campos Basin (offshore NE Brazil).

After recognition and mapping of the main units within the Lagoa Feia Group at seismic scale, the main seismic character of the various syn- and post-rift sub-units has been further analysed. In order to recognise patterns across the seismic dataset, different complex attributes (*sensu* Taner & Sheriff, 1977) and attribute combinations have been applied. Specifically the use of some attributes, such as the sweetness (specially to highlight the rift basement/first infill), the reflection strength, cosine of the phase, and relative acoustic impedance, have been crucial to resolve some of the internal seismic expression representing the main units of the Lagoa Feia. Before describing the main seismic facies recognized in this study, we will first briefly describe the various attributes utilized and outline their utility in resolving signal properties during seismic facies analysis. A summary of their properties and image visualization across the Campos Basin seismic data analysed is proposed in Figure 4.

1) Root mean Square amplitude (Taner & Sheriff, 1977): we define the RMS as the root mean square amplitude of the signal (also known as "instantaneous amplitude or envelope"), calculated by taking the root of the summation of the squared real components of the signal. It is similar (but analytically not equivalent) to the RMS amplitude as it highlights, by doing the square rooted amplitude, the various anomalies within the seismic datasets. RMS is amplitude independent of phase attributes, it is always positive, and has the same range of squared values as the amplitude from which it is derived. To appreciate the main description and effect refer to the table in Figure 4.

2) Cosine of the phase (Taner & Sheriff, 1977): The instantaneous phase is defined as the tangent of the argument of any complex signal. The cosine of phase strictly derives from it, as it represents the cosine of the instantaneous phase. This attribute is of central importance, since it describes the location of events in the seismic trace and leads to the computation of other instantaneous quantities. It also makes strong events clearer and is effective at highlighting discontinuities of reflectors, faults, pinch-outs, angularities and bed interfaces. Seismic sequence boundaries, sedimentary layer patterns and regions of onlap/offlap patterns often exhibit extra clarity by using this attribute.

3) Sweetness (Radovich et al., 1998; Hart, 2008): the sweetness is derived mathematically by dividing reflection strength by the square root of instantaneous frequency. The instantaneous frequency is the rate of change of phase, has units of Hertz, and is related to both the bandwidth of the seismic data and bed thickness; as a consequence, it is very sensitive to frequency-dependent amplitude variation. In our seismic analysis this attribute has proved to be very effective in highlighting and mapping the top of the Cabiúnas Formation across the entire dataset.

4) Relative acoustic impedance (RAI). The relative acoustic impedance (called here RAI) was proposed by Chopra et al. (2009) and is the result of a simple integration of the complex trace. To calculate it first we invert the seismic amplitudes into a reflectivity series using spectral inversion. Then we transform this reflectivity series into a relative impedance layers. This step is a trace-by-trace calculation process. It basically represents the approximation of the relative acoustic impedance at high frequency components. In our

study it was extremely effective in highlighting the seismic textures of the various subunits recognized and mapped within the Lagoa Feia Group.

4.2 Structural validation

Low resolution and frequency of the seismic expression of the Cabiúnas and above Lagoa Feia formations, coupled with the lack of robust well constraints across these pre-rift and early syn-rift deposits, has posed significant challenges during seismic mapping. Following the seismic interpretation of these pre-salt intervals using available well and core data, several half graben structures within the top-Cabiúnas and lower Lagoa Feia group were identified, the geometries of which are controlled by the listric bounding fault (Fig. 4a, Fault 3) and a number E-dipping normal faults (Fig. 5a, Fault set 2). To test the validity of fault and the horizon identification during seismic interpretation, and in an attempt to constrain relative timings of Fault 3 and Fault set 2, a simple kinematic restoration technique was applied to this pre salt interval of the seismic line. This was performed using a simple line-length balance technique (Dahlstrom, 1969; Gibbs, 1984), with respect to seismically imaged extensional settings, of the top Cabiunas (red dotted in Fig. 5a). Given the low resolution and frequency of the seismic expression, and consequent paucity of clear stratal terminations within this part of the succession, no attempt was made to define geometries within the tilted fault blocks. Thus, two simple scenarios were used for comparison: (1) Fault Set 2 pre-exists the large listric fault (Fault 3), and is related to an early rifting phase affecting the Cabiúnas Fm and underlying deposits (Fig. 13). (2) Fault Set 2 and Fault 3 were kinematically linked during rifting, with Fault Set 2 representing a listric counter-fan along a floor fault (sensu Gibbs,1984), related to offset along Fault 3 (Fig. 13).

5. Results

We will firstly focus on the characterization of the regional seismic sequence, and then concentrate on the recognition and interpretation of the main seismic facies by combining a detailed amplitude seismic mapping, image processing techniques and well bore analysis. Finally using a constant line-length approach, some kinematic models fitting the observed geometry and seismic stratigraphy are proposed and discussed.

5.1 **Seismic sequence stratigraphy surfaces.**

The first approach of our seismic characterization consisted of distinguishing the main regional seismic surfaces, with the aim of mapping the major seismic units using reflection terminations and sequence stratigraphic principles. Here we refer the seismic interpretation of the main seismic units with respect to the main rift faults observed. Therefore we simplify the conceptual interpretation by referring our seismic interpretation to the observed fault rift related structures even if we are aware that at regional scale some of the main pre salt units unaffected by faults (traditionally interpreted as sag units) may still comprise part of the syn-rift supersequence controlled by lower crust extension (see Karner & Gamboa, 2007 for an extended discussion). A discussion and integration of the various seismic stratigraphic units and a chronostratigraphic chart of the basin locally utilized here for the Campos Basin has been presented elsewhere (Ene et al., 2015; Goldberg et al., 2017). Here we paid specific attention to the pre-salt rift basin deposits and their relation to the main rift structure by subdividing the stratigraphy into genetically related units – systems tracts, as originally defined by Brown & Fischer (1977) but following the methodology proposed in the North Sea by Prosser (1993). The main seismic units and related surfaces that have been recognized and mapped are the following (Figs. 1, 4a to d and 8):

Pre-rift Unit: This is the deepest seismic unit of the framework. It consists of Pre-Cambrian plutonic and metamorphic rocks. The seismic reconnaissance of the pre-rift unconformity is precluded due to (1) its deep occurrence (over 8km), and (2) low acoustic impedance contrast between these crystalline basement rocks and the basalts of the syn-rift section and their low frequency characteristic. The main driving information are the well core and log information used to tie and calibrate the main seismic units and response to the sweetness attributes. Here we will refer to three main seismic sections named A and B and C and to three main wells here referred to as well A, B and C all located in Fig 1.

Top Cabiúnas Formation: This represents a lithological contrast between the basalts and the overlying sediments, with no time significance. The well data (the purple unit in wells B in Figs. 5b, well C in figure 5c and well A in Fig 9) characterize the Cabiúnas Formation as sediments inter-fingered with thin basalt sills. Using the well tie information, the Top Cabiúnas Formation has been mapped and defined by a very discontinuous reflection represented as a red dotted reflector in figures 5, 8 and 9. This unit is only clearly mappable by using the wells and a combination of amplitude- and frequency-dependent attributes such as the sweetness (Fig 4) that helped to enhance the very low impedance reflection. The reflection doesn't show any real lateral continuity, suggesting heterogeneity at the base of the overlying sedimentary unit. As shown in all the seismic lines (Figs 5, 8 and 9), the seismic interpreted Top Cabiúnas Formation (red dotted reflector) is intensely dissected by the extensional faults associated with the initiation of rifting.

Syn-rift unit. On top of the Top Cabiúnas Formation a thick syn-rift unit characterized internally by two main discontinuities has been systematically mapped and recognized in the sub-salt rift basin. The base of this unit is defined by the top of the Cabiúnas Formation, while the top of the entire unit is defined by a *pre salt Unconformity (base sag?)* (reflection highlighted in red in Figs. 5a,b and c), which consists of an intense erosional truncation observed across the entire rift basin which is probably locally equivalent to the pre Alagoas transitional megasequence (Guardado et al, 1990; Karner, 2000). The real significance of this unconformity will be further investigated and questioned in the following paragraph. As stated above, this syn-rift unit has been subdivided into three additional sub-units using internal reflection termination and geometry.

Subunit 1: Following the terminology by Prosser (1993) we refer to the first unit as the *Rift Initiation Systems Tract*, which is stratigraphically comprised between the top Cabiúnas volcanics and the first lower lateral thickening reflection of the Lagoa Feia called *Half graben development surface* and mapped as a dotted orange reflector. The reflectors characterizing this subunit are very difficult to interpret due to their low resolution and poor contrast of impedance. However some characteristic reflector terminations can still be observed and help to understand the initial rift depositional history respect to the small scale rift fault. As shown in figure 5b the reflections below the *Half graben development surface* shows the following characteristics :

a) the reflectors (arrow 1, sub section 1) are parallel slightly diverging / conformable to the top Cabiunas but onlap the faults.

b) Within some of the internal small rift half graben the first reflector above the top Cabiúnas (arrows 2 in figures 5) show a slightly fan thickening relation with some of the rift faults. The reflection termination against the faults are unclear or chaotic (Sub section 2)

c) very low amplitude and lateral continuity with a conformable parallel reflector geometry to the top cabiunas , but dissected by the faults (arrows 3, Sub section 3).

Those three type of reflector terminations have been recognized and indicated on the seismic line B (Fig 5b) and A (Fig 5c).

Above those generally comfortable reflectors (part of the *rift initiation tectonic system tract)* is the *Half-Graben Development Surface*. This surface (orange reflector in the seismic line shown in Figures 5) is characterized by a discontinuous reflector with low amplitude and parallel wavy orientation that slightly onlap the large listric fault. Here it is interpreted as syn-tectonic with respect to both the minor and certainly to the main listric fault arrays associated with the rift system and, occasionally it shows a lateral thickening towards the faults.

Subunit 2: Above the Half-Graben Development Surface is the *High Tectonic Activity Systems Tract (*sensu Prosser, 1993*)*. This second subunit represents the principal syn-depositional half-graben structural pattern expressed as a clear lateral thickening with respect to the main large listric fault, with an intense divergent reflection pattern along the half-graben structures. It is equivalent to the mid-rift climax system tract defined by Prosser (1993). At the top of the *High Tectonic Activity Systems Tract* it is possible to define a second important regional surface called here the *Tectonic Change Surface* (mapped in blue across the seismic lines in Figs. 5a and b and c). This surface is regionally developed across the entire Campos Basin defining a clear erosional truncation that separates the *High Tectonic Activity Systems Tract* below from the *Low Tectonic Activity Systems Tract* above. It can represent the transition to a late rift climax system right before the cessation of the fault activity marking the post rift or sag system tract. Part of these units (as the lower units) are clearly affected by late syn - rift faults with an eastward vergence and clear higher dipping angle.

