Revision to be subm to Marine and Petroleum Geology

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

Iacopini D[1], Alvarenga R. S.[2], Kuchle J[2], Cawood A. J.[1], Goldberg K[2], Kneller B[1],

1 School of Geosciences, University of Aberdeen, UK

2 Instituto de Geociências, BG Rift Lab, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil

Abstract

The exploration of pre-salt offshore SE Brazil 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 an extensive 2D seismic dataset and two deep well logs and core information, we propose a seismic facies analysis and structural characterization of the Lagoa Feia group focused in the inner proximal domain of the Campos basin. 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. 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. 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, offshore E Brazil, has an area of roughly 100 000 km^{2}and is one of the most prolific zones of the South Atlantic, with more than 2900 drilled wells (Guardado et al., 2000; ANP-BDEP, 2015). Prior to the recent discoveries of significant hydrocarbon volumes in the pre-salt intervals, suprasalt reservoir accumulations corresponded to more than 90% of Brazil's petroleum reserves

(Winter et al., 2007). Recent estimates (ANP-BDEP, 2018), however, suggest that 51% of total proven reserves in the Campos Basin are related to pre-salt accumulations. The Lagoa Feia Group, (Schaller, 1973), contains both supratidal and upper-intertidal facies (Wright, 2012; Wright and Barnett, 2015; Herlinger et al., 2017) which provide reservoir intervals for these pre-salt accumulations, and the organic-rich lacustrine source rocks (Armelenti et al., 2016; Goldberg et al., 2017) from which hydrocarbons across the basin are derived. The Lagoa Feia Group, deposited in the pre-salt rift and sag phases of the basin evolution, thus represents an important component of the Campos Basin petroleum system.

In light of recent pre-salt discoveries in the Campos Basin, existing understanding of the Lagoa Feia Group (Abrahão & Warme, 1990) has recently been re-interpreted and refined. Detailed petrologic-sedimentologic studies (Armelenti et al., 2016; Herlinger et al., Wright and Barnett, 2015) and seismic stratigraphic approaches have resulted in interpretion of this interval as either re-sedimented gravitational deposits within a rift lacustrine environment (Alvarenga et al., 2016; Goldberg et al, 2017;) or as thicknesses of lacustrine carbonate facies in the more distal part of the margin (Muniz & Bosence, 2018). In spite of these detailed studies, and the large number of wells drilled across the basin, the depositional and structural evolution of the Lagoa Feia Group remains poorly constrained. Few (40?) of the 2900 Campos wells penetrate the Lagoa Feia Group rift section (Armelenti et al.,2016; Muniz and Bosence, 2018) and it is estimated that less than 600 m of publicly-available cored intervals exist for the Lagoa Feia Gp. across the entire basin (Goldberg et al., 2017), despite the regional importance of this interval.

This paper aims to build on existing petrographic, stratigraphic and sedimentological interpretations (Armelenti, 2016; Alvarenga et al. 2016; Goldberg et al. 2017; Herlander et al. 2017) of the Lagoa Feia Gp. by focusing on the seismic expression of the mnain units and structural elements within this pre-salt rift and sag interval.
By extracting the main seismic reflection parameters (which include geometry, continuity, amplitude, frequency) and analysing core data from two wells tied to the sub-salt seismic data, we propose several structural seismic facies that have regional significance across the Campos Basin for the Lagoa Feia Group. Based on the distribution of these proposed seismic facies and their spatial relationships to major normal faults through the pre-salt section, we explore several kinematic scenarios for the rift evolution of the Campos Basin. By comparing alternative kinematic scenarios, we discuss the significance for understanding the rift evolution of the Campos Basin.

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). During this major tectonic event, both the Atlantic margin of Brazil and the west African margins 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). The sedimentary wedge within the Campos Basin is at least 4-6 km thick at depocenter locations, but thins locally over basement highs (Kumar et al.,1977; Zalan et al., 2011). Refraction experiments (Zalan et al., 2011; Moulin et al., 2011) suggest that to the east of the basin, the sedimentary pile overlies thinned continental crust and contienental –oceanic boundary have been tentatively proposed through gravity and magnetic data analysis (Demercian et al.,1993; Zalan et al.,2011)

Within this tectonic framework, the sedimentary record since the Mesozoic in the Campos Basin has been traditionally described in terms of three supersequences (Winter et al., 2007, Fig. 2): (1) Rift Supersequence, (2) Post-Rift Supersequence and (3) Drift Supersequence. These supersequence classifications, as defined by Winter et al. (2007) are appraised in detail in the following sections, based on recent work and newly seismic interpreted data from the Campos Basin.

(1) According to Winter et al. (2007), 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, as defined by the Atafona, Coqueiros and Itabapoana formations. The Barremian aged Atafona Formation consists of siltstones, sandstones and lacustrine shales with a distinctive talc-stevensite mineralogy (REF), and interbedded thin lacustrine limestones. The overlying Coqueiros Formation is of upper Barremian to lower Aptian age and has been described as coquina facies (“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, according toGoldberg 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, which includes the upper Itabapoana, laterally equivalent Gargau, and Macabu Formations. Overlying the Lagoa Feia Gp is the evaporitic Retiro Fm. The upper Itabapoana Fm. is dominated by marls, calcilutites and low-density turbidity current deposits, with the overlying Macabu Formation dominated by bioticabiotic stromatolites, laminated microbialites and chemical precipitates controlled by the geochemistry of alkaline lacustrine waters (Wright 2012; Herlinger et al., 2017). The Retiro Fm., which overlies the Lagoa Feia Group, is an evaporitic sequence 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). The upper portion of the Retiro Formation displays a retrogradational pattern, and is interpreted to represent a eustatic sea-level rise (Winter 2007; Davison, 2007). This unit marks the clear boundary between the post-rift and the underlying syn-rift (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).

(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).

In spite of these detailed lithostratigraphic classifications, particularly within the Post-Rift Supersequence, these units are not chronostratigraphically or regionally consistent, but are in fact related to specific depositional environments that varied substantially along the rift and across the Campos Basin (Karner & Gamboa, 2007; Stanton & Masini, 2013).

3. 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 have been selected here as representative), and 40 wells, of which only 13 have well logs data and two have core (referred to here as wells A 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. Most of the seismic data (2D) released for the project (Fig. 1) was acquired in the inner slope, primarily for the purpose of imaging the supra-salt, post-rift sedimentary units. They all represent pre stack time Kirchoff migrated seismic sections. 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 (a coherent velocity model of the pre salt area is in fact missing). In Figure 3a, a sample of a 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 (15, 35, 55 Hertz frequencies) using a constant mean frequency/ total bandwidth ratio. The blended image indicates that the highest frequencies over 35 Hz (bluish 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 35 Hz. Using the check-shot information available within the Lagoa Feia Group (Fig 3b), which yield measured velocities varying between 2.4 and 2.7 km/sec (Fig. 3c), 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. This is the maximum resolution we can thus expect in the presented seismic interpretation. Figure 3b shows the calibration of some of the major reflectors using the well log B which clearly confirms the resolution values of 10-30 m (at best), supporting the frequency analysis.

1) 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 interpret the main internal variations or lateral continuity of the seismic facies, reducing our ability to interpret details of 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 2 wells stored useful core information across the full dataset and only two could match the entire pre-salt sequence. Another well named well C* (Fig 1) contains well log data that have been used to calibrate some reflectors. Therefore most of our seismic facies analysis will be devoted to seismic lines that are tied to those wells (Fig. 1).

4. Methods

Using the reflector terminations, picking the main amplitudes and using seismic attributes, allowed us to recognize the main unconformities and seismic facies. Core data from well A and B |(Figs 3 and 5) have been used to interpret and constrain some of the main seismic package and the seismic facies recognized. Check shot and sonic log data when available have been also used to estimate average velocities and depth convert the seismic data . data.

4.1 Seismic velocities

Interval and average velocities utilized for the seismic intepretation have been obtained mostly from both the well log, sonic log and the check shots released for this research activity. The velocities vary considerably within the different formations of the Lagoa Feia but two main packages have been recognized. The unit directly below the salt unit, across the main upper syn-rift unit, records interval velocities that vary between 2.1 to 3 km/sec. The second package, with an average velocity of 2.4 to 2.5 km/sec, is defined through two interval velocities of 2.4 (upper part) and 2.5 km/sec (fig 3c) which occurs directly below the main thick redeposited carbonate rich units as, suggested by the two check shots velocities indicated in figure 3c (and white values in figure 3b). These two packages are approximately delineated in figure 3c. respectively by the two bold thick lines in light orange and pale blue. Those two average of velocities has been used to calculate the mean depth across the wells.

4.2 Seismic attributes analysis

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) 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.

2) 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.

3) 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.

5. Results

5.1 Seismic sequence stratigraphy and regional mapping

The first approach of our seismic characterization consisted of identifying the main regional seismic surfaces, with the aim of mapping the major seismic units using reflection terminations and sequence stratigraphic principles. Here we constrain the seismic interpretation of the main seismic units to the large-scale, extensional structural elements observed in the seimic lines (Figs. 5). This first approach to analysis therefore simplifies the conceptual interpretation of the area by emphasising the importance of structural-stratigraphic interactions. 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). 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), and are outwith the scope of this study. The main seismic units and related surfaces that have been recognized and mapped are the following (Fig. 5; see Fig. 2 for stratigraphic framework):

4.1 Pre-rift unit

This is the deepest seismic unit of the framework (Figs. 2 & 5) and consists of Pre-Cambrian plutonic and metamorphic rocks (Goldberg et al., 2017). 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, with their low frequency characteristic (Fig 3A). The majority of information regarding this deep section comes from well core and log data which were used to tie and calibrate the main seismic units, and the response of this section to sweetness attributes. Here we refer to three main seismic lines (sections A, B and C; Fig. 5) and the two main wells used in this study: well A and well B(see Fig. 1 for locations of seismic lines and wells).

- Top Cabiúnas Formation: The well data (the purple unit in well B in Figs. 5A, and 5b and well A in Fig 5C) characterize the Cabiúnas Formation as sediments inter-fingered with thin basalt sills (Goldberg et al.,2017). The top of the Cabiunas formation represents a lithological contrast between the basalts and the overlying sediments, with no chronostratigraphic significance (Goldberg et al.,2017). The top Cabiunas formation is represented as a red dashed line (Figs 5a to c, 8 to 10). The top of this unit is only clearly mappable by using the wells and a combination of amplitude- and phase attributes (Fig 4) that helped to enhance the very low impedance reflection (see Fig. 5b). Using the well tie information, the Top Cabiúnas Formation appear defined by a very discontinuous reflection marked by a red dotted interpretation (Fig. 5a-c). This reflection doesn't show any real lateral continuity, which may be suggestive of a non-planar interface between this interval and the overlying deposits. As shown in all the seismic lines (Figs. 5), the Top Cabiúnas Formation is also extensively offset by several extensional faults through the seismic sections (white faults, figs 5a-c).

5.2 Syn-rift unit

Above the top Cabiúnas Formation a thick syn-rift unit, characterized internally by two main discontinuities, has been systematically mapped and recognized across all the seismic lines 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* (reflection highlighted as bold red in Figs. 5a,b and c), which consists of an intense erosional truncations observed across the entire rift basin. The real significance of this unconformity will be further investigated and questioned in the following paragraph. As stated above, using seismic stratigraphy criteria this syn-rift unit has been subdivided into three additional sub-units using internal reflection termination and geometry.

Subunit 1: This unit represented by the pre-rift package above top Cabiunas horizon. 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 above the Cabiunas formation the following characteristics :

a) the reflectors) are mostly parallel and onlapping to the rift faults (Fig. 5a, sub-section 1; fig 5b, subsection 1; fig 5c sub-section1) or truncated by the faults (fig 5a, sub section 2; fig 5c sub-section2) 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 (Fig. 5c, sub-section 2, see dotted lines) show a slightly fan thickening relation with some of the rift faults. The reflection termination against the faultsin some case are unclear or chaotic (fig 5b sub-section 2 ; fig5c sub-section1).

c) very low amplitude and lateral continuity with a conformable parallel reflector geometry to the top Cabiunas , but dissected by the faults (Fig 5a, sub section 2; Fig. 5b, sub-section 1 and 3).

Above those generally comformable reflectors we observe a second unit with a clear distinctive reflector geometry that we will call subunit 2.

Subunit 2: 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 a strong amplitude and divergent reflection pattern along the half-graben structures (Figs. 5). We have defined the regionally mapped surface that separates Subunit 1 and Subunit 2 here as a orange dotted line. (Fig. 5, orange dashed line).

Subunit 3: this third subunit is stratigraphically positioned above the subunit 2 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. The surface separating the sub-unit 3 from sub-unit 2 has been mapped as a continuous blue line The top of sub-unit 3 is defined by a red bold surface here named the (*pre salt base) post rift Unconformity* (in red in Figs. 5 and 8 and 9) as it lie below the salt unit.

Subunit 4: this subunit is defined at bottom by the *post rift unconformity horizon* and at the top by the base salt (Fig. 5, green bold line). It is characterized by thinning out horizontal versus slightly divergent reflectors. It is un-affected by fault displacement. On top of this unit we define a pre-salt base unconformity (or simply salt based represented in green) that define an intense erosional truncation observed and mappable across the entire basin analysed.

5.3 Post-rift unit

As clearly indicated in Fig 5c, outside the mini syn-rift basin bordered by the main syn-rift fault system, subunits 1 and 2 between the top Cabiúnas Formation and the *post rift unconformity* thin out, or are strongly reduced/eroded.

5.4 Structural elements

As shown in the large seismic section in Fig. 5a, the deposition of the Lagoa Feia group pre-salt subunits is controlled and defined by a series of normal faults. alternating with half-grabens where the main boundary fault develops, which affects the all subunits 1, 2, part of 3. A closer look at the mapped normal faults (with red numerations in figures 5 a, b) is proposed through the figures 5a to c representing respectively the seismic line named A, B and C in figure 1. The all seismic lines are biased by a vertical exaggeration of 3:1.

Figure 5a shows a complete section of one of the half grabens.. The half graben structure is controlled by three different oriented fault systems: high angle fault with an antithetic orientation (fault 1 red) with respect to the low angle faults; low angle, small displacement normal fault (fault 2 in red) affecting the base of the Lagoa Feia and the top Cabiunas formations; and the large-offset listric fault (fault 3 red) which controls the main graben geometry. Timing of fault populations will be further investigated through a restoration model but the geometry and the relationship with the stratigraphy indicate that the three different fault systems were all active during the half graben units 1 and 2 structuration. 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 (as by the onlapping reflection termination described, Fig. 5a, sub-section 1; fig 5b, subsection 1; fig 5c sub-section1). In some other cases the lower Lagoa Feia units do not have reflector terminations with a clear relationship (fig 5b sub-section 2 ; fig5c sub-section1) or they seem to be cutted by the faults (Fig 5a, sub section 2; Fig. 5b, sub-section 1 and 3) suggesting a later displacment. The fault system 1 (red number) are high angle normal faults and appear to cross most of the Units 1 and 2 of the Lagoa Feia formation, with an opposite dipping direction respect to the fault population 2. This is clearly observed in all the seismic lines represented in figures 5a to c, confirming the syn-rift nature of the Lagoa Feia depositional unit.

The reflection terminations and cutting relationship suggest that the fault population 1 has been active for longer and probably represents a later stage with respect to the fault system 2; the fault population 3 is defined by a low angle listric-type of fault (fault 3 red). It clearly displaces the top Cabiunas formation by several hundred of meters (see wells A and C represented in Fig 5a) and is systematically bordered by a chaotic seismic facies where the lateral thickening Unit 2 interrupt its reflector terminations (Fig 5a to c). The fault is draped by the *pre-salt post-rift unconformity* that in all seismic lines appears unaffected by any visible displacement (figs 5).

5.6 Seismic facies

The main seismic interpretation and seismic image analysis consisted in recognizing the seismic facies that are repeatedly observed within the various systems tracts observed and recognized. The seismic facies are 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 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 (Fig 5 a to c, Figs 8-10).

Seismic facies 2: This seismic facies (see Figure 6) is 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 has a 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 (Fig 7b). This seismic facies is systematically observed across all syn-rift units (high to low system tract), and characterizes the package with an onlapping and slightly lateral thickening geometry (FigS 8-11).

Seismic facies 3. This seismic facies is observed throughout the Lagoa Feia unit between the top cabiunas formation and the post rift unconformity 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 better 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 salt and pre salt unconformity, suggesting a late/post depositional event with respect to rifting. For an extensive analysis and discussion of those feature in the pre salt campos basin 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 will be 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.

5.7 Correlation of seismic facies to well data

Seismic 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 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. Therefore although we are lacking a robust well log 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/socic logs information. Two of these well data (Well A and Well B) represented the only geological and petrophysical constraints available across 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). Well C has no core available but had useful well log information to correlate the top Unit 4 across the seismic dataset (Fig 5a). We first briefly describe below the main stratigraphical information obtained from the three 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 facies 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). 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.

Well A (Fig 8) extends to some distance below the salt, and penetrates the pre- and syn-rift deposits. 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 C contain information only for the shallow post-rift pre salt part of the Lagoa Feia Group (Unit 4) flanking the half graben minibasin.

5.7.1 Well A

Well A (Fig. 8) tying seismic line C: well A shows three main package of unit part of the high and low stand system tract. The enclosed white numbers, indicate the seismic facies and the black dotted lines marks their distribution across the syn-rift units. A first package (yellow bracket) just below the red bold line 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 facies described as 2. A second package placed within the lateral thickening reflectors and characterized by a strong correspondence of the "fat and bright" reflectors (described as seismic facies 3) 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 marl/S limestone units). A third package bounded between the second package and the Cabiúnas formation 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.

5.7.2Well B

Well B (Figs 9, 10 and magnified version in Figure 11) tying seismic linesA and B: this well penetrates through the Lagoa Feia Group depositional units at a more proximal 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 to well A (from top to bottom) can be recognized (refer to Fig 9). A first package located mostly in the upper part 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 again within the lateral thickening fat and bright reflectors and characterized by alternation of coarse-grained limestones, calcilutite with mudstone / shale and the Coquinas unit. A third package is again 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 in a lateral thickening package 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. 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 facies 1, are systematically juxtaposed to small or large fault bordering the small sub-basin underlying the sag and salt unit.

6. Discussion

7.1 Interpretation of the Lagoa Feia seismic stratigraphy

The detailed sedimentological analysis obtained from well correlation of our area of interest, have been proposed in previous companion paper by Goldberg et al. (2017) and indicates that the absence of clear retrogradational or progradational stacking patterns suggests a dominant intrabasinal depositional system, mostly controlled by the small normal and border fault. Our seismic description indicates that all the major seismic units and structure described in the Lagoa Feia formation are deposited within a setting mostly controlled by an active tectonic expressed through the normal high angle faults and the large border fault bounding asymmetric graben. This allow us to interpret the reflector geometry and their internal facies characteristics described, within a depositional system dominated by the tectonic control with poor input from extrabasinal system. Therefore for the seismic interpretation of the Lagoa Feia subunits (refer to Figs. 2 and 5), we adopted the criteria and scheme proposed by Prosser (1993) and Norverdt et al. (1995) following their proposed tectonic system tracts.

- The first subunit has been described as concordant to or onlapping both the small normal block faults (fault system 2, involving mostly the basement units) and to the chaotic seismic facies bordering the large listric fault structures (fault 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). 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 (dotted red) and the first lower lateral thickening reflection of the Lagoa Feia called *Half graben development surface* and mapped as a dotted orange reflector.
- Above the *Half-Graben Development Surface* is deposited the second subunit. It shows an aggradation, lateral thickening (versus the listric fault) and then draping the *Rift Initiation Systems Tract* but laterally onlapping the main boundary faults (system 3) or the product of the scarp degradation, always confined within individual half-graben systems. The reflectors all terminate more or less abruptly against the chaotic facies 1, bordering the listric fault controlling the geometry of the asymmetric graben. 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). As the geometry of those reflectors is mainly controlled by the lystric faults and affected by late high normal faults we call that unit as the *High Tectonic Activity Systems Tract*.

- The third subunit is again draping and transgressing the previous unit and still downlapping to onlapping (in places) the large chaotic facies bordering the boundary faults across the small half-graben at a more regional scale. It is bounded at the bottom by the *Maximum rifting sequence (blue line).* As the reflector clearly show a reduced lateral thickening (but still downlapping the chaotic zones close to the footwall scarp) we suggest that unit may 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 post rift unconformity (red)*. This pre salt top uncomformity is probably locally equivalent to the pre Alagoas transitional megasequence (Guardado et al, 1990; Karner, 2000) but better chronostratigraphic data are needed to support this interpretation.
- Finally we observe the subunit 4 that appear totally unaffected by the listric fault and the re activated high normal fault. It may be interpreted as *late post rift system* sensu Prosser (1993).

6.2 Seismic facies & structural characteristics

The workflow and seismic characterization proposed here allowed us to map and reconstruct the main pre salt units structures and interpret the seismic facies of the major subunits 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 (1 to 2 sec TWT), the quality of the seismic data over the main sequence and sub-units is low and the vertical resolution is limited to the tuning thickness (10-30 m) producing large 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 tectonic activity systems tract*, *late rift system tract* and the post rift units all stratigraphically above the Cabiúnas Formation. Using limited well log and core information to calibrate their seismic waveform properties, three major seismic facies (facies 1, 2 and 3) have been recognized and associated with three different lithological units characterizing the Lagoa Feia Group (Figure 9). In figurews 8, 9 and 10 representing respectively the seismic line CA, A and B (with a different vertical exaggeration respect to Fig 5) the facies are numbered by the white number enclosed in the round box.

1) The units associated with seismic facies 1 show chaotic reflectors, without continuity (see the yellow area in Fig 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 8 , 9 and 10). 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. Across the all lines, the unit shows also marked amplitude discontinuities, 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 in Figs 5A to C) 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 (Fig 5a-c and Figs 8-10) 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). Therefore facies 1 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).

2) Seismic facies 2 (Figs 8-10) 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 to 10). 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 tectonic change surface.. This facies is rather characterized and controlled by the thick layered and low amplitude continuous reflectors (Figs 5 and 6 and 8 to 10). 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) but also the lower Aptian age, partly laterally equivalent to

the Macabu formation characterized by laminated microbialites and chemical precipitates controlled by the geochemistry of alkaline lacustrine waters (Armelenti et al., 2016; erlinger et al 2017 . The two units have been interpreted by Goldberg et al. (2017) as fine-grained lake sediments, associated with sediment gravity flow deposits.

3) 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, 8-10). As shown in Figure 5 they show the highest frequency response within the *Hightectonic system tract*. 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 equivalent) , 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 re-deposited 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).

4) 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).

The distribution of the recognized facies across two analysed seismic lines are show in figures 8 (Line C), 9 (Line A) and 10 (line B) through the white numbers. A full colour representation of the main facies is shown in Fig 12 and it clearly indicate the scattered nature of the main re-deposited units within the layered and low amplitude facies characterizing the top and bottom unit.

6.3 Structural considerations and kinematic restoration test

The 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 a punctuated tectonic extension, when certainly faults populations 2 and 3 (red numbers) 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 tectonic change surface) of the Lagoa Feia Fm and thus suggest a stage of extension that post-dates that of faults set 2 and Fault set 3. 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. 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.

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.

Therefore a simple restoration approach applied to Seismic Line A, which retains line lengths of key reflectors (Fig. 13), helped to explore and 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.

As indicated in Figs 13 b and 13 c both scenarios, when restored, produce very similar results and in both cases can lead to 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 (or re-activate pre existing structural high) 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).

6.4 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 listric 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 Tectonic change 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 create the 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 tectonic changes) 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 through an interfingered relationship with the border fault deposit, suggested that the Lagoa Feia unit is mostly 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.