Subunit 3: the *Low Tectonic Activity Systems Tract* represents the top of the syn-rift unit and is characterized by a decrease in the divergence of the depositional reflectors, with dominance of wavy and parallel reflections, and lower displacement of the border faults, indicating a reduction in tectonic activity. It is equivalent to the late rift climax system tract of Prosser (1993). A third regional surface called the *pre salt base Unconformity* (in red in Figs. 5 and 8 and 9) defines the top of the subunit *Low Tectonic Activity System Tract*, now characterized by horizontal versus slightly divergent reflectors. The Pre salt base unconformity is represented by an intense erosional truncation observed and mappable across the entire basin analysed. As clearly indicated in Fig 5c, outside the mini syn-rift basin bordered by the main syn rift fault system, subunits 1 and 2 are strongly reduced between the top Cabiúnas Formation and the *pre salt base unconformity*.

Pre salt late-syn rift unconformity:

In our seismic dataset above the post rift unconformity (Red) and below the base of the salt (green) we observe an un-faulted seismic unit characterized by sub-parallel reflector capping the clear brittle faulted syn rift depocenters. This pre salt unit is characterized by wavy and discontinuous reflections with synformal structures strongly influenced by the base of the salt. No visible fault is affecting the unit that seems conformable (with no lateral thickening) onto the previous low tectonic activity system track. This unit overfills and extends beyond the margins of the previous rift structures (Fig 5c), The top surface is mapped as a green reflector (Figs. 5 and 8) and represents the base of the salt. This top surface appear as an unconformity equivalent to the *post rift system tract* sensu Prosser (1983) or to n intermediate stage devoid of visible fault structure leading to a *post rift system tract*.

5.2 Structural setting and major system tracts

The Lagoa Feia Group in the Campos Basin is associated with basement-involved block rotation faulting on a subsiding crust, with widespread mafic volcanism between 111 and 134 Ma (Amaral et al., 1966; Cordani et al., 1972; Mizusaki et al., 1988). As shown in the large seismic section in Fig. 5c the pre-salt units are mainly characterized by a series of normal faults associated with an early rift stage, alternating with half-grabens where the main boundary fault develops, probably relatively late in the basin evolution, and which affects both the high tectonic activity system tract and low tectonic activity system tract. A closer look at the overall normal faults (with red numerations in figure 5 a, b and c) is proposed through the figure 5a and 6b representing the seismic line named B and A in figure 1. The reader should note that their represented geometry is here biased by the vertical exaggeration here 1.5:1.

In figure 5a a complete section of one of the half grabens is shown with a low vertical exaggeration (x 1.5, for all the section 5 a to c). The half graben structure is controlled by three different oriented fault systems: low angle, small displacement normal fault (fault 2) affecting the base of the Lagoa Feia and the top cabiunas formations; high angle fault with an antithetic orientation (fault 1) with respect to the low angle faults and the large-offset listric fault (3) which controls the main graben geometry. Timing of fault populations will be further investigated through a restoration model (section in Fig 13) but the geometry and the relationship with the stratigraphy indicate that the three different fault systems were all active during the half graben structuration. The fault system 1 appears to cross most of the Lagoa Feia formation both in figures 5a to c, confirming the syn rift nature of this depositional unit, and appear to have been active for longer and probably represents a later stage with respect to the fault system 2; the low angle fault (fault 2) localized in the low part of the Lagoa Feia appear to have been the triggering structure of the first rift structuration. While in some cases the main stratigraphy seems to have a clear onlapping relation with those faults while in other cases (arrow 1 figure 5b) the lower Lagoa Feia units do not have reflector terminations with a clear relationship. The later listric fault (fault 3) clearly controls and defines the main geometry and space of the half graben and certainly affects the lateral thickening observed which is bound by the maximum rifting surface. This suggests that intermittently the listric fault has been active for a long time and that most of the deposition of the pre salt unit included the late *Low Tectonic Activity Systems Tract*.

Therefore From a stratigraphical point of view (refer to Fig. 2) the Lagoa Feia subunits have been structurally interpreted following the criteria and scheme proposed by Prosser (1993) and Norverdt et al. (1995):

The *Rift Initiation Systems Tract*, onlapping both small normal block faults (system 2, involving mostly the basement units) and the large listric fault structures (system 3) controlling most of the tectonic subsidence; In a rift related linked depositional system, those succession roughly correspond to the rift initiation starting with an early syn rift unconformity sensu Prosser (1993) and Norverdt et al (1995).

The *High Tectonic Activity Systems Tract* (in blue) showing an aggradation and then draping the Rift Initiation Systems Tract but laterally onlapping the main boundary faults (system 3) or the product of the scarp degradation, but still confined within individual half-graben systems. They clearly represent the early and later onset of the rift climax where subsidence controlled by the fault activities is still faster than the sedimentation. As a consequence those units are comparable with what Prosser (1993) calls the units sequence of early - mid climax syn rift and are certainly part of the syn rift megasequence of Winter (2007).

The *Low Tectonic Activity System Tract*, again draping and transgressing the previous unit and still onlapping (in places) the large boundary faults across the small half-graben at a more regional scale. It is bounded at the bottom by the *tectonic change surface (blue line)* that represents the late rift climax (sensu Prosser, 1993) where the listric fault activity start to decelerate leading to the first immediate post rift succession through an intermediate late *pre salt syn-rift unconformity*.

5.3 Characterization of the seismic facies

The main seismic interpretation and seismic image analysis consisted in recognizing the seismic facies that are repeatedly observed within he various system tract observed and recognized. The seismic facies is here defined through a combination of reflector geometry (using both continuity and reflection termination), waveform properties as the five seismic attributes appearance described so far (table in Figure 4). Specifically the use of the cosine of the phase, combined with the usual mapping of the reflection terminations, proved very useful and efficient in highlighting both the thin bed, and the continuity between various reflectors. To further fine-tune the internal facies we also extracted seismic attributes related to the relative amplitude and contrast of impedance, such as the reflection strength and RAI. We then linked the various facies to their position within the fault related sub-basin to predict the environments of deposition that controlled the types of deposits (e.g. to differentiate carbonates from sandstones and mudstone units).

Seismic facies 1: this seismic facies is defined by chaotic and/or low amplitude reflectors (Figure 6), with no clear internal stratigraphy, often inferred to be strongly damaged by small faults and fractures. The seismic package characterized by this facies is observed mostly across the syn-rift units and is systematically juxtaposed to fault planes.

Seismic facies 2: This seismic facies show a facies (see Figure 6) characterized by thinly layered, semi-continuous strong to medium amplitude reflections. This facies is best observed through the RAI attributes (fig. 7) that enhance the discontinuous character as it hasa granular and dotted signal in clear contrast with the surrounding facies 3. The cosine of phase expression of the texture confines the thin and non-continuous phase character of the reflectors (Figure 7b). This seismic facies is systematically observed across the all syn-rift units (high to low system tract), and characterizes the package with an onlapping and slightly lateral thickening geometry.

Seismic facies 3. This seismic facies is observed throughout the Lagoa Feia unit from the syn rift to the high and low system tract sub units scattered across the half graben basin. It is characterized by very continuous, thick and strong reflections, interbedded with or even floating within the thinly-layered seismic package (seismic facies 2). The seismic character is clearly represented by the RAI attributes, highlighting strong continuous and bright reflectors (Fig. 7a). Similarly the cosine of phase shows quite thick and continuous reflectors (figure 7b). The packages show quite abrupt boundaries, but do not show any onlap or lateral thickening. They appear as the brightest and distinctive reflectors of the pre-salt units.

Seismic facies 4. A fourth seismic facies (Fig. 6) is characterized by a wipe-out zone where the seismic reflections are strongly disrupted, affected by low amplitude, and pull-ups typical of intrusive features. This seismic character crosses all of the Lagoa Feia connecting the Cabiúnas Formation, reaching the base of the Sag units, suggesting a late/post depositional event with respect to rifting. For an extensive analysis and discussion of those feature we refer to Alvarenga et al (2016).

The seismic facies recognized has been then mapped across the seismic lines B,C and A using the proposed classification (Figs 6 and 7) and the results are shown respectively in Figures 8, 9 and 10 (the numbers 1 to 3 represent the seismic facies described above). The dotted lines represent the boundaries of seismic facies 3.

5.4 Constraints from the well data

Image analysis of individual units recognized through their facies response can potentially improve our understanding of the volumetric distribution of the various lithological units, and prepare the ground for future reservoir characterization and seismic facies analysis of the sub-salt Lagoa Feia units. Brown & Fisher (1980) defined seismic facies as the expression on seismic reflections of geological factors that generate them, such as lithology, stratification, depositional features, etc. In this case although we are lacking a robust lithological calibration of seismic facies we matched the seismic facies with the two available wells (called here well A and well B) after time-converting them using checkshots information. These two well data represented the only geological and petrophysical constraints available in the mapping area. They have been part of the dataset used to define the main petrography and sedimentology background by Armelenti et al (2016) and Goldberg et al (2017). Their location and relative position respect to the seismic line proposed for this studies are indicated in figure 1. We first briefly describe below the main stratigraphical information obtained from the two wells (Fig 11 for a description), and then use it to define the main seismic units matching the seismic facies mapping analysis.

As shown in Figures 8 to 10, wireline log data and continuous core information from two wells (well A and B) have been used to assess the seismic textures recognized within the Lagoa Feia, and assign them a geological significance. A legend describing the main lithological units representation is proposed in figure 11 using the Well B (Fig 11). The following main lithological units have been recognized: conglomerate (orange); sandstone (red); layered limestones (calcarenite, light blue and calcilutite pale blue) and coquine (dark blue) shale and shaly sandstone (green); and marl/mudstone (grey) units. In yellow are represented the sandstone observed within and above the salt unit (Figs 8 and 9). The basalts in the Cabiúnas Formation are marked by the purple colour (Figs 8-10). A detailed petrographical, petrological and sedimentological description of these cores is given by Armalenti et al. (2016) and Goldberg et al. (2017). Here we use only the main lithologies for calibration purposes, to constrain and interpret the main seismic facies. The Well A (Fig 8) extends to some distance below the salt, and penetrates the pre- and syn-rift deposits. The well B is instead represented in figures 9 and 10. The section crossing the main facies 2 and 3 has been zoomed in Fig 11.

Well A (Figure 8) tying seismic line C: well A shows three main package of unit part of the high and low stand system tract. A first package between the maximum rifting surface (top High tectonic activity system track) and the post rift unconformity characterized by semi-continuous, thinly layered reflections of low amplitude defined by a complex alternation of thick units of sandstone and shale/mudstone the seismic facies correspond to the seismic texture described as 1. A second package placed within the High tectonic system track) and characterized by a strong correspondence of the “fat and bright” reflectors (described as seismic facies 2) matching with the occurrence of very finely layered units characterized by alternation of coarse-grained limestones, calcilutite with mudstone / shale and the Coquinas unit (see the yellow brackets indicating the limestone units). A third package bounded between the *high system track* and the Cabiúnas formation (but mostly within the *Rift initiation system track*) is characterized by similar semi-continuous, thinly layered reflections of low amplitude as the first package. This package is characterized instead by an alternance of thick conglomerate unit with shale units and thin layer calcarenite. This seems to suggest that the bright and thick reflections are associated with the presence of coarse-grained limestones within the Lagoa Feia Group.