6.5 Pre-salt post rift unconformity: still tectonically - controlled?

In this paper we restrict the analysis of our observation to specifics single half graben systems located in the proximal zone of the passive margin (Fig 1) as we do not have data to compare this section with the distal one along the abyssal plane. This pose uncertainty in pushing our interpretation further into the distal portion of the margin and may explain some clear difference in the depositional system and tectonic reconstruction proposed by other authors exploring more distal units (Muniz &Bosence, 2018). We think it is difficult to compare the seismic facies and seismic units observed and proposed in this paper with the interpreted seismic sections (imaging a more distal part of the Campos basin) discussed in the paper by Muniz & Bosence (2018) as no details of seismic facies are proposed and most of their interpretations rely on well log correlation.

However using a more regional seismic profile (Line D, 12 sec TWT Fig 15) as reference for the crustal structure of the area and extending along NW-SE from near the area of our analysis to the more slope basin part of the margin, we could better define the regiona context of our analysis. It is beyond the scope of this paper to discuss the regional and deep nature of the basement and the regional structure but we will use this seismic line (Line D) as reference for locating the half graben structure controlling the Lagoa Feija Group.

The seismic line D clearly indicate the top basement (named Top Cabiunas formations, dotted red), the post rift unconformity (light red bold line) and the base salt units (green bold line) defining respectively the subunit 4 and the top of the subunit 3. The top basement define below a thick crustal unit where some clear dipping structure (dotted white colour) plunging ocean-ward can be mapped (also defined by the base of the parabolic diffractive smiles). The lack of a refraction velocity model doesn't allow us to define the nature of this discontinuity, but using and comparing the interpretation from a not far Campos section proposed by Unternehr et al (2010) those features can be interpreted or as a fault or crust structures affected by a changes of seismic facies. In the shallow part of the seismic line D we can clearly observe that all the half graben pre salt structures described and interpreted in this paper are fully located in the proximal continental domain of the Campos basin. The Sub-Unit 4 can be also clearly interpreted as the pre salt Sag deposition unit draping on top of the syn-rift half graben subunits. This structural motif is observed all across the area of interest as indicated by interpretation of near seismic lines (Fig 14.

From our mapping (Figs. 5 a to c and Figs. 8-10) but using the interpretation of other near seismic profile (Fig 14) and a more regional line (Fig 15), the Lagoa Feia Group appear draped by the transitional late Syn-Rift pre salt sequence (subunit 4) bounded at the base by the pre salt unconformity (red unit) and at the top by the base salt (green line) and observed at a regional scale (see sections in Fig 5). It is tectonically characterized by a phase where the differential subsidence across the fault plane ceases to be important (Figs 5, 8-10) and this is observed all across the proximal area (Fig 14, 15). Within our area of investigation the surface we interpreted as pre salt unconformity (red line in Figs 5) separate a domain still affected by faults characterized by lateral thickening unit with coarse grain re deposited rudstone from a domain where parallel reflector are concordant to the surface and are thinning out versus the inner part of the margin. The two well A and B (Goldberg et al.,2017) indicate this portion is characterized at the base by the dominance of fine sediments dominated by heterolithics and massive mudrocks suggesting the action of low-density turbidity currents, associated to distal portions of turbidite lobes.

The seismic lines interpreted (Line A to D) but also the intepretation of near seismic line (Fig 14) indicate the pre salt unconformity is observed laterally beyond the rift basins (Fig 5a-c) and it consistently remains below the salt unit (Fig 15). Across the all seismic lines this unit is always a sedimentary precursor of the salt units characterized by halokinetic features (Fig 5 a to c). Further insight of the units above the Coqueiros formation, come from the well data description propsoed by Muniz& Bosence (2018), both located in the proximal Badeiro High and External High, in a more distal portion respect to our dataset but approximately located in the green square indicated in Fig 15. The authors describe those pre-salt units as characterized by aggradational coarse carbonate grainstones comprising ooid spherulites and stevensite grain and therefore interpret these units as part of the Macabu Formation and assign a post rift sag stratigraphic significance.

Following the well log correlations, seismic and structural interpretation proposed in this paper and in the existing literature (Goldberg et al,2017; Muniz and Bosence, 2018) , the pre salt post-rift unit assigned to the Macabu Formation may correspond to the onset of a regional lower Aptian unconformity, termed by some authors (Karner, 2000), as the pre Alagoas unconformity and would support these units here being interpreted as a gentle sag phase part of the rift supersequence leading to the evaporatic or salt sequences (Guardado et al.1990; Goldberg et al., 2017).

Taking into account a more regional point of view, 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 determined by the rate of crustal/lithosferic extension (Karner & Gamboa, 2007). Therefore we cannot exclude that this late syn rift unit could still be related to the last crustal adjustments or still 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). Again the major uncertainty derive from the lack of data allowing us to trace the relationship of this upper units with the more distal portions of the margin where the extended crust have been observed (Zalan, 2011). Following the Ocean/continent border unit (Fig 1a) proposed by Zalan (2011), our data appear to be grounded on a proximal high angle fault poorlty extended crust. Nothing really forbid to interpret this succession as a pre salt basin fill, deposited into a continued late syn-rift extension without major visible extensional faulting typical of the upper crust (Guardado et al.1990; Karner, 2000; Karner and Gambôa, 2007, Contrera et al., 2010). If so, given the regional nature of the pre salt post rift unconformity preceding a transgressive unit, that is draping the main asymmetric graben and preceding the salt deposition the Pre-salt *post-rift unconformity,* that unit can be interpreted as a breakup unconformity followed by a breakup surface (Soares et al., 2012) here represented by our Unit (4). *Per se* it can merely represent the end of activity in local syn-rift faults, rather than the true end of crustal stretching and the initiation of the drifting phase on newly formed divergent margins (Reston, 2005; Péron-Pinvidic et al., 2007, Soares et al., 2012). The lack of regional seismic line helping us in correlating those structures with the more distal deposition system (potentially more crustally extended) does not allow us to push further consideration on the regional significance of our findings.

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.

- The Unit embedded between the pre-salt late-rift unconformity and the base salt unit, is draping the all half graben faults controlled. It is un-affected by faults and the well correlation (Goldberg et al.,2017; Muniz & Bosence, 2018) suggest it can be interpreted as stratigraphically equivalent to the Macabu Formation. The pre-salt late-rift unconformity may represent a breakup unconformity followed by an intermediate (syn- rift) sag phase preluding to the salt deposit affecting the entire Campos basin.

Acknowledgement: The authors thank BG Brasil, a wholly owned subsidiary of Royal Dutch Shell plc, for financial support for this project and permission to publish. This work was sponsored by the BG funded Deep Rift project (BG-UFRGS-Aberdeen). The paper used Petrel (Schlumberger) and Geoteric (ffA) to interpret the seismic dataset. Constructive comments on an initial draft by T.Alves and Moriak , Douglas Paton are greatly appreciated. We thanks Brent Wignall for comments.

Bibliography

Abrahao, D., Warme, J.E. 1990. Lacustrine and associated deposits in a rifted continental margin-lower Cretaceous Lagoa Feia Formation, Campos Basin, Offshore Brazil. in Lacustrine Basin Exploration, Case Studies and Modern Analogs, Vol. 50, pp. 287–305, ed. Katz B.J., AAPG Memoir.

Amaral, G., Cordani, U. G., Kawashita, K., and Reynolds, J. H, 1966.Potassium argon dates of basaltic rocks from southern Brazil. Geochim. Cosmochim. Acta, 30:159-189.

Alvarenga, R., Iacopini, D., Kuchle, J., Scherer, C. & Goldberg, K. 2016. 'Seismic characteristics and distribution of hydrothermal vent complexes in the Cretaceous Offshore Rift Section of the Campos Basin, Offshore Brazil'. Marine and Petroleum Geology.

Armelenti, G.,Goldberg, K., Kuchle, J.,, De Ros. L.F. 2016 Deposition, diagenesis and reservoir potential of non-carbonate sedimentary rocks from the rift section of Campos Basin, Brazil. Pet. Geosci., 22, 223-239

Brown, L.F., Fisher, W.L., 1977. Seismic-stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull-apart basins. In: PAYTON, C.E. (Ed.) Seismic tratigraphy: applications to hydrocarbon exploration. AAPG, Memoir 26, Tulsa, p. 213-248.

Chopra, S., Marfurt, K.J. 2007. Seismic attributes for prospect identification and reservoir characterization. SEG books.

Chopra S, Castagna J P., Xu Y. Relative acoustic impedance defines thin reservoir horizons. Search and Discovery Article #40435 (2009)

Contrera, J., Zuhlke., Bowman., S., Bechstadt., T., (2010). Seismic stratigraphy and subsidence analysis of the southern Brazilian margin (Campos, Santos and Pelotas basins). Marine and Petroleum Geology. 27, 1952-1980.

Demercian S., Szatmari P.,. Cobbold P.R. 1993. Style and pattern of salt diapirs due to thin-skinned gravitational gliding, Campos and Santos basins, offshore Brazil. Tectonophysics, 228, 393-433

Colpaert,A., Pickard,N., J Mienert, j., Henriksen,L.B., Rafaelsen, b., Andreassen, K.. 2007 3D seismic analysis of an Upper Palaeozoic Carbonate succession of the Eastern Finnmark Platform area Norwegian Barents Sea. Sedimentary Geology, 79-98.

Davison. 1999. Tectonics and hydrocarbon distribution along the Brazilian South Atlantic margin. In: Cameron, N. R., Bate, R. H. & Clure, V. S. (eds) The Oil and Gas Habitats of the South Atlantic. Geological Society, London, Special Publications, 153, 133-151

Davison, I. 2007. Geology and tectonics of the South Atlantic Brazilian salt basins. In: Reis, A. C., Butler, R. W. H. & Graham, R. H. (eds) Deformation of the Continental Crust: the Legacy of Mike Coward. Geological Society, London, Special Publications, 272, 345–359.

Dahlstrom, C.D.A., 1969. Balanced cross sections. Canadian Journal of Earth Sciences, 6(4), pp.743-757.

De Matos. M; Osorio P., Johann, PRS. 2007. Unsupervised seismic facies analysis using wavelet transform and self-organizing maps. Geophysics, 72, 9-22.

Duda, R.O.,Hart, P. O., and Stork, D.G. 2001, Pattern classification, 2nd ed.:JohnWiley & Sons, Inc.

Gibbs, A.D., 1983. Balanced cross-section construction from seismic sections in areas of extensional tectonics. Journal of structural geology, 5(2), pp.153-160.

Gibbs, A.D., 1984. Structural evolution of extensional basin margins. Journal of the Geological Society, 141(4), pp.609-620.

Goldberg, K., Kuchle,J., Scherer, S; Alvarenga, R. Ene, PL., Armelenti. G. 2017. Re-sedimented deposits in the rift section of the Campos Basin. Marine and Petroleum Geology 80, 412-431

Haralick, R. M., K. Shanmugam, and I. Dinstein, 1973, Textural features for image classification: IEEE Transactions on Systems, Man and Cybernetics, SMC-3, 610–621.

Hart, B.S (2008) Channel detection in 3D seismic data using sweetness,AAPG, 92, 733-742.

Herlinger, EJ; Zambonatto, EE., De Ros L.F. (2017) Influence of the diageneseis on the quality of the lower cretaceous prec salt lacustrine carbonate reservoir from northern Campos Basin, Offshore Brazil, Journal of Sedimentary Research, 87, 1285-1313.

Karner, G.D. (2000) Rifts of the Campos and Santos Basins, Southeastern Brazil: Distribution and Timing, AAPG Memoir 73, 301315.

Karner, G. D. & Gamboa, L. A. P. 2007. Timing and origin of the South Atlantic pre-salt sag basins and their capping evaporates. In: Schreiber, B. C., Lugli, S. & Babel, M. (eds) Evaporites through Space and Time. Geological Society, London, Special Publications, 285, 15–35.