Well B (Figures 9, 10 and magnified version in Figure 11) tying seismic lines B and A: this well penetrates through the Lagoa Feia Group depositional units at a more distal position respect to the large scale listric fault. This unit is slightly more condensed and the bottom part slightly penetrates the Cabiúnas Formation. Again a similar sequence of packages (from top to bottom) can be recognized. A first package located mostly in the low system track (above the *maximum rifting surface*) characterized by a seismic facies of the type 2 tying mostly an alternation of thick units of sandstone and shale/mudstone. A second package defined mostly by a seismic facies of type 3 mostly confined within the High tectonic system track and the low system track characterized by alternation of coarse-grained limestones, calculutite with mudstone / shale and the Coquinas unit. A third package is extremely similar to what has been described with the well A where seismic expression is defined mostly by the seismic facies 2 characterized by the alternance of thick shale, conglomerate units and thiny calcarenite, Therefore well B confirms similar relations described by the well A, where the presence of dense coquinas and calcarenite is clearly marked by fat and bright reflections associated with seismic facies 3 across the entire unit. In both case the basalts (in the pre/syn rift units) of the Cabiúnas Formation do not generate any real contrast of impedance, possibly due to the absorption effect of the high frequency component of the signal of the above layered limestone subunits.

None of the two wells adds any information about the seismic facies 1, as they do not intersect the associated unit. However the following seismic consideration can help to recognize and assign a clear relationship of the seismic texture to the chaotic and conglomeratic deposit bordering the main faults. All the seismic sections imaging the deep rift structure represented in Figures 8, 9 and 10 indicate that the chaotic and low amplitude seismic texture without any internal stratigraphy recognized here as seismic texture 1 area systematically juxtaposed to small or large fault bordering the small sub-basin underlying the sag and salt unit.

The unit shows also marked amplitude discontinuity, often intersected by small faults, producing a dotted signature of the signal. The seismic character, location and geometry all suggest the deposit may be related to a range of hanging-wall collapse mechanisms. Collapse of the hanging-wall to the main listric fault (Fault 3) may be attributed to listric fan formation during extensional faulting (Gibbs, 1984) and associated rock fall, debris flow and sediment slumping processes (Prosser,1993). Similarly, recurrent extensional pulses along this border fault may have remobilized shallow-water sediments and allowed gravitational mixing and re-deposition of both pre-rift footwall and syn-rift hanging-wall material (Goldberg et al., 2017). Figure 12 shows a small fault-related basin imaged by the seismic line A and characterized by the Lagoa Feia infilling, in which the seismic facies proposed above have been recognized and mapped out. From what observed the two seismic facies 2 and 3 seem to both characterize the Atafona Formation and they consist of siltstones, sandstones and lacustrine shales with a distinctive talc-stevensite mineralogy, interbedded thin lacustrine limestones (for a detailed sedimentological analysis see Goldberg et al., 2017)

5.5 Structural considerations and kinematic restoration test

Large-scale seismic mapping of the Lagoa Feia Formation (across the seismic lines A,B and C) allowed for a clear description of their stratigraphic relationship with the syn-rift faults. All of the structures and reflection terminations observed (Figs 5) suggest that the Lagoa Feia Formation was deposited during tectonic extension, when certainly faults populations 2 and 3 were active and displacing (Figs. 5a and 5b). Cross-cutting relationships also show that the W-dipping faults in the western parts of Lines A and B (Fault Set 1) post-dating the deposition of the upper part (*high to low tectonic system tract*) of the Lagoa Feia Fm and thus suggest a stage of extension that post-dates that of faults set 2 and Fault set 3. Seismic mapping of the Top Cabiúnas and its relation with the extensional faults in the lower part of the *rift initiation system track* however, does not provide an obvious relative timing between the Fault Set 2 and Fault set 3 - whether movement on these faults were synchronous or one population pre-dated the other. Therefore a simple restoration approach applied to Seismic Line A, which retains line lengths of key reflectors (Fig. 13), provides some first approximations and simple observations that help to clarify some of these aspects. Two scenarios have been investigated. A Scenario 1 (Fig. 13 a to d) in which the E-dipping faults are kinematically linked and coeval to the large listric fault. A scenario 2 (Fig. 13), in which E-dipping normal faults which deform the base of the Lagoa Feia Formation, the Cabiúnas Formation, and underlying deposits, before the onset of fault movement along the large W-dipping listric fault. Both scenarios, when restored, produce very similar results and in both cases a final restorable structure similar to those mapped in Seismic Line A (Fig. 13d). Essentially the following kinematic evolution can be proposed:

An initial extensonal rift event where the low angle small rift fault are active and create the small rift structure with syn depositional structure which geometry and architecture correspond to the *Rift initiation system track (*Fig 13 b). At a certain point the stress field condition produces some strain localization where one of the small west dipping faults start to localize the extension (Figs. 13 c to d) producing a large listric fault (Fig. 13d) that will control the main half graben structure. That listric fault will produce the main conglomerate breccia and reworked deposit observed in all the seismic lines (Figs. 8 , 9 and 10) and described as seismic facies 1 (Fig. 6) . The system will continue till the extension will relax or decelerate or till the stress field will re orient activating new extensional fault population aside of the main basin (Fig. 13 e).

Due to poor resolution and the degraded nature of the seismic data, particularly in the hanging-wall to Fault 3 (Seismic Facies 1), and in the lower part of the Lagoa Feia Formation (Seismic Facies 2), refinement of structural models, and a determination of relative fault timings (of Fault Set 2 and fault 3) has not been possible. Therefore two problems still remain of limited solutions:

Bedding geometries (and their reflector terminations) of syn-rift deposits in the initial units of the Lagoa Feia Formation are poorly constrained and thus do not provide a definitive solution to relative fault timings. The lack of clearly defined seismic horizons in the hanging-wall of Fault 3, particularly adjacent to the fault, does not allow for estimates of syn-rift deposition rates.

Similarly, the presence of listric fault roll-overs or synthetic fans cannot be deduced from the available data (Gibbs, 1983). Thus, the nature of the seismic expression does not provide sufficient data for robust kinematic restoration and a definitive relative timing for Fault Set 2 and Fault 3 but clearly does not exclude kinematically their mutual activities.

Finally the age of or nature of the main low angle fault have not been resolvedeither as the restoration does not rule out the possibility that part of those initial faults were not inherited from previous structural history (Fig 5b, zoomed example 1 where the reflector seem to onlap the structure)

6. Discussion

6.1 Facies interpretation

The workflow and seismic characterization proposed here allowed us to map and reconstruct the main pre salt units structure and interpret the seismic facies of some of the major units of the lower Lagoa Feia Group. Due to the particular position of the lower Lagoa Feia, sandwiched between the salt unit above and the basalt below, in a present-day deep water location, the quality of the seismic data over the main sequence and sub-units is very noisy and the resolution is limited producing a lot of uncertainty. Most of the high frequencies are in fact absorbed by the salt and partly by the main calcarenite, calcilutite and coquinas-limestone units (Fig 3a). Moreover the seismic properties observed indicate the pre/syn-rift units constituted by basalt and interlayered shale (Cabiúnas Formation and lower portion of the Lagoa Feia Group) are rendered almost invisible, or characterized by very weak reflections. The basaltic units are in fact inferred mainly through well bore and well log information but cannot be traced out through a clear amplitude seismic distinctive response. This could suggest that within the Cabiúnas Formation the thin bed character of the interlayered basaltic intrusion is probably producing an extremely damaged or poor signal, certainly hiding more complex relationships than simple layering structure as various other authors has suggested (Magee et al.,2015).

As a consequence our attention has been here focused on the above seismic package part of the *rift initiation tract, high and low tectonic system tract* and the post rift units above the Cabiúnas Formation.

Using limited well log and core information to calibrate their seismic waveform properties three major seismic facies have been recognized and associated with three different lithological units characterizing the Lagoa Feia Group (Figure 9).

1) The units associated with seismic facies 1 show chaotic reflectors, without continuity (see the area enclosed by the blue line in Figs 11 and 12) and with low average amplitude. Its occurrence is geographically associated with the border faults, suggesting that their deposition is controlled by the fault movement (Figs 11 and 12). This facies seems never to occur within the earliest syn-rift deposit, probably because there was insufficient topographic relief at this time to form the deposit. The same applies to the top units of the basin (as observed in seismic line in figures 8 and 9), where this seismic facies seems not to occur, probably because during the late its later stages of development the basin was already starting to behave as a post rift with low fault related subsidence. As a consequence, this facies is interpreted as breccia and re depositional slope deposits originated from erosive mechanism along the fault edge due to the displacement increase of the footwall block right after its failure. They are commonly interpreted as conglomeratic deposits, named as border-fault deposits (Goldberg et al, 2017). Seismic facies 2 shows instead a diverging configuration across the majority of the sub-basin analyzed, suggesting a hummocky configuration in the depocenter across all the half-grabens examined (Figures 8 and 9). The shale/marl and thick sandstone units that compose the facies unit 2 are characterized by the absence of coquinas or other carbonates. They affect both unit from the *initial rift system tract* as much as the upper part of the *High tectonic system tract* and the l*ow system tract.* This facies is rather characterized and controlled by the thick layered and low amplitude continuous reflectors (Figs 5 and 6) rather than the compositional component (within which the bright thick units of seismic facies 3 are embedded). According to the well data, and to the existing petrographical information (Armelenti et al., 2016; Goldberg et al., 2017), facies 2 can be linked both to the Barremian aged Atafona Formation consisting of siltstones, sandstones and lacustrine shales with a distinctive talc-stevensite mineralogy, interbedded thin lacustrine limestones as to the Itabapoana Formation (alluvial fans/fan deltas proximally and lacustrine/lagoonal sediments distally) and also of Barremian to lower Aptian age, partly laterally equivalent to Atafona. The two units has been interpreted By Goldberg et al. (2017) as fine-grained lake sediments, associated with sediment gravity flow deposits.

2) Seismic facies 3 shows reflections with a rather parallel configuration, but with an average high amplitude and good continuity, producing a rather tabular geometry (Figs 5 and 6). As shown in Figure 5 they show the highest frequency response within the High and low tectonic system tract and the. The reflector terminations seem to indicate onlap geometry characterized also by some structural truncation. The facies 3 is usually dispersed or sandwiched within the facies 2 (Atafona and Itabaquana formations) , and can occur both along the basin margins as well as in the depocenter of half-grabens (Figs 8, 9 and 10). This facies has been interpreted, using the existing well log information and petrographical information (Armelenti et al. 2015; Goldberg et al.,2016), as rudstone/grainstone carbonate units, which

are locally arranged in the form of mounds, and laterally shading into texture 2. Some authors such as Abrahão & Warme (1990) and Rangel & Carminatti (2000) state that the deposits of thick carbonate can be interpreted as shallow marine deposits. However, due to its scattered location, texture 3 is here interpreted as a result of reworking and erosion of a shallow bank. The deposits associated with this seismic facies have been here named as coarse grain-dominated re-sedimented deposits (Goldberg et al.,2017).

A fourth seismic facies shown in Figure 8 indicates an intrusive feature, characterized by a large wipe-out zones with some pull-up velocity effects enhanced (possibly exaggerated by an incorrect velocity model) affecting the entire Lagoa Feia Group and touching the sag unit. This feature has not previously been described, but its geometry and texture suggest that important gas chimneys affect the entire pre-salt unit. The nature and significance of this structure has been extensively described in the companion paper by Alvarenga et al (2016)

6.2 Structural evolution

The simple kinematic test coupled to the seismic mapping across three seismic line A to C (driven by the three well data analysis) helped us to reframe and define the structural characteristic of the Campos pre salt structure in the area of investigation. The rifted half graben basin where most of the re-depositional system has been described and here investigate show a story characterized by west dipping low angle fault initially triggering the main extension , affecting the top Cabiúnas Formation and creating the initial space for the first Lagoa Feia unit (Fig 13 a to c). Those fault seem to remain active during the enucleation and main displacement activity of the large lystric fault (Fig 13 d to e) that will shape the final half graben structure and allow for the major unit of the Laoga feia to be deposited and preserved so far. During the deposition of the mid-upper unit of the Lagoa Feia (High to low syn rift deposition system tract) the rift system seem to still be active and probably affected by a different stress orientation that re activate or enucleate east dipping fault (fault system 3 in fig 5a and Fig 13 d). Those two fault systems will contribute to createthe syncline type half graben system observed across the Campos Basin. Different cross section, represented in Fig 14, seem to confirm that trend and that overall geometry: from the different seismic line crossing along the extension (Fig 14, section 1 2 and 4) and orthogonally to it (3 in Fig 14) they all show that the pre salt Lagoa Feia unit (rift initiation, High and low rift system) has been deposited and controlled by the large listric fault and some of the out of sequence extensional late fault. As suggested by some reflection termination (Fig 5d) there is no reason to rule out the possibility that some of the initial low angle faults may have been in reality part of a pre-existing inherited structure affecting the Cabiúnas Formation, re activated during the main rifting activity. Overall the framework seems to suggest a long lived extensional system affected by several low angle and listric faults which in some cases were re activated during the final subsidence history. The lateral thickening but also onlapping thrpugh an interfingered relationship with the border fault deposit, suggested that the Lagoa Feia unit is a syn rift depositional unit. In that case they should not be assigned to the post rift supersequence as originally suggested by Winter et al. (2007). Finally the faults do not affect the pre salt unit confined between the pre salt syn rift unconformity and the base salt but there are no obvious relation to rule out the possibility that this unit may still be affected by a syn rift activity driven by a deep crustal extension devoid of visible upper fault.

6.3 Pre salt late-syn rift unconformity: Sag unit?

From our mapping the Lagoa Feia Group is covered by the transitional late Syn-Rift pre salt sequence bounded here by the *pre salt unconformity* (red units), observed at a regional scale (see sections in figures 5) and characterized by a phase where the differential subsidence across the fault plane ceases. In this paper we restrict the analysis of our observation to a specific single half graben system. Moreover the lack of informations from the well bore doesn't allow us to further investigate the nature of this post rift unconformity unit with respect to the regional tectonic of the passive margin. Within our area of investigation the lack of upper crustal rift deformation in our seismic sections (Figs 5 and 8) can' t rule out the possibility that this Pre salt late-syn rift unit was still subsiding under the depth-dependent extension (Karner & Gamboa, 2007) determined by the rate of crustal extension. Therefore we cannot exclude that this late syn rift unit could be related to the last crustal adjustments before the continental effective break-up (as predicted by Wernicke, 1985). Asimilar interpretation would then place this unit as structurally linked to the deformation transition from fault-controlled brittle deformation to depth-dependent lithospheric thinning, essentially triggered by ductile stretching of the lower crust (Kusznir and Karner, 2007). Other authors instead have interpreted that unit as a Sag Unit (Guardado et al.1990; Contreras, 2010) and therefore as a sedimentary precursor of the salt units characterized by halokinetic features. In that case the pre salt late syn rift unconformity may correspond to the onset of a regional lower Aptian unconformity, termed by some authors as the pre Alagoas unconformity (Karner, 2000), which could support these units here being interpreted as a gentle sag phase part of the rift supersequence leading to the evaporate or salt sequences (Guardado et al.1990). The lack of stratigraphic constrain and ages still allows us to interpret this succession as a pre salt basin fill, involved into a continued syn-rift extension without major visible extensional faulting typical of the upper crust (Karner, 2000; Karner and Gambôa, 2007, Contrera et al., 2010). If this is the case this implies that the unconformity needs to be interpreted as pre salt base unconformity. A secondary implication is that the upper part of the Lagoa formation may not be included or interpreted as a post rift units and therefore may be considered part of the post rift supersequences by suggested by Winter et al. (2000).

7 Conclusion

A seismic and structural interpretation of the pre-salt Lagoa Feia Group is here proposed through the analysis of a combination of seismic and well data from the Campos Basin. Our analysis shows that:

- By using some basic attributes of the seismic signal it is possible to recognize some distinctive seismic facies characterizing the main lacustrine depositional environment across the entire region of the Campos Basin.

- The main seismic facies, calibrated through well data, can be linked to the main depositional units of the Lagoa Feia Group, characterizing border fault deposits; dominantly fine-grained re-sedimented deposits; dominantly coarse-grained, carbonate-rich re-sedimented deposits; and intrusive wipe out zones affecting the entire pre-salt unit.

- The seismic facies allow the description and characterization of an internal seismic architecture of the sub-basin related to the syn-rift tectonic activity, suggesting that the Lagoa Feia seismostratigraphy represents a fault-restricted lacustrine depositional environment, strongly affected by long-lived intermittent rift tectonics.

- Restoration models suggest that the extensional rift tectonics has been intermittent but affected by different populations of normal faults through the pre salt depositional history. All the faults likely contributed to trigger the main re depositional nature of the main lacustrine deposit but also to shape the syncline geometry of the main half graben preserving the Lagoa Feia unit.

- A unit here described as pre salt late rift unconformity may represent or a later syn- rift response to lithospheric deformation or a intermediate (syn- rift) sag phase preluding to the salt deposit affecting the entire campos basin.

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Figure captions:

Figure 1: a) Location of the study area offshore Campos Basin, southeastern Brazil. b) Seismic grid of the 2D lines analyzed for this studies. In bold the location of the three seismic lines (A, Band C) selected and the two well data |(A and B) utilized for this studies.

Figure 2 : Schematic table representing : the main litostratigraphic units, seismic stratigraphy units recognized and proposed in this study, the main regional tectonic framework and the super-sequences (sensu Winter, 2001) for comparison. The color within the seismic stratigraphy units represents the main mapped horizon and unconformity as represent in the seismic line interpreted.

Figure 3. a) seismic image indicating a Red Green and Blue (RGB) blend of three main frequencies (20 Hz red, 48 Hz green, 70 Hz Blue Hertz). In white are represented the area with concentration of the three frequencies. The yellow arrow points respectively the top and the bottom of the salt unit. The white arrow point the main coquinas unit.b; representationof part of the Well B calibrating some of the reflectors within the sub-salt Lagoa Feia. The white points represents the interval velocity from check shot data (2519m/sec; 2402 m/sec). Rge

bold number represent the thickness of a single reflection. The color legend represent the principal lithological information observed from well core data released.

Figure 4 Synthetic overview of the various attributes applied (Sweetness; RMS; Cosine of the phase; RMS amplitude; Relative Acoustic Impedance) and a description of their utility and interpretation rules within our seismic facies analysis is represented.

. Figure 5: A.Seismic line A represent as amplitude expression with 3x vertical exaggeration. White line represent the main rift faults. Numbers 1, 2 and 3 represent respectively the three faults family: late syn-rift west dipping fault; 2. Syn-rift east dipping faults. 3. Syn rift listric fault. Mapped horizons from youngest to oldest: red the post rift unconformity; blue; maximum rifting surface; yellow the half graben development surface; B. Seismic line B and the main Well B representing the main lithological units; The white and yellow numbers (1,2 and 3) as pointed by the white arrows across the all image 5a to c represents areas characterized by distinctive reflection terminations respect to the main syn-rift fault system. The yellow number shows the location of the sub-sections. Subsection 1) Reflectors on-lapping on the west dipping syn rift fault. Subsection 2) Lateral thickening reflectors but on-lapping on a chaotic zone bordering the syn-rift fault. Subsection 3) reflector on-lapping on the main fault but concordant respect to the top Cabiunas formation; C. Seismic line A crossed by the well A and well C.

Figure 6. Representation, imaging and description of the main seismic facies (1 to 4) observed and recognized in the sub- salt Campos Basin.

Figure 7 a, b . Seismic attributes images extracted and zoomed from the seismic line A represented in figure 6. a) seismic image represented as relative acoustic impedance. Note the clear and distinctive seismic facies 2 and 3 defined by the different brightness and continuity. b) seismic image (a) expressed as cosine of the phase. Note the facies 2, 3 now characterized by distinctive thickness and continuity properties.

Figure 8 Seismic line C (4x vertically exaggerated) and crossed by the well A. showing the distribution of the main seismic facies 1,2 and 3. Numbers 1, 2 and 3 represent the units characterized by the proposed facies 1, 2 and 3. The dotted lines represent the boundaries of the main seismic facies.

Figure 9 Seismic line B with the location of the well B and the mapped seismic facies (1-3)

Figure 10 Seismic line A with the location of the well B and the mapped seismic facies (1-3)

Figure 11 . Enlarged view of the seismic line 2 (see figure 10) with the location of the well B. In orange are represented the conglomerate and arenitic sandstone; in blue and acquamarine the coarse grained/rudstone carbonate/coquinas unit; in pale green silty argillite; strong green the shale and grey the marly units. The basalts in the Cabiúnas Formation are marked with the purple colour.

Figure 12 Representation of the main facies across the Seismic line A. In orange is represented the seismic facies 1; In green the seismic facies 2; In blu the seismic facies 3.

Figure 13 Kinematic restoration test of Line A. a) Mapped normal faults and main units of the pre-salt interval, corresponding to described systems tracts and seismic facies referred to in the text. B) Pre-rifting geometries with dashed fault locations. C) Scenario 1, in which Fault set 2 pre –dates Fault 3 and depositional geometries of the lower part of the lagoa Feia Fm are largely controlled by Fault Set. d) Scenario 2: kinematically linked fault sets, in which Fault set 2 branches off a detachment floor fault, which may be linked to Fault 3. e) Border fault 3 zone formation, with Seismic Facies q related to slump deposits and possible hanging-wall collapse. f) Activation of Fault Set 1, which post-dates movement on other fault populations and the deposition of the Lagoa Feia Fm.

Figure 14: Schematic sections of the major sub basin structures mapped in the Campos Basin . A) the large scale normal fault/rift related structures as mapped from the seismic dataset. In green the trace representing the main sections shown in B. B) Some examples of the rift structures and their syn/post rift units mapped and interpreted in this work. In yellow the rift initiation system track, blue: high tectonic activity system track; purple: low tectonic activity systems tract. Green: the SAG/salt units.; pale blue: passive margin units; white: sea water.