Kumar, N., L. A. P. Gamboa, B. C. Schreiber, and J. Mascle (1977), Geologic history and origin of Sao Paulo Plateau (southeastern Brazilian margin), comparison with the Angolan margin, and the early evolution of the northern South Atlantic, in Initial Reports of the Deep Sea Drilling Project, vol. 39, edited by P. R. Supko and K. Perch-Nielsen, pp. 927–945, Texas A & M Univ., College Station, Tex.

Magee, C., Maharaj, S.M., Wrona, T., and Jackson, C.A.L., 2015, Controls on the expression of igneous intrusions in seismic reflection data: Geosphere, v. 11, p. 1024–1041, doi: 10 .1130 /GES01150 .1

Mohriak, W., Szatmari, P. & Anjos, S. M. C. (eds) 2008. Salt: Geologia e Tectonica. Beca Edicoes Ltda, Sao Paulo, Brazil.

Mitchum Jr., R.M., Vail, P.R., Sangree, J. B., 1977. Seismic stratigraphy and global changes of sea level, Part 6: Stratigraphic interpretation of seismic refletion patterns in depositional sequences. In: Payton, C.E. (ed.). Seismic Stratigraphy - Applications to Hidrocarbon Exploration. Tulsa, AAPG, 117-133 (Memoir # 26).

Mizusaki, A.M.P., Thomaz Filho, A. Valença, J.G. 1988. VolcanoSedimentary Sequence of Neocomian age in Campos Basin (Brazil). Revista Brasileira de Geociências, 18:247-251.

Mohriak. W.U.,, Mello, M.R., Dewey, J.F., Maxwell., J.R, 1990. Petroleum geology of the Campos Basin, offshore Brazil. Geological Society London Special Publications 50(1):119-141

Mohriak, W. U., Hobbs, r. & Dewey, J. F. . 1990.Basin-forming processes and the deep structure of the Campos Basin, offshore Brazil. Marine and Petroleum Geology, 7, 94–122.

Moriak, W U, Szatamri,P. Anjos, S. 2012. Salt: geology and tectonics of selected Brazilian basins in their global context. From:Alsop, G. I.,Archer, S. G.,Hartley, A. J.,Grant, N. T.&Hodgkinson, R. (eds) 2012. Salt Tectonics, Sediments and Prospectivity. Geological Society, London, Special Publications, 363, 131–158.

Muniz, M.C, Bosence, D.W.J. 2018. Lacustrine carbonate platforms; facies, cycles and tectono-sedimentary models for the pre-salt Lagoa Feia Group (Early Cretaceous), Campos Basin, Brazil. AAPG Bulletin, in press. doi: 10.1306/051118162061708

Mohriak,W.U.,Nemčok., N and Enciso.,G. 2008. South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil. Geological Society, London, Special Publications 2008, v. 294, p. 365-398

Moulin, M., D. Aslanian, M. Rabineau, M. Patriat, and L. Matias (2012), Kinematic keys of the Santos-Namibe basins, in Conjugate Divergent Margins, Spec. Publ., vol. 369, edited by W. U. Mohriak et al., Geol. Soc., London.

Peron-Pinvidic, G.,Manatschal,G., Minshull, T.A., Sawyer, D.S., 2007. Tectonosedimentary evolution of the deep Iberia–Newfoundland margins: evidence for a complex breakup history. Tectonics26, TC2011.

Posamantier, H., Kolla, V, Seismic Geomorphology and Stratigraphy of Depositional Elements in Deep-Water Settings 2003, Journal of Sedimentary Research,73, 367–388.

Prosser, S. Rift related linked depositional system and their seismic expression. 1993 From Williams G,D & A.Dobb, 1993. Tectonics and seismic sequence stratigraphy. Geological Society Special Publication, 71, 35-66.

Prather, B. E., J. R. Booth, G. S. Steffens, and P. A. Craig, 1998, Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water Gulf of Mexico; errata: AAPG bulletin, v. 82, p. 707R

Prather B. E., Booth J. R.,. Steffens G. S, and Craig P. A.. 1998. Classification, Lithologic Calibration, and Stratigraphic Succession of Seismic Facies of Intraslope Basins, Deep-Water Gulf of Mexico. AAPG Bulletin, 82, 701–728.

Radovich, B. J., and R. B. Oliveros, 1998, 3-D sequence interpretation of seismic instantaneous attributes from the Gorgon field: The Leading Edge, 17, 1286–1293.

Rangel, H.D., Martins, F.A.L., Esteves, F.R., Feijó, F.J. 1994. Bacia de Campos. Boletim de Geociências da PETROBRAS, 8:203-218.

Reed IV, T.B. and Hussong, D. 1989. Digital image processing techniques for enhancement and classification of SeaMARC II Side Scan Sonar Imagery. Journal of Geophysical Research *94: doi: 10.1029/89JB00409. issn: 0148-0227.*

Reston, T.J.,2005. Polyphase faulting during the development of the west Galicia rifted margin. Earth Planet. Sci. Lett. 237, 561–576.

Sarg J. F., James S. Schuelke. 2003. Integrated seismic analysis of carbonate reservoirs: From the framework to the volume attributes The Leading Edge, 2, 640-645

Soares ,DM., Alves M.T, Terrinha, P. 2012. The breakup sequence and associated lithospheric breakup surface: Their significance in the context of rifted continental margins (West Iberia and Newfoundland margins, North Atlantic) . Earth Planetary Sciecne Letters, 355, 311-336.

Stanton N., Masini, E. 2013.The rifting evolution of the Santos Basin: A Geophysical view. 13th International Congress of the Brazilian Geophysical Society & EXPOGEF, Rio de Janeiro, Brazil, 26–29 August 2013: pp. 1690-1693. doi.org/10.1190/sbgf2013-346)

Taner, M. T., and Sheriff, R. E., 1977, Application of amplitude, frequency,and other attributes to stratigraphic and hydrocarbon determination,in Payton, C. E., Ed., Seismic stratigraphy—applicationsto hydrocarbon exploration: AAPG Memoir, 26, 301–327.

Taner,M. T., Schuelke, J. S., O'Doherty, R., and Baysal, E., 1994, Seismic attributes revisited: 64th Ann. Internat. Mtg., Soc. Expl. Geophys.,Expanded Abstracts, 1104–1106

Tedeschi et al., 2017. New age constraints on Aptian evaporites and carbonates from the South Atlantic: Implications for Oceanic Anoxic Event 1a: Geology, doi:10.1130/G38886.1.

Vail, P.R., Todd, R.G. & Sangree, J.B., 1977. Seismic Stratigraphy and Global Changes of Sea Level, Part 5: Chronostratigraphy Significance of Seismic Refletions. In: Payton, C. E. (ed.). Seismic Stratigraphy – Applications to Hydrocarbon Exploration. Tulsa, *AAPG Memoir 26*, p. 99-116.

Vinther, R., K. Mosegaard, K. Kierkegaard, I. Abatzis, C. Andersen, O. Vejbaek, F. If, and P. Nielsen, 1995, Seismic texture classification: A computer-aided approach to stratigraphic analysis: 65th Annual International Meeting, Society of Exploration Geophysicists Expanded Abstracts, v. 95, p. 153–155.

Wright, V.P., 2012, Lacustrine carbonates in rift settings: the interaction of volcanic and microbial processes on carbonate deposition, in Garland, J., Neilson, J.E., Laubach, S., and Whidden, K.J., eds., Advances in Carbonate Exploration and Reservoir Analysis: Geological Society of London, Special Publication 370, p. 39–47.

Wright, V.P., and Barnett, A.J., 2015. An abiotic model for the development of textures in some South Atlantic Early Cretaceous lacustrine carbonates, in Grotzinger, J.P., and James, N., eds., Microbial Carbonates in Space and Time: Implications for Global Exploration and Production: The Geological Society of London, Special Publication 418, p. 209–219.

Zalán, P. V., M. d. C. G. Severino, C. A. Rigoti, L. P. Magnavita, J. A. B. De Oliveira, and A. R. Vianna 2011, An entirely new 3D-view of the crustal and mantle structure of a South Atlantic Passive Margin—Santos, Campos and Espírito Santo Basins, Brazil, in AAPG Annual Convention and Exhibition, Houston, Texas.

Weszka, J., Dyer, C., Rosenfeld, A., 1976. A comparative study of texture measures for terrain classification. IEEE Trans.Systems Man Cybernet. 6, 269–285.

Winter, W. R.; Jahnert, R. J.; França, A. B. 2007. Bacia de Campos. Boletim de Geociências da Petrobras, Rio de Janeiro. v. 15, n. 2, p. 511-529.

Zhang, Z., and M. Simaan, 1989, Knowledge-based reasoning in SEISIS: A rules-based system for interpretation of seismic sections based on texture, in F. Aminzadeh and M. Simaan, eds., Expert systems in exploration: Society of Exploration Geophysicists Geophysical Development Series, v. 3, p. 141–159.

Figure captions:

Figure 1: a) Location of the study area offshore Campos Basin, southeastern Brazil. COB (Continental Ocena Boundary following Zalan et al.,2011); b) Seismic grid of the 2D lines

analyzed for this studies. In bold the location of the three seismic lines (L.A, L.Band L.C) selected and the two well data |(A and B) which ocre 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 et al., 2001) for comparison. The color within the seismic stratigraphy units represents the mapped horizons and unconformities as represented in the intepreted seismic line..

Figure 3. a) seismic image indicating a Red Green and Blue (RGB) blended image using three main frequencies (15 Hz red, 35 Hz green, 55 Hz Blue Hertz). In white are represented the areas with a concentration of the three frequencies. The arrow points respectively the top and the bottom of the salt unit and the main rudstone-coquinas units. (b) Representation of 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). The thickness of a single reflection is also represented. The colors legend represent the principal lithological information observed from well core data released. (c) the diagram show the velocity function obtained form the che check shots. The average velocity obtained form the diagram are represented with bold brown and blue line along the well. White numbers represents the depth position.

Figure 4 Synthetic overview of the various attributes applied (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: All lines are TWT time seismic line represented as 3x vertical exaggeration. The depth scale has been calculated using the velocities scheme proposed in figure 3C. A). Seismic line A represented as amplitude expression with 3x vertical exaggeration. White lines represent the main rift faults. Red numbers 1, 2 and 3 represent respectively the three main faults family recognized: 1. late syn-rift west dipping fault; 2. Syn-rift east dipping faults. 3. Syn rift pseudo listric fault. Mapped horizons from youngest to oldest: red the post rift unconformity; blue the maximum rifting surface; dotted orange the half graben development surface; dotted red the Top cabiunas formation; the yellow sub section (boxes) focus on the reflection termination toward the faults. They are magnified below the main seismic section with the white arrows pointing at the reflection terminations geometry. The white 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 . Sub section1 show the onlap geometry of the syn rift deposit; Sub section 2 show the reflectors (relatively bright) cutted off by the faults. B). Seismic line B and the main Well B representing the main lithological units;. 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. Sub section1 show the onlap geometry of the syn rift deposit; Sub section 2 show the reflectors (relatively bright) cutted off by the faults.

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 5 A. A) seismic image represented as relative acoustic impedance. Note the clear and distinctive seismic facies 2 and 3 defined by the different brightness and (dis-)continuity. B) seismic reflectors from (a) now expressed as cosine of the phase. Note the facies 2, 3 are now characterized by distinctive thickness and (dis-)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 (see main text). The dotted lines represent the boundaries between the main seismic facies.

Figure 9. Seismic line A with the location of the well B and the mapped seismic facies (1-3). Numbers 1, 2 and 3 represent the units characterized by the proposed facies 1, 2 and 3 (see main text). The dotted lines represent the boundaries between the main seismic facies.

Figure 10 Seismic line A with the location of the well B and the mapped seismic facies (1-3). Numbers 1, 2 and 3 represent the units characterized by the proposed facies 1, 2 and 3 (see main text). The dotted lines represent the boundaries between the main seismic facies.