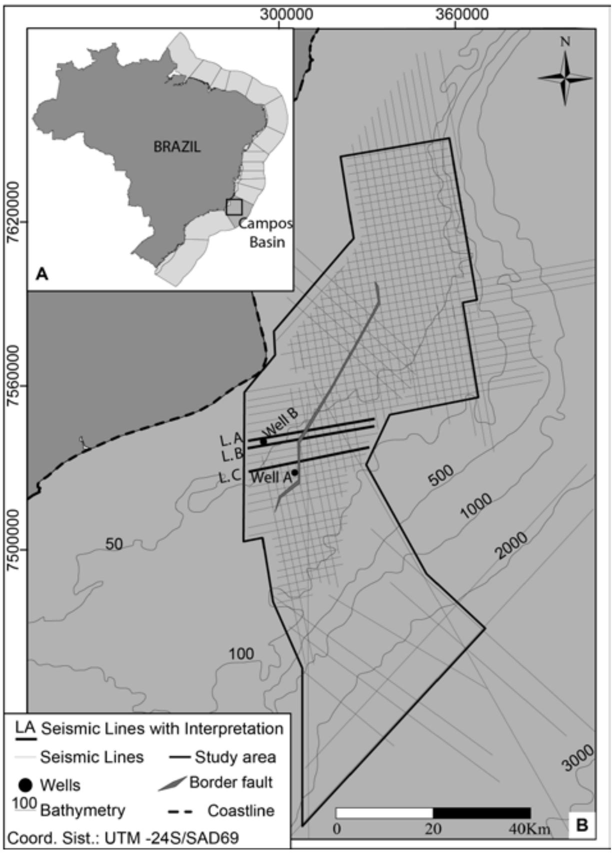

300000
360000
7620000
7560000
7500000
BRAZIL
Campos
Basin
A
N
L. A
L. B
L. C
Well B
Well A
50
100
500
1000
2000
3000
LA Seismic Lines with Interpretation
Seismic Lines
Study area
Wells
Border fault
100 Bathymetry
Coastline
0
20
40Km
B
Coord. Sist.: UTM -24S/SAD69

Fig 1

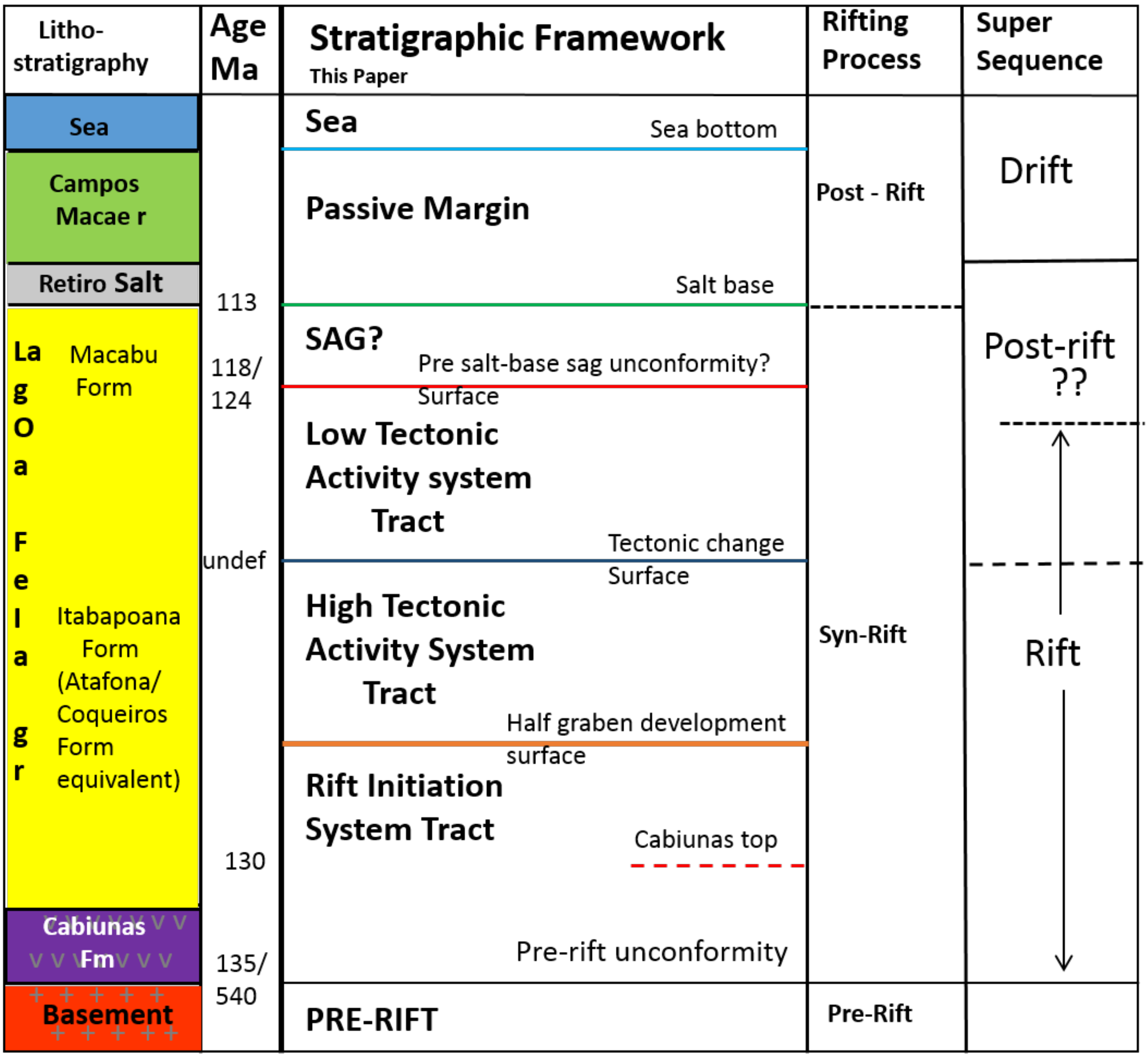

Litho-stratigraphy
Age Ma
Stratigraphic Framework
This Paper
Rifting Process
Super Sequence
Sea
Campos Macae r
Retiro Salt
Lagoa Feia gr
Macabu Form
Itabapoana Form (Atafona/ Coqueiros Form equivalent)
Cabiunas Fm
Basement
113
118/ 124
undef
130
135/ 540
Sea
Sea bottom
Passive Margin
Salt base
SAG?
Pre salt-base sag unconformity? Surface
Low Tectonic Activity system Tract
Tectonic change Surface
High Tectonic Activity System Tract
Half graben development surface
Rift Initiation System Tract
Cabiunas top
Pre-rift unconformity
PRE-RIFT
Post - Rift
Syn-Rift
Pre-Rift
Drift
Post-rift ??
Rift

Fig 2

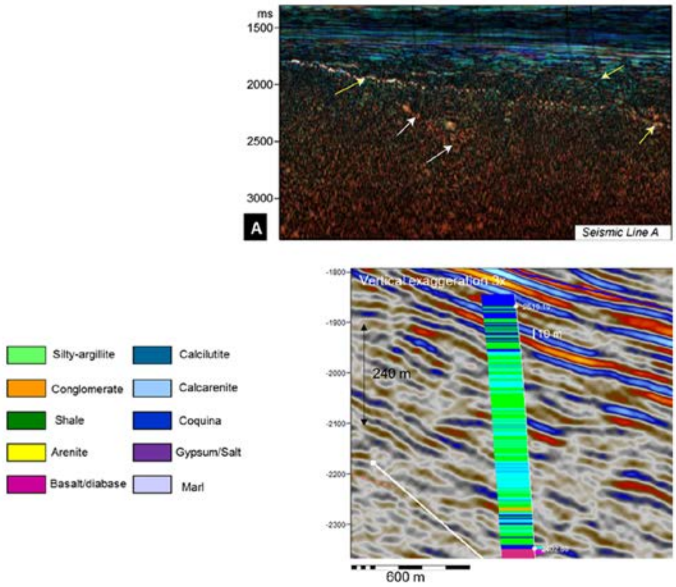

ms
1500
2000
2500
3000
A
Seismic Line A
-1800
-1900
-2000
-2100
-2200
-2300
240 m
600 m
Silty-argillite
Conglomerate
Shale
Arenite
Basalt/diabase
Calcilutite
Calcarenite
Coquina
Gypsum/Salt
Marl

Fig 4

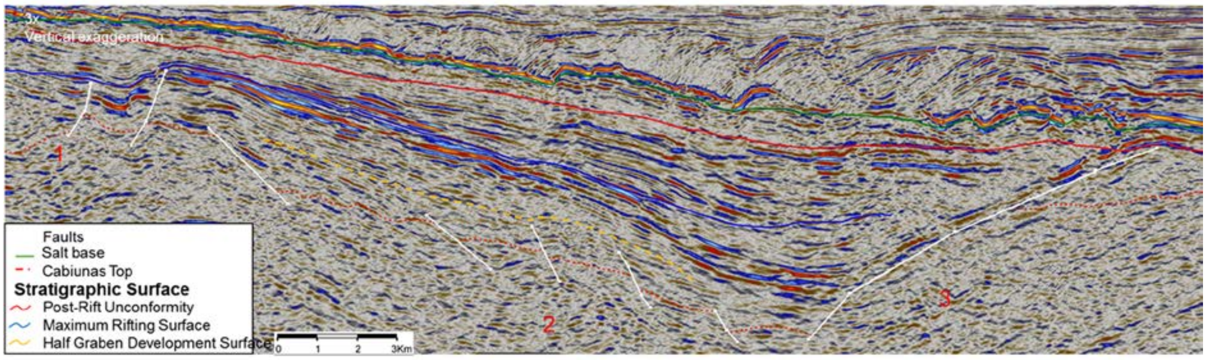

3x
Vertical exaggeration
Faults
Salt base
Cabiunas Top
Stratigraphic Surface
Post-Rift Unconformity
Maximum Rifting Surface
Half Graben Development Surface
0 1 2 3Km
1
2
3

Fig 5a

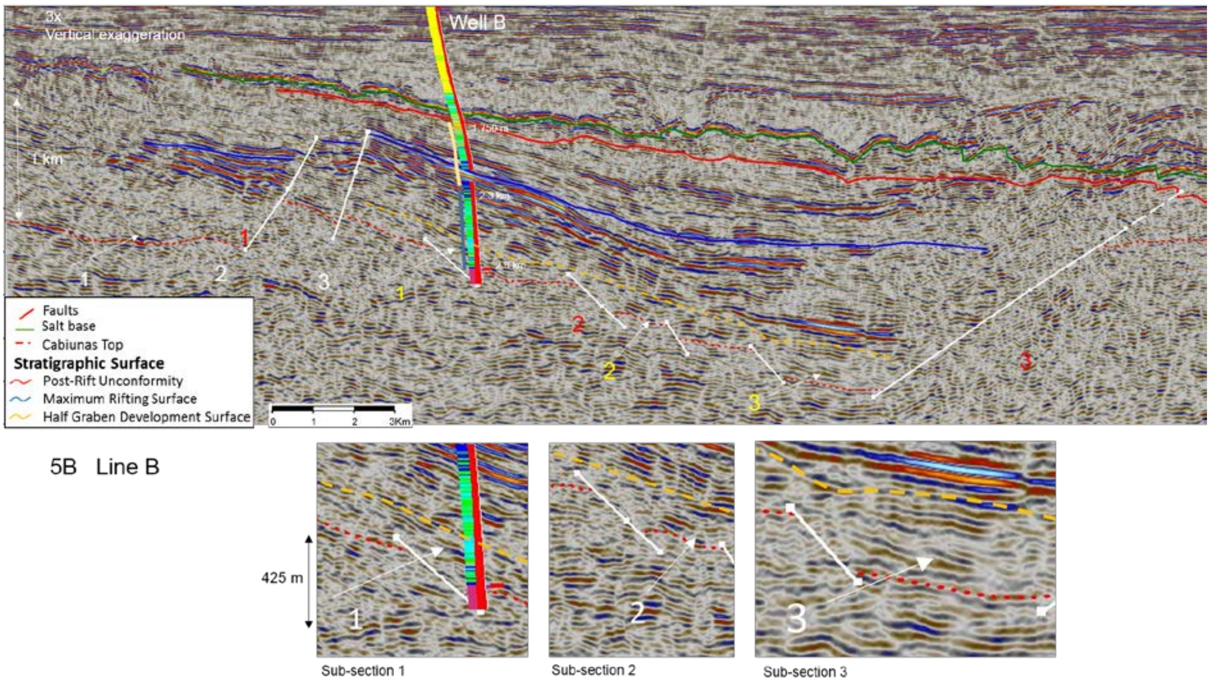
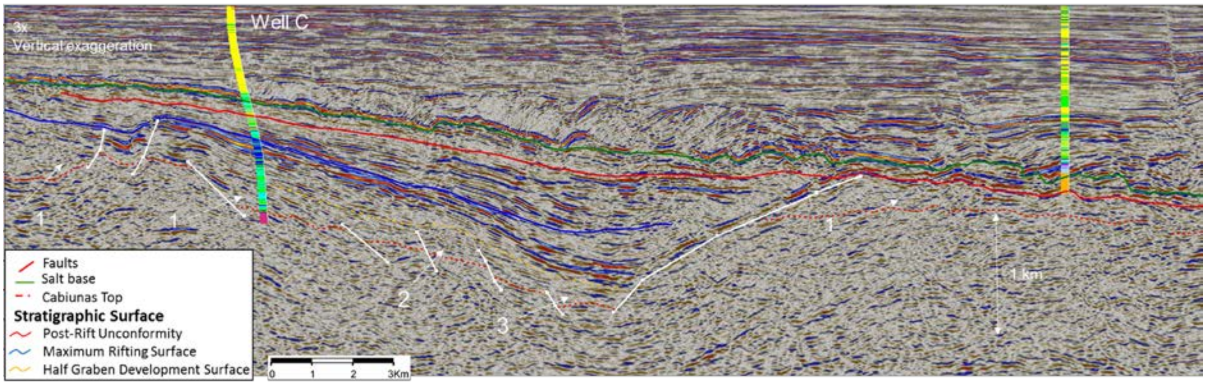
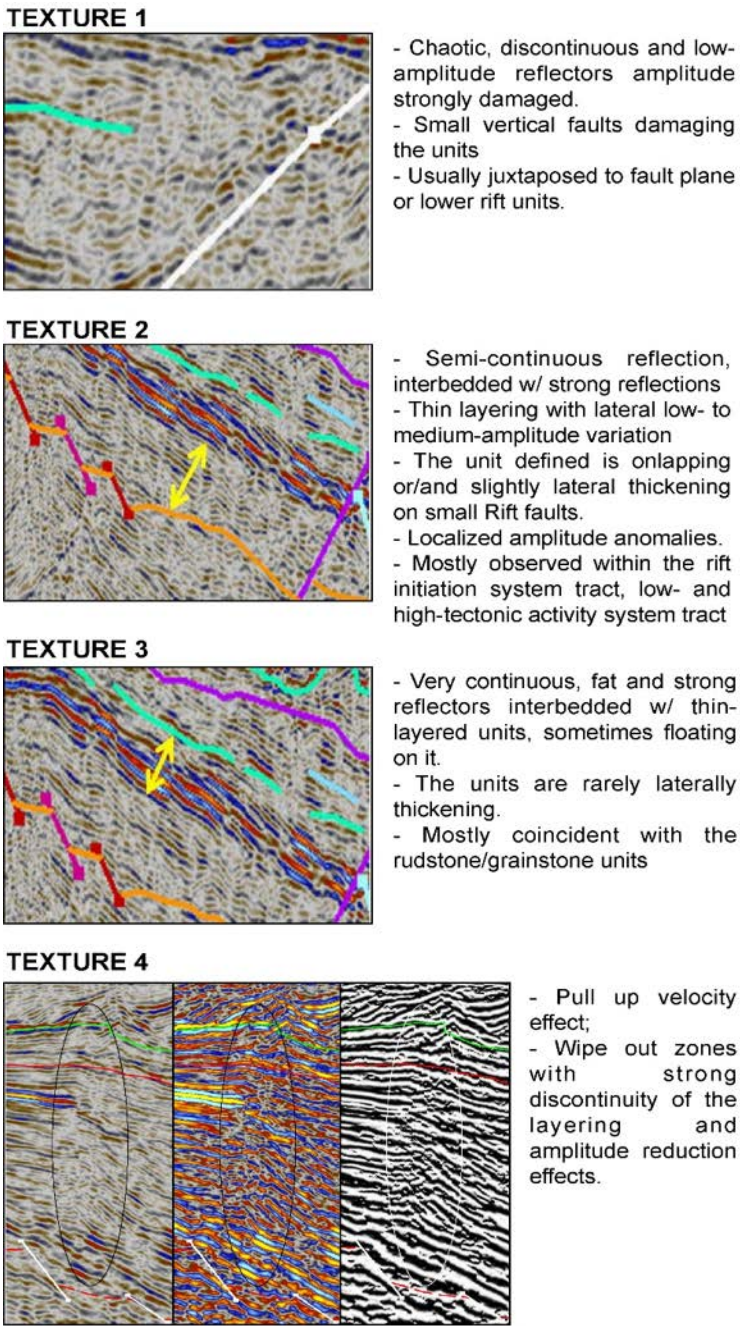

3x
Vertical exaggeration
Well B
1 km
Faults
Salt base
Cabiunas Top
Stratigraphic Surface
Post-Rift Unconformity
Maximum Rifting Surface
Half Graben Development Surface
0 1 2 3Km
5B Line B
425 m
Sub-section 1
Sub-section 2
Sub-section 3

Fig 5b



3x
Vertical exaggeration
Well C
Faults
Salt base
Cabiunas Top
Stratigraphic Surface
Post-Rift Unconformity
Maximum Rifting Surface
Half Graben Development Surface
0 1 2 3Km
1 km
1
1
2
3
1

Fig 5c



TEXTURE 1
- Chaotic, discontinuous and low-amplitude reflectors amplitude strongly damaged.
- Small vertical faults damaging the units
- Usually juxtaposed to fault plane or lower rift units.
TEXTURE 2
- Semi-continuous reflection, interbedded w/ strong reflections
- Thin layering with lateral low- to medium-amplitude variation
- The unit defined is onlapping or/and slightly lateral thickening on small Rift faults.
- Localized amplitude anomalies.
- Mostly observed within the rift initiation system tract, low- and high-tectonic activity system tract
TEXTURE 3
- Very continuous, fat and strong reflectors interbedded w/ thin-layered units, sometimes floating on it.
- The units are rarely laterally thickening.
- Mostly coincident with the rudstone/grainstone units
TEXTURE 4
- Pull up velocity effect;
- Wipe out zones with strong discontinuity of the layering and amplitude reduction effects.