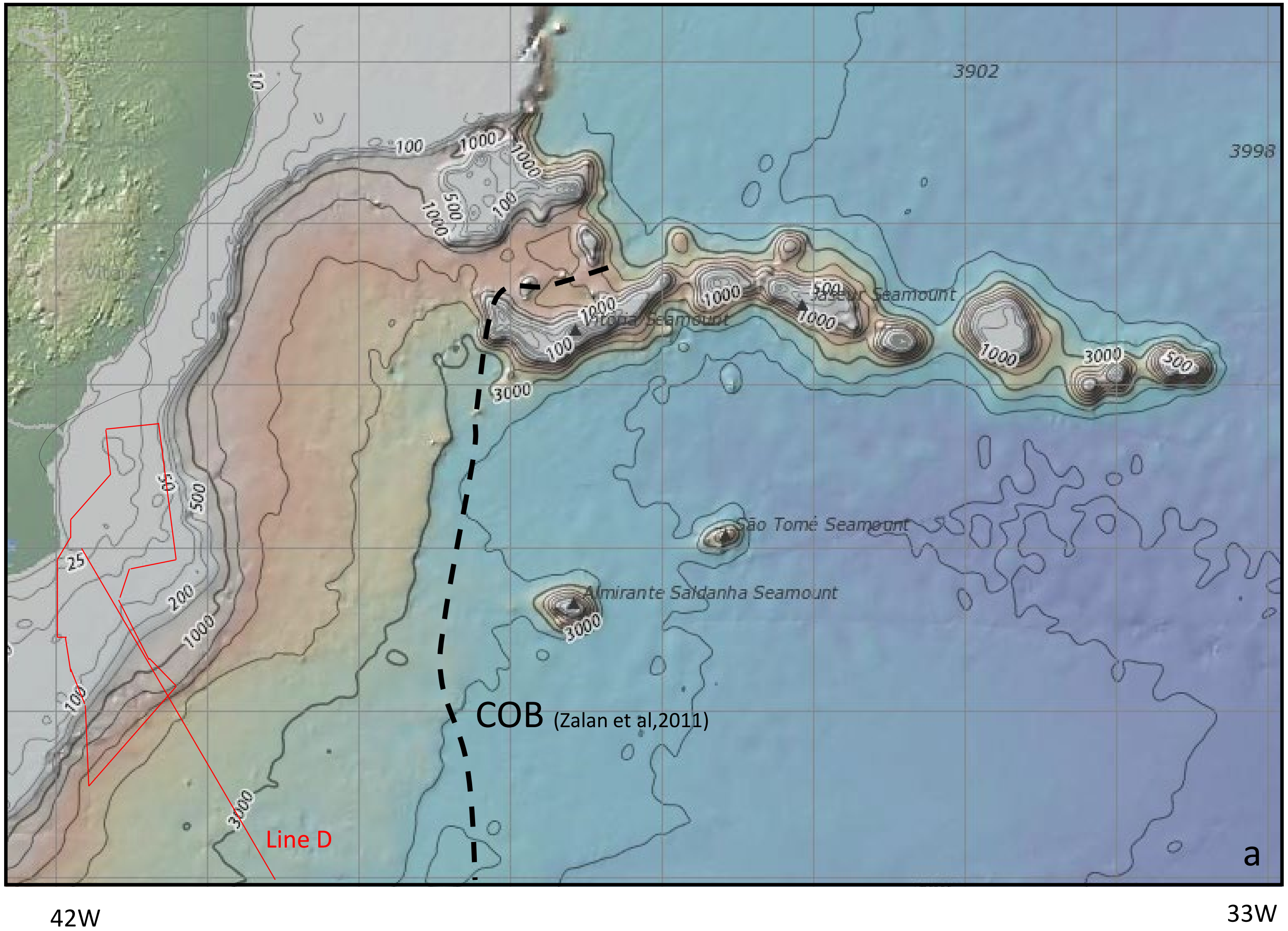
Figure 11. Enlarged view of the seismic line A (from figure 10) with the location of the well B. In orange are represented the conglomerate and arenitic sandstones; in blue and acquamarine the coarse grained/rudstone carbonate/coquinas units; in pale green silty argillite; strong green the shale and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

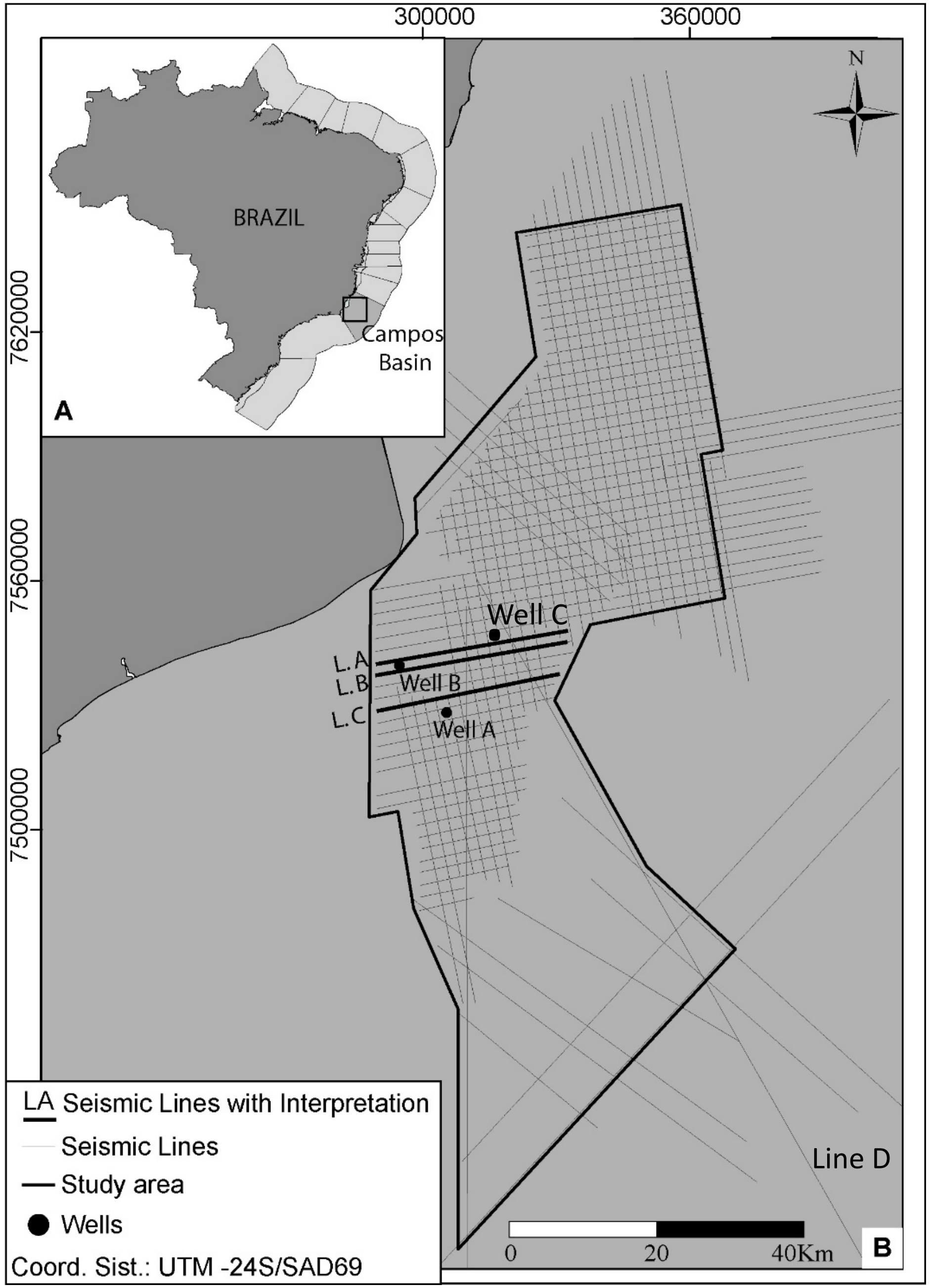
Figure 12 Representation of the main facies across the pre salt units; Seismic line A. In orange is represented the seismic facies 1; In green the seismic facies 2; In blu the seismic facies 3.

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.

Fig 15. This represent a regional seismic lines (Line D, courtesy of BG) with indicated the main regional units. In dotted red: Top Cabiunas formation; Bold red: Post rift Unconformity; Bold green: the base and top unit of the Salt. In bold Blue the the Neogene base. The yellow box in the proximal zones, represent the location of the intepeted Lines from A to C. In dotted green is represented the equivalent location of the Lines interpreted by Muniz & Bosence 2018.


3902
3998
Vitória Seamount
Jaseur Seamount
São Tomé Seamount
Almirante Saldanha Seamount
COB (Zalan et al,2011)
Line D
a
42W
33W


300000
360000
7620000
7560000
7500000
BRAZIL
Campos Basin
A
N
Well C
Well B
Well A
L.A
L.B
L.C
Line D
LA Seismic Lines with Interpretation
Seismic Lines
Study area
Wells
Coord. Sist.: UTM -24S/SAD69
0
20
40Km
B

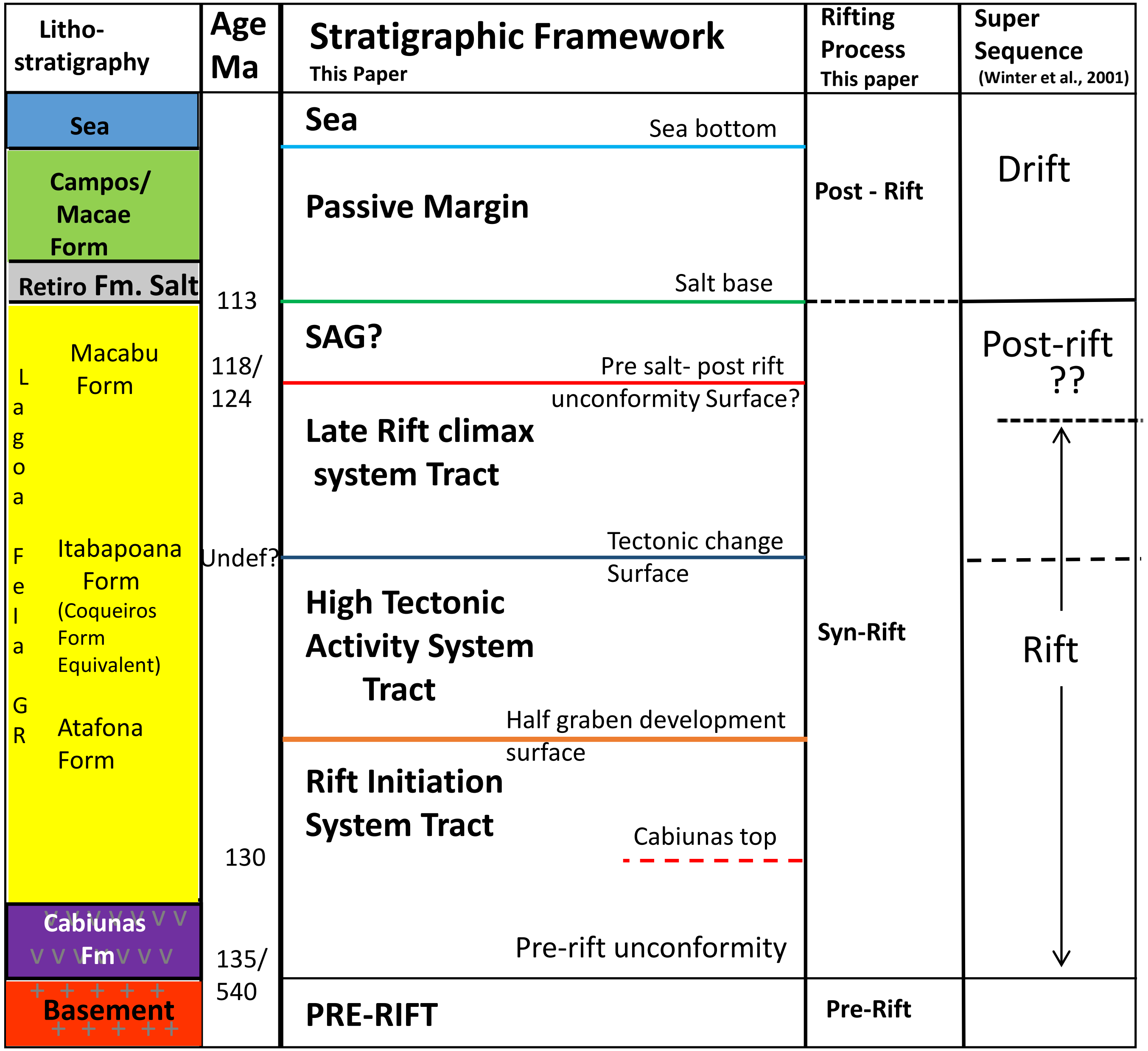

Litho-
stratigraphy
Age
Ma
Stratigraphic Framework
This Paper
Rifting
Process
This paper
Super
Sequence
(Winter et al., 2001)
Sea
Campos/
Macae
Form
Retiro Fm. Salt
Macabu
Form
Lagoa Feia GR
Itabapoana
Form
(Coqueiros
Form
Equivalent)
Atafona
Form
Cabiunas
Fm
Basement
113
118/
124
Undef?
130
135/
540
Sea
Sea bottom
Passive Margin
Salt base
SAG?
Pre salt- post rift
unconformity Surface?
Late Rift climax
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