Fig 6

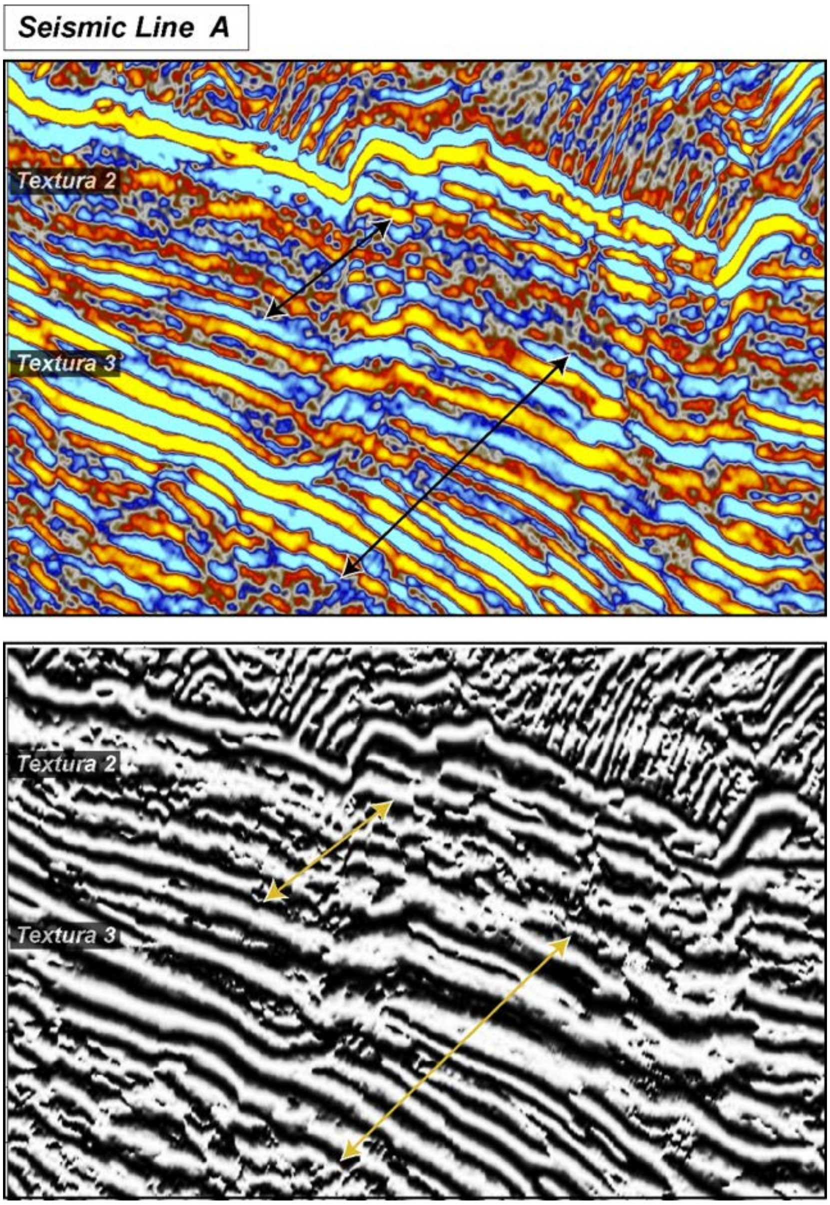


Fig 7

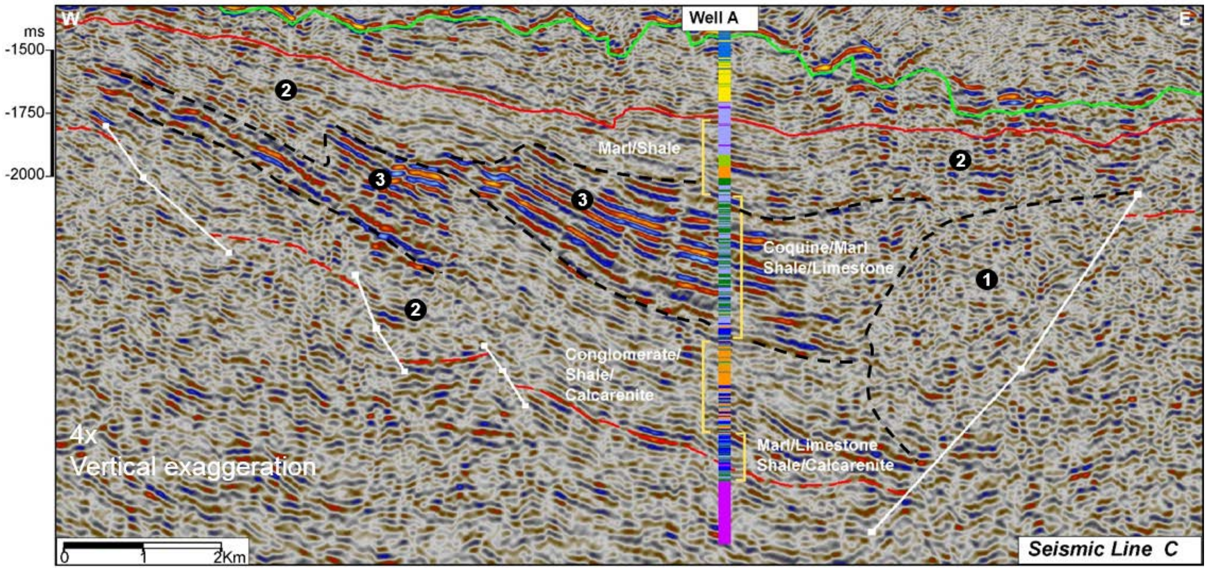

W
E
Well A
ms
-1500
-1750
-2000
Marl/Shale
Coquine/Marl
Shale/Limestone
Conglomerate/
Shale/
Calcarenite
Marl/Limestone
Shale/Calcarenite
4x
Vertical exaggeration
0
1
2Km
Seismic Line C

Fig 8

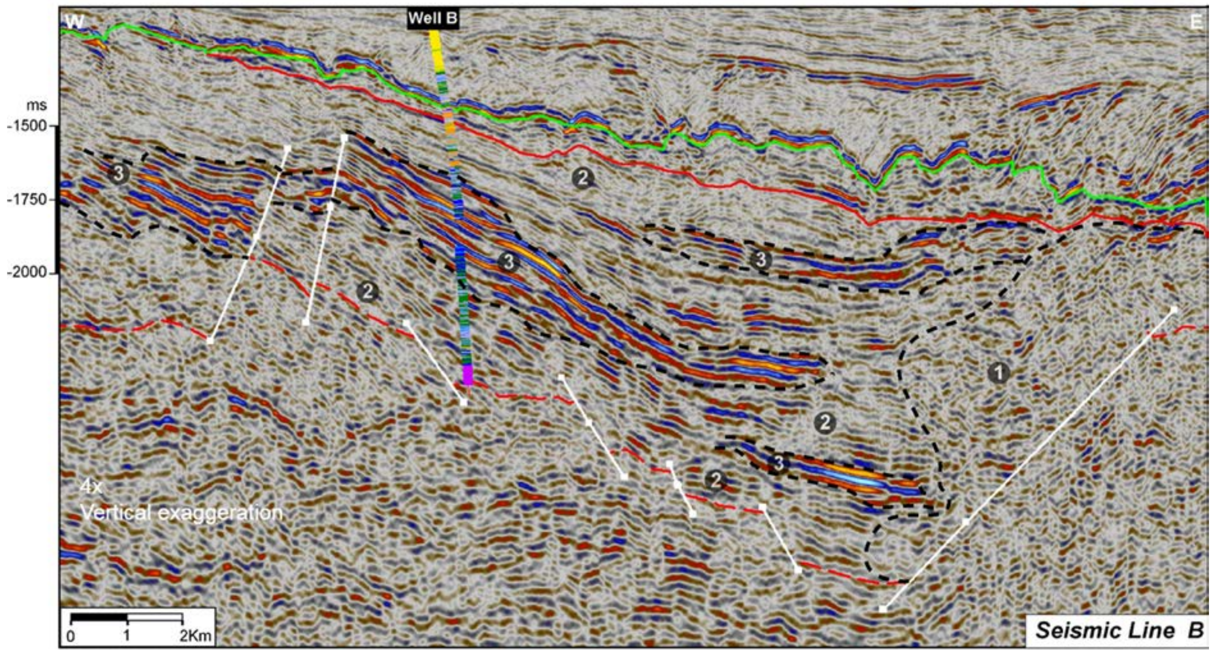

W
E
Well B
ms
-1500
-1750
-2000
4x
Vertical exaggeration
0
1
2Km
Seismic Line B

Fig 9

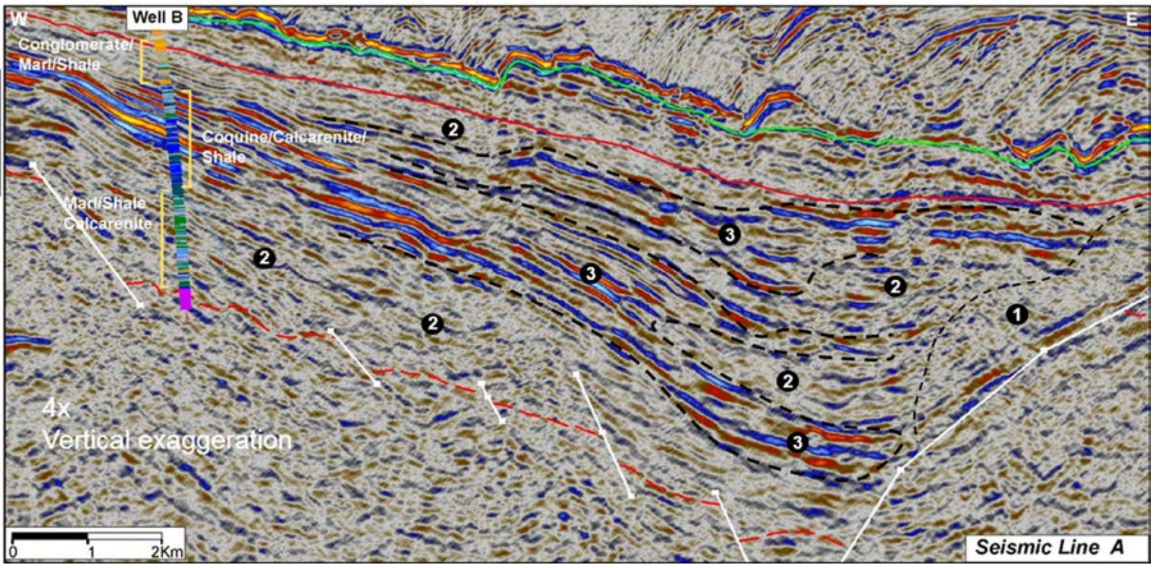

W
Well B
E
ms
-1600
-1800
-2000
Conglomerate/
Marl/Shale
Coquine/Calcarenite/
Shale
Marl/Shale
Calcarenite
1
2
3
4x
Vertical exaggeration
0
1
2Km
Seismic Line A

Fig 10

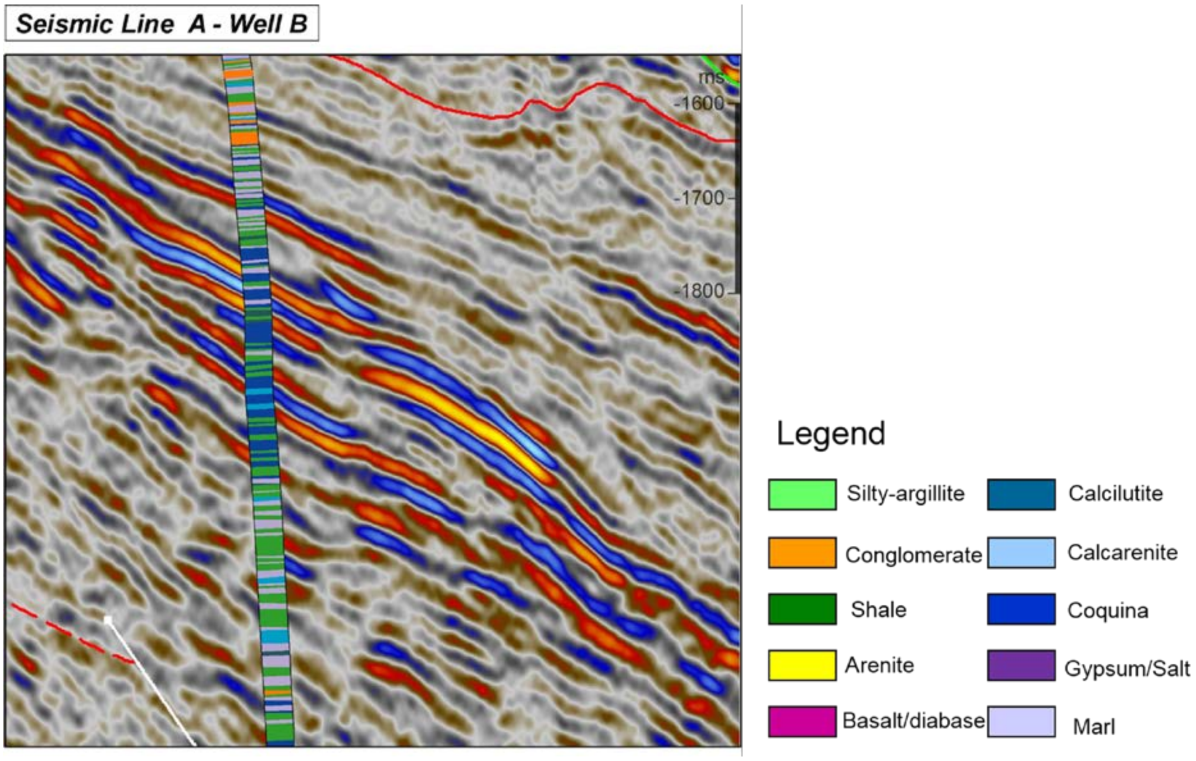

Seismic Line A - Well B
ms
-1600
-1700
-1800
Legend
Silty-argillite
Calcilutite
Conglomerate
Calcarenite
Shale
Coquina
Arenite
Gypsum/Salt
Basalt/diabase
Marl