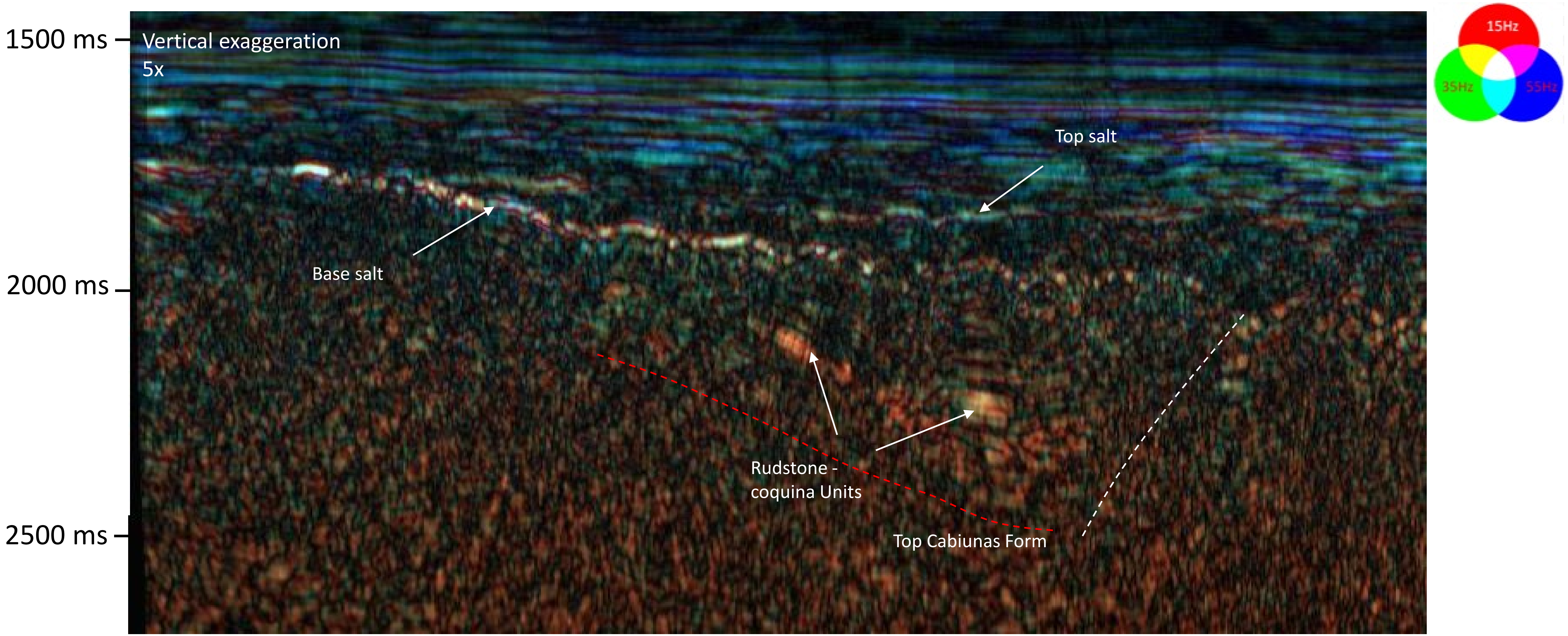
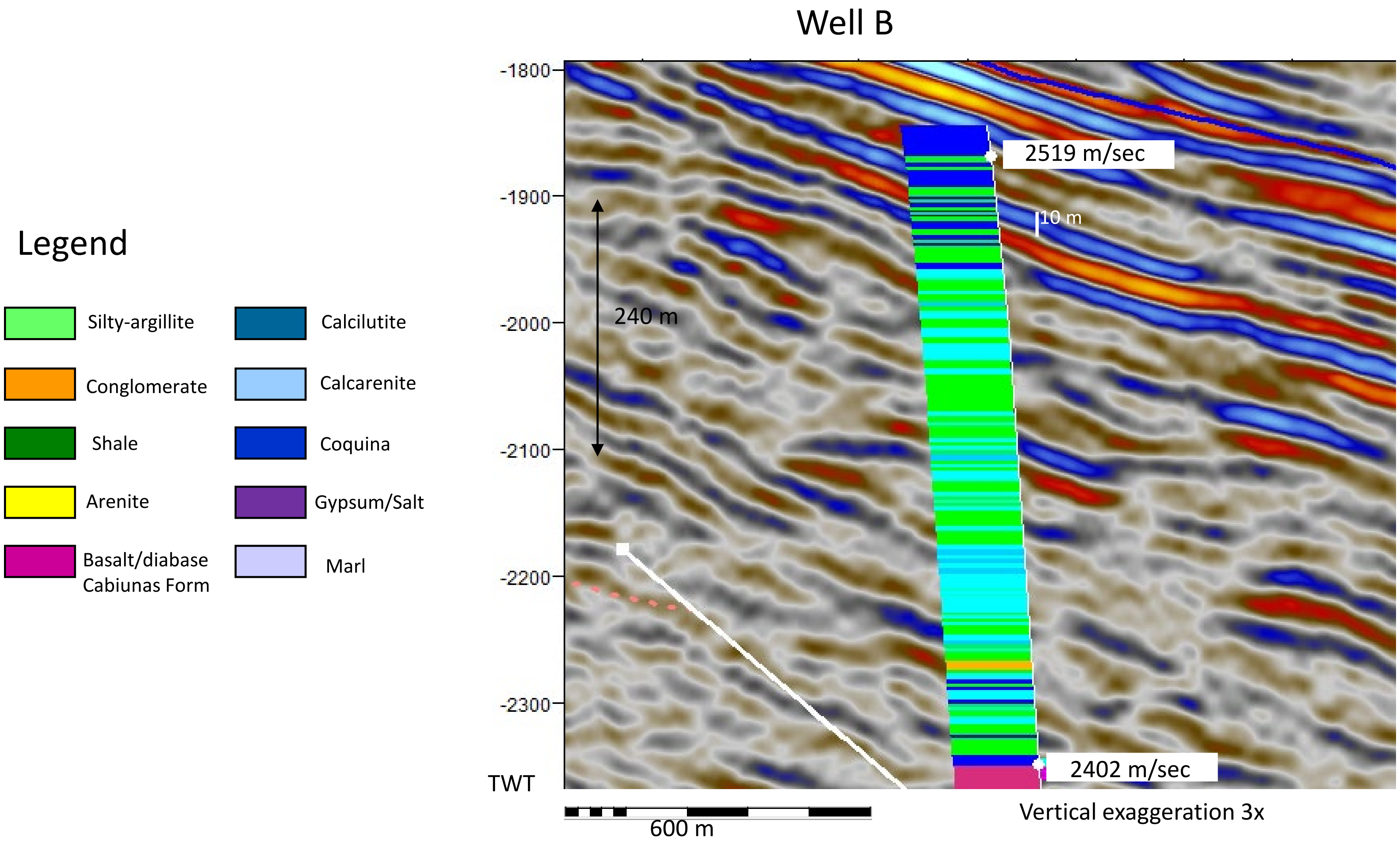
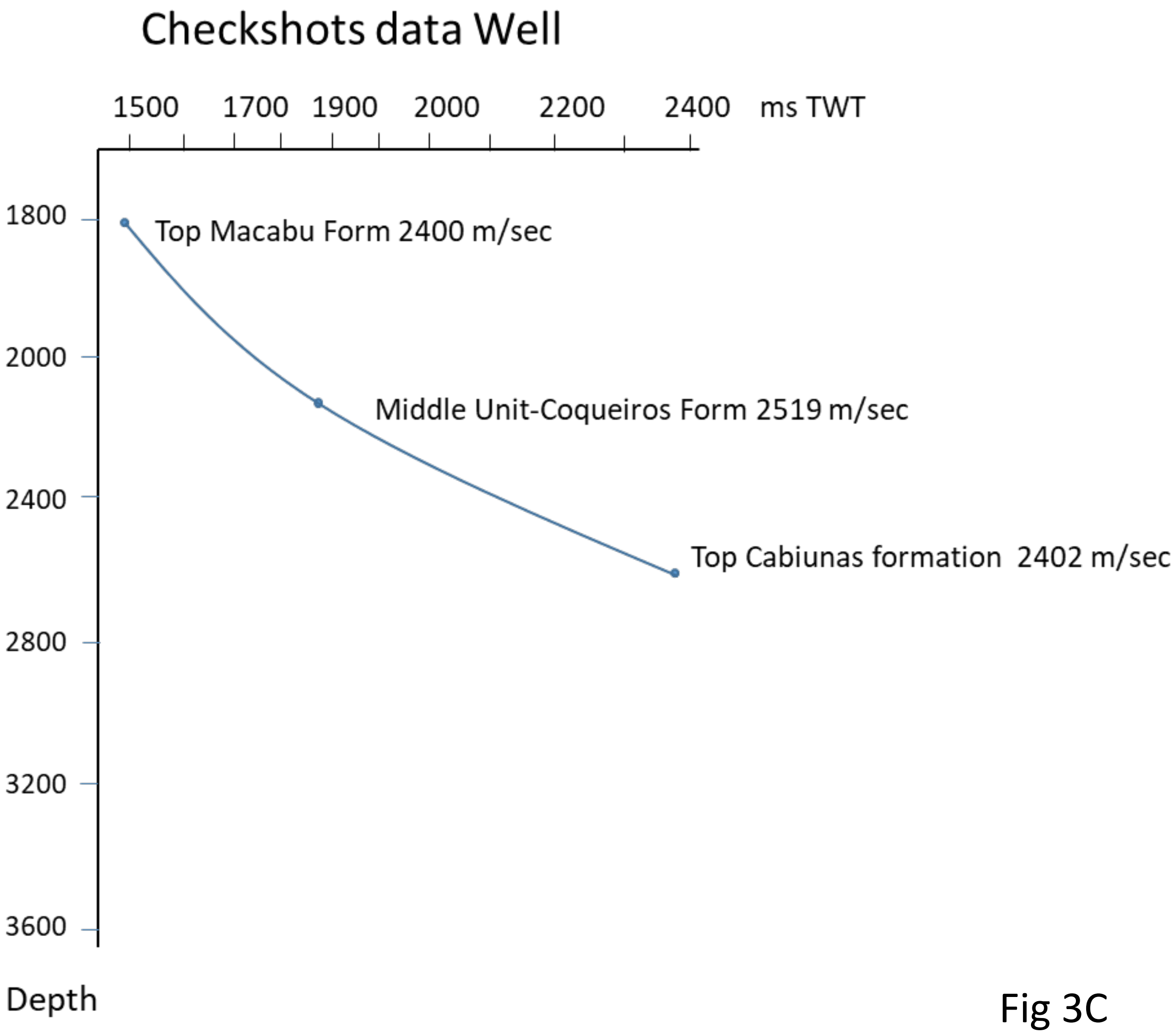

1500 ms
2000 ms
2500 ms
Vertical exaggeration
5x
Top salt
Base salt
Rudstone -
coquina Units
Top Cabiunas Form
15Hz
35Hz
55Hz

Fig 3A



Well B
Legend
Silty-argillite
Calcilutite
Conglomerate
Calcarenite
Shale
Coquina
Arenite
Gypsum/Salt
Basalt/diabase Cabiunas Form
Marl
-1800
-1900
-2000
-2100
-2200
-2300
TWT
240 m
2519 m/sec
10 m
2402 m/sec
600 m
Vertical exaggeration 3x

Fig 3B


Checkshots data Well
1500
1700
1900
2000
2200
2400
ms TWT
1800
2000
2400
2800
3200
3600
Depth
Top Macabu Form 2400 m/sec
Middle Unit-Coqueiros Form 2519 m/sec
Top Cabiunas formation 2402 m/sec

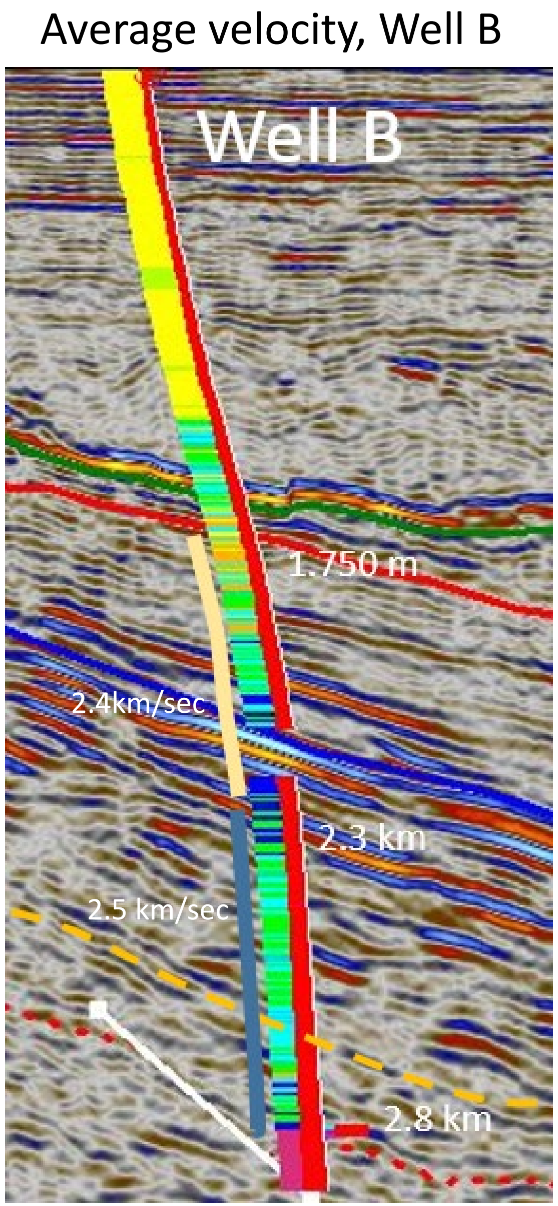

Average velocity, Well B
Well B
1.750 m
2.4km/sec
2.3 km
2.5 km/sec
2.8 km

Fig 3C

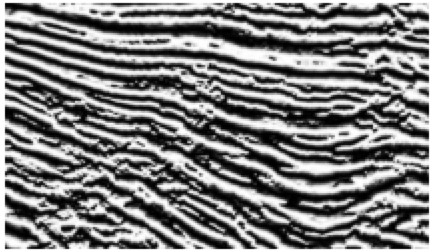
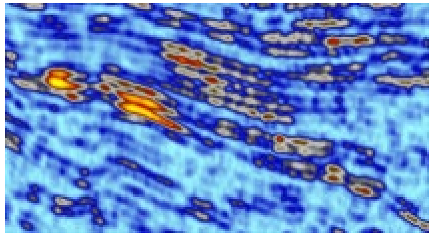
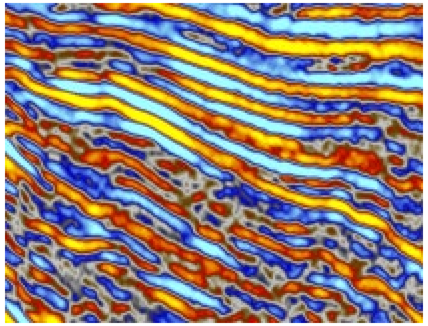
Seismic attributes	Utilities for the paper	Interpretation rules	Visual expression
Cosine Phase	Check Continuity of reflection patterns ; enhance fault visualization	Use the boundaries between patterns	
RMS Amplitude	Enhance seismic facies -mainly for carbonates and evaporites- -Good to map the base of salt	Makes Peak & Trough as (+)	
RAI – Relative Acoustic Impedance	Enhances seismic facies -mainly carbonates and evaporites -good to map base of salt -together with cosine phase, to map faults	Inversion of Peak & Trough P – (-); T – (+) - Enlarge the reflection frequency - Highlight the signal texture	

Fig 4

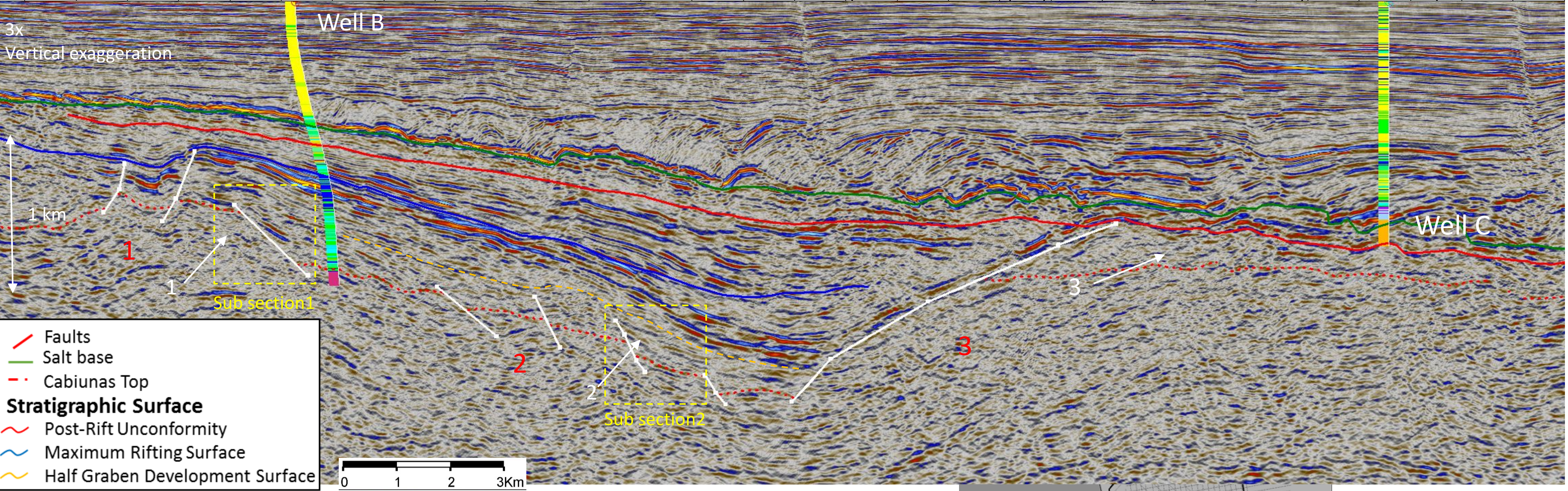
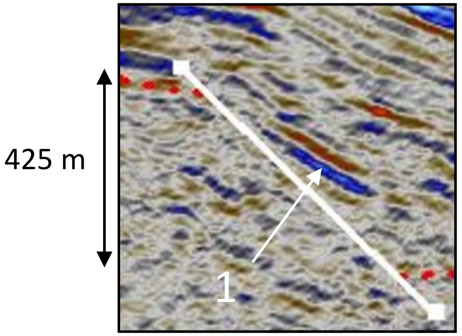
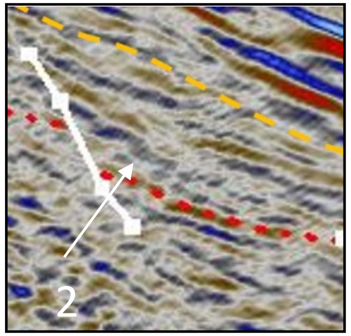