Fig 11

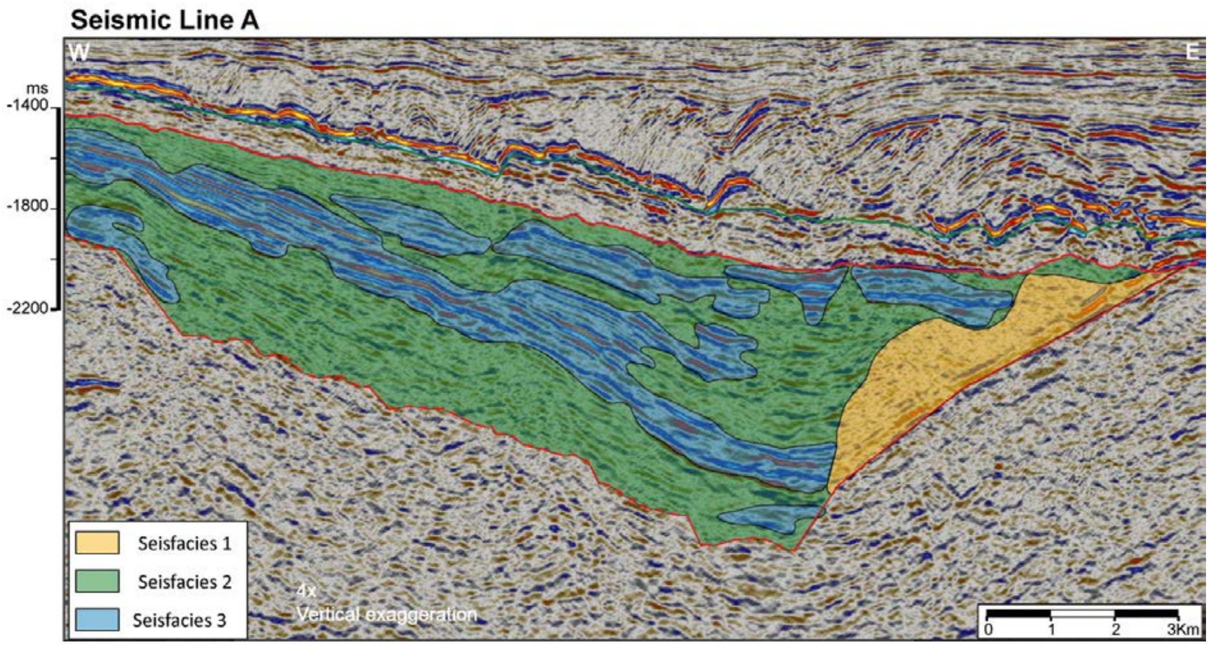

Seismic Line A
W
E
ms
-1400
-1800
-2200
Seisfacies 1
Seisfacies 2
Seisfacies 3
4x
Vertical exaggeration
0
1
2
3Km

Fig 12

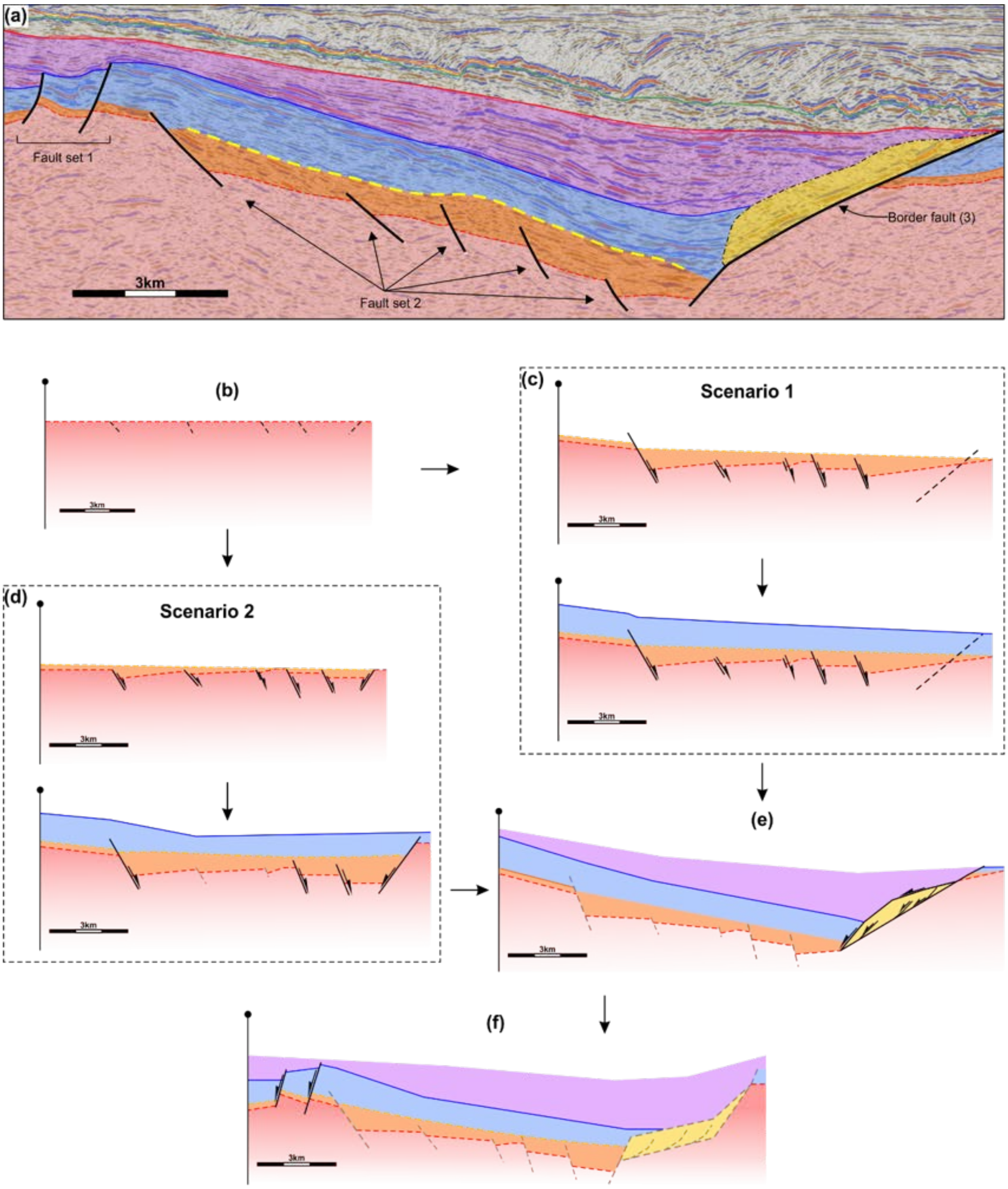

(a)
Fault set 1
3km
Fault set 2
Border fault (3)
(b)
3km
(c)
Scenario 1
3km
3km
(d)
Scenario 2
3km
3km
(e)
3km
(f)
3km

Fig 13

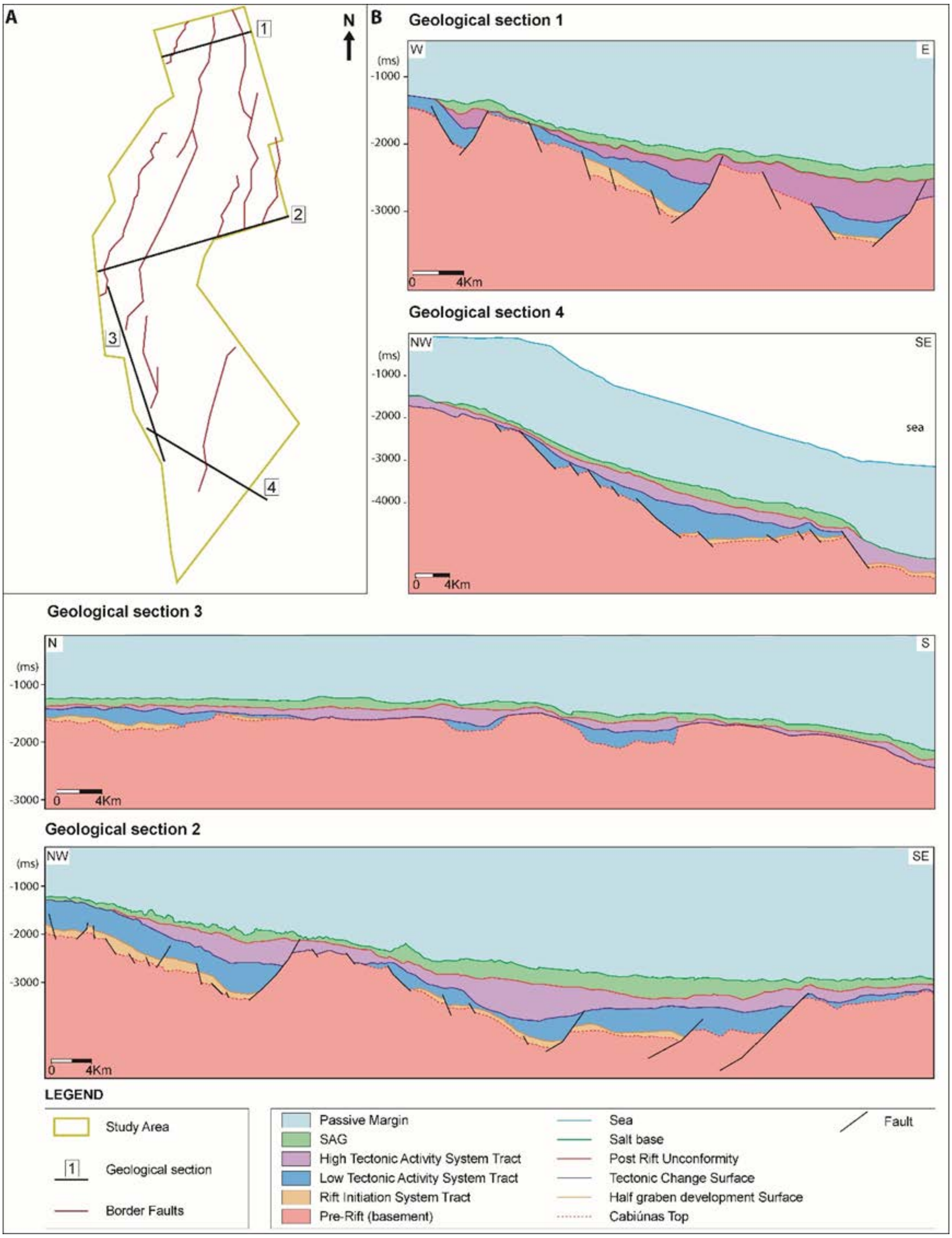

A
N
1
2
3
4
B
Geological section 1
W
E
(ms)
-1000
-2000
-3000
0 4Km
Geological section 4
NW
SE
sea
-4000
Geological section 3
N
S
Geological section 2
LEGEND
Study Area
Geological section
Border Faults
Passive Margin
SAG
High Tectonic Activity System Tract
Low Tectonic Activity System Tract
Rift Initiation System Tract
Pre-Rift (basement)
Sea
Salt base
Post Rift Unconformity
Tectonic Change Surface
Half graben development Surface
Cabiúnas Top
Fault

Fig 14