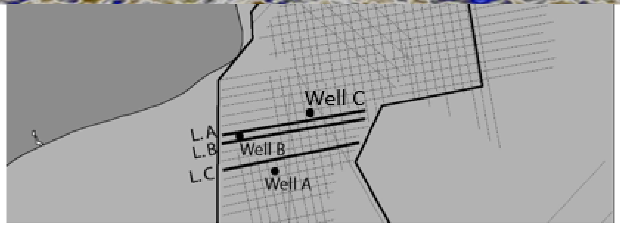
Fig 5A



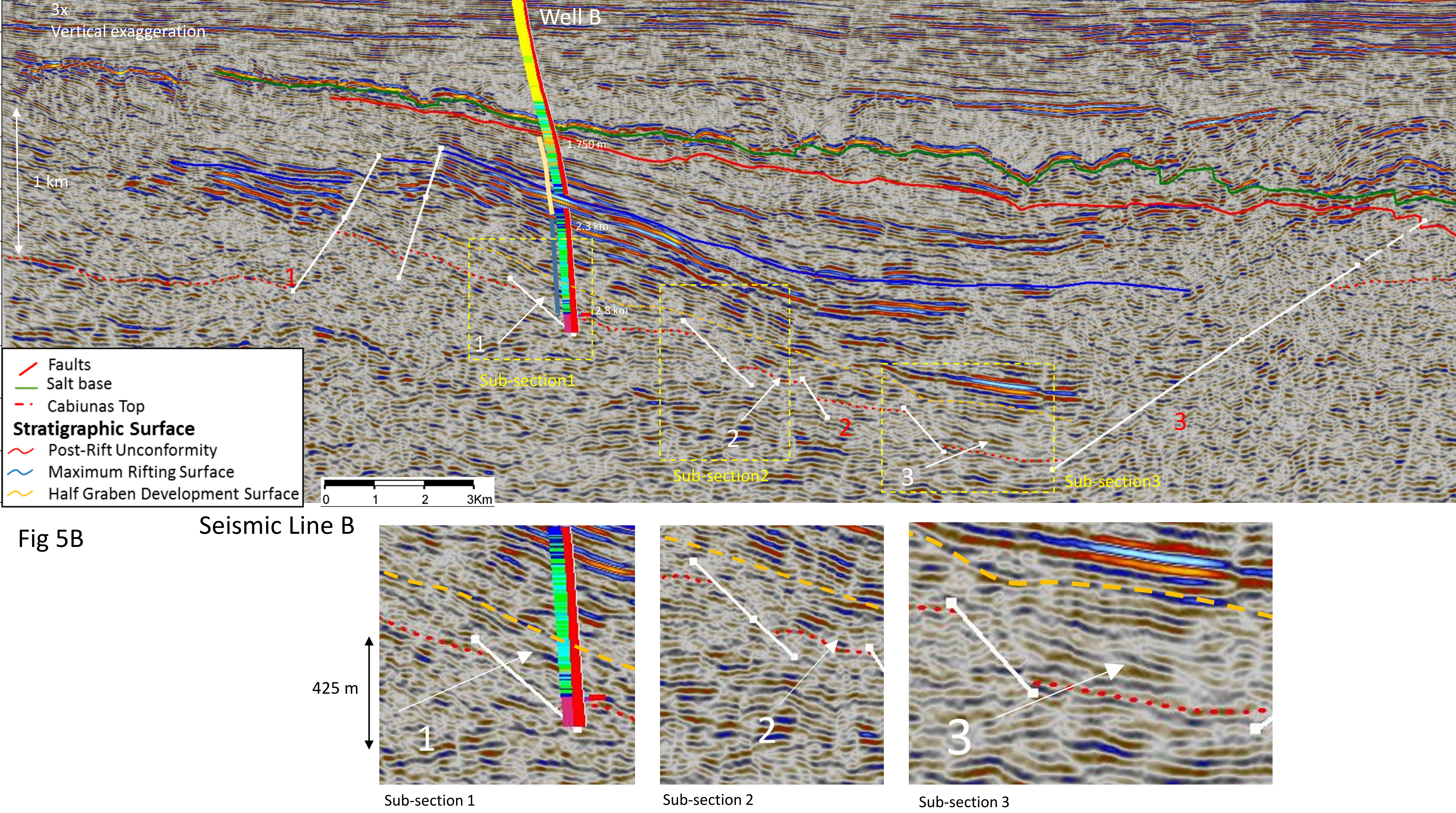
Sub-section1



Sub-section2

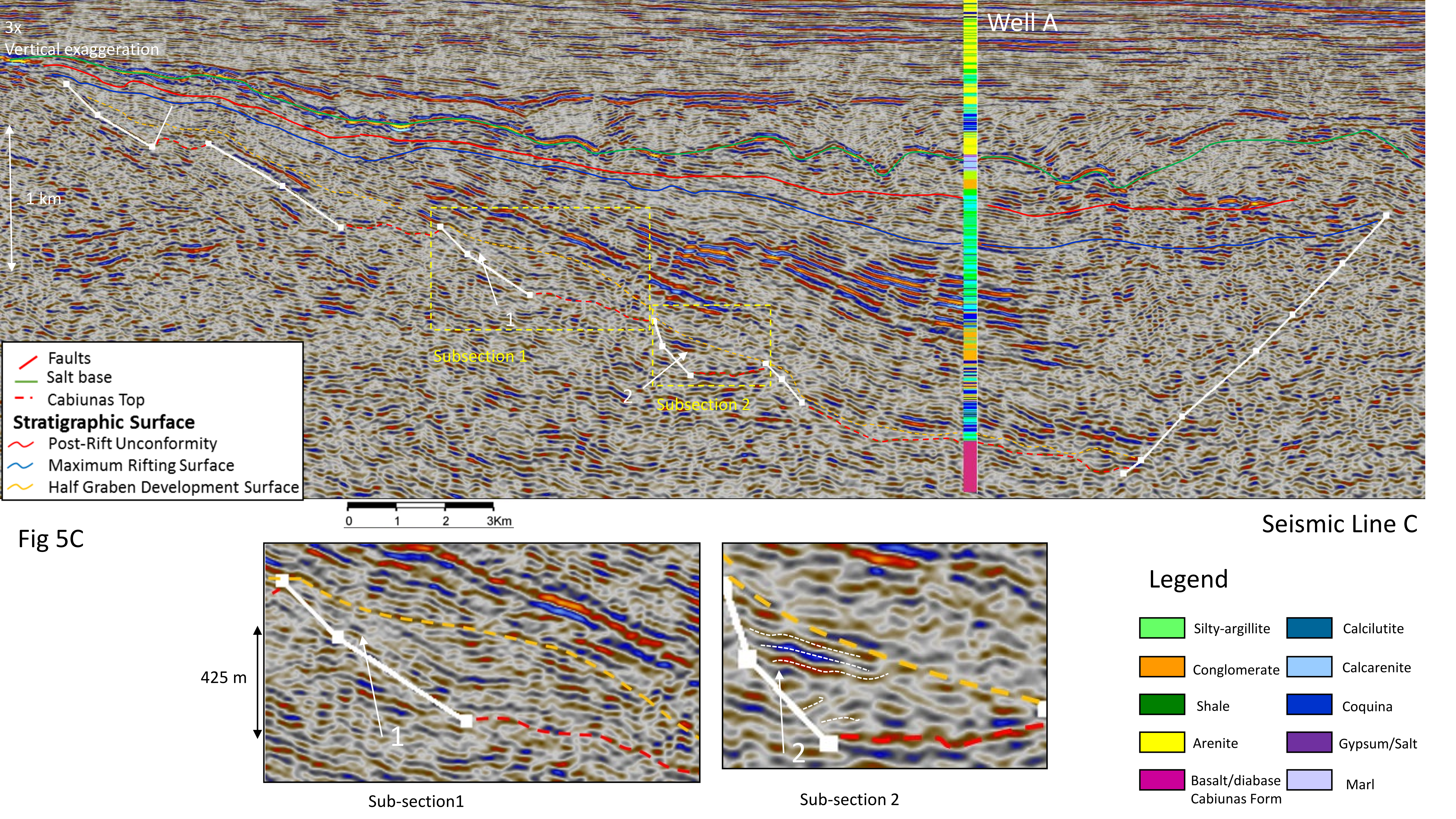


Seismic Line A

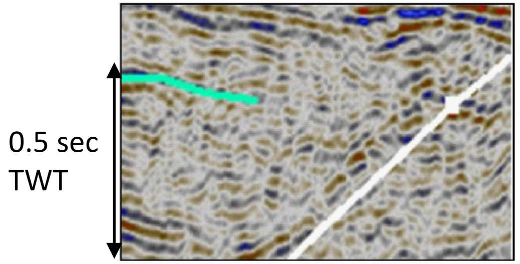


3x
Vertical exaggeration
Well B
1 km
1.750 m
2.3 km
2.8 km
1
2
3
Sub-section1
Sub-section2
Sub-section3
Faults
Salt base
Cabiunas Top
Stratigraphic Surface
Post-Rift Unconformity
Maximum Rifting Surface
Half Graben Development Surface
0 1 2 3Km
Seismic Line B
425 m
Sub-section 1
Sub-section 2
Sub-section 3

Fig 5B

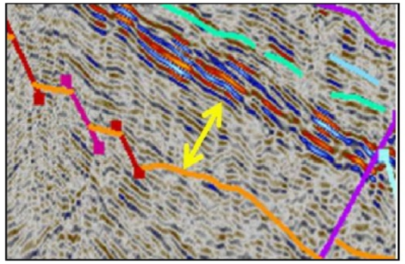

3x
Vertical exaggeration
1 km
Well A
1
2
Subsection 1
Subsection 2
Faults
Salt base
Cabiunas Top
Stratigraphic Surface
Post-Rift Unconformity
Maximum Rifting Surface
Half Graben Development Surface
0
1
2
3Km
Fig 5C
Seismic Line C
425 m
Sub-section1
Sub-section 2
Legend
Silty-argillite
Calcilutite
Conglomerate
Calcarenite
Shale
Coquina
Arenite
Gypsum/Salt
Basalt/diabase Cabiunas Form
Marl

Facies 1



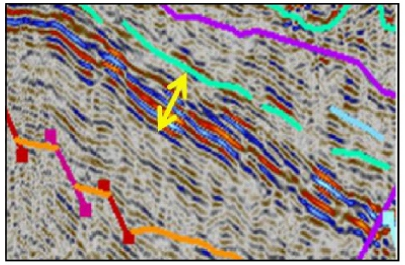
- Chaotic, discontinuous and low-amplitude reflectors amplitude strongly damaged.
- Small vertical faults damaging the units
- Usually juxtaposed to fault plane or lower rift units.

Facies 2



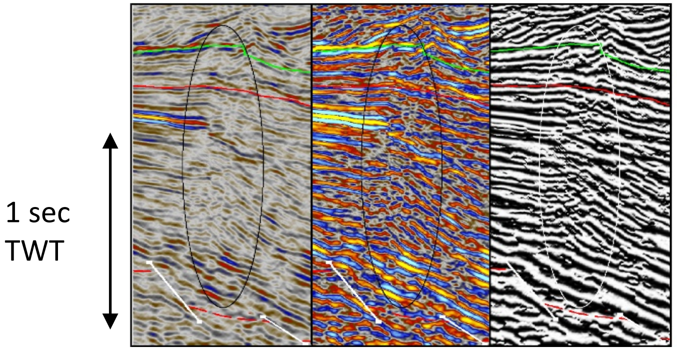
- Semi-continuous reflection, interbedded w/ strong reflections
- Thin layering with lateral low- to medium-amplitude variation
- The unit defined is onlapping or/and slightly lateral thickening on small Rift faults.
- Localized amplitude anomalies.
- Mostly observed within the rift initiation system tract, low- and high-tectonic activity system tract

Facies 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

Facies 4



- Pull up velocity effect;
- Wipe out zones with strong discontinuity of the layering and amplitude reduction effects.

Figure 6

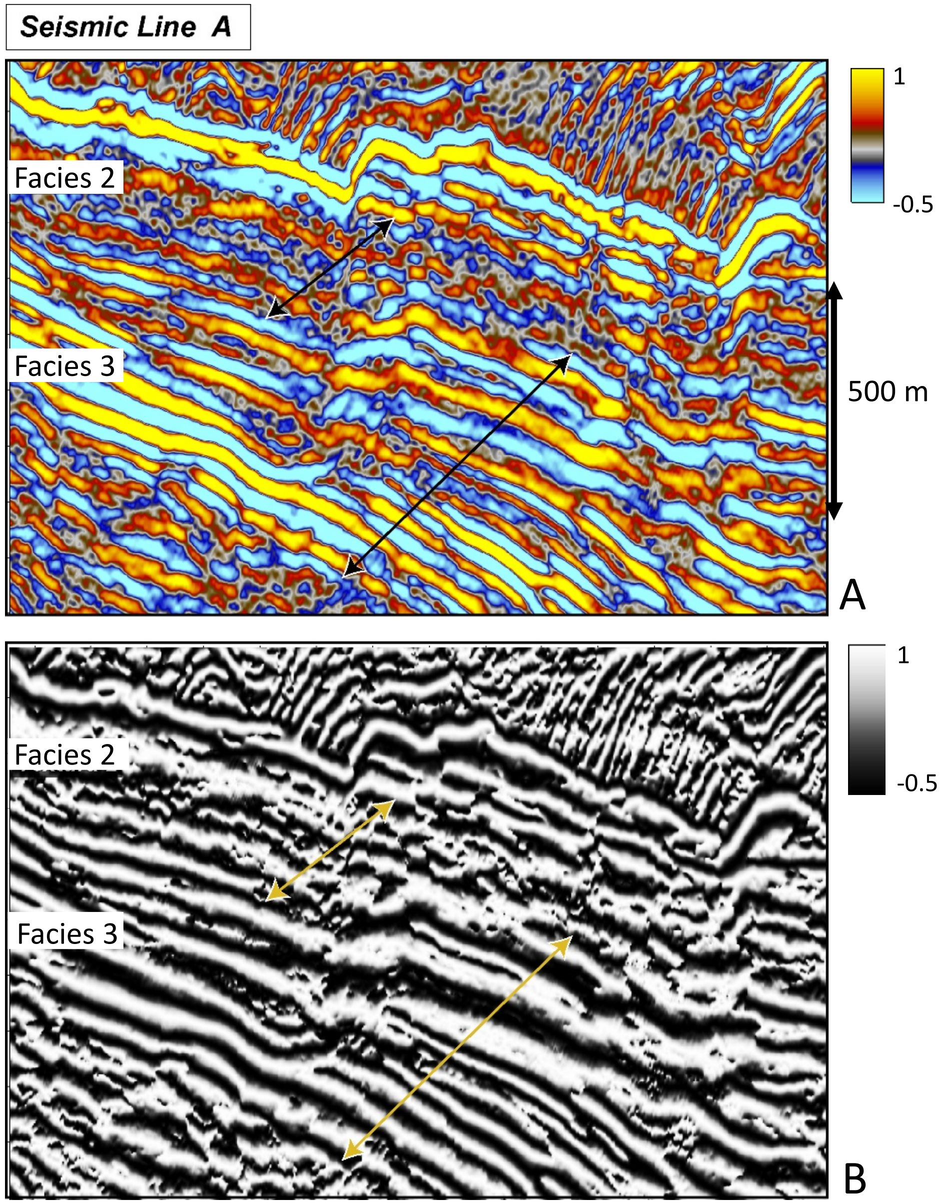

Seismic Line A
Facies 2
Facies 3
1
-0.5
500 m
A
Facies 2
Facies 3
1
-0.5
B

Fig. 7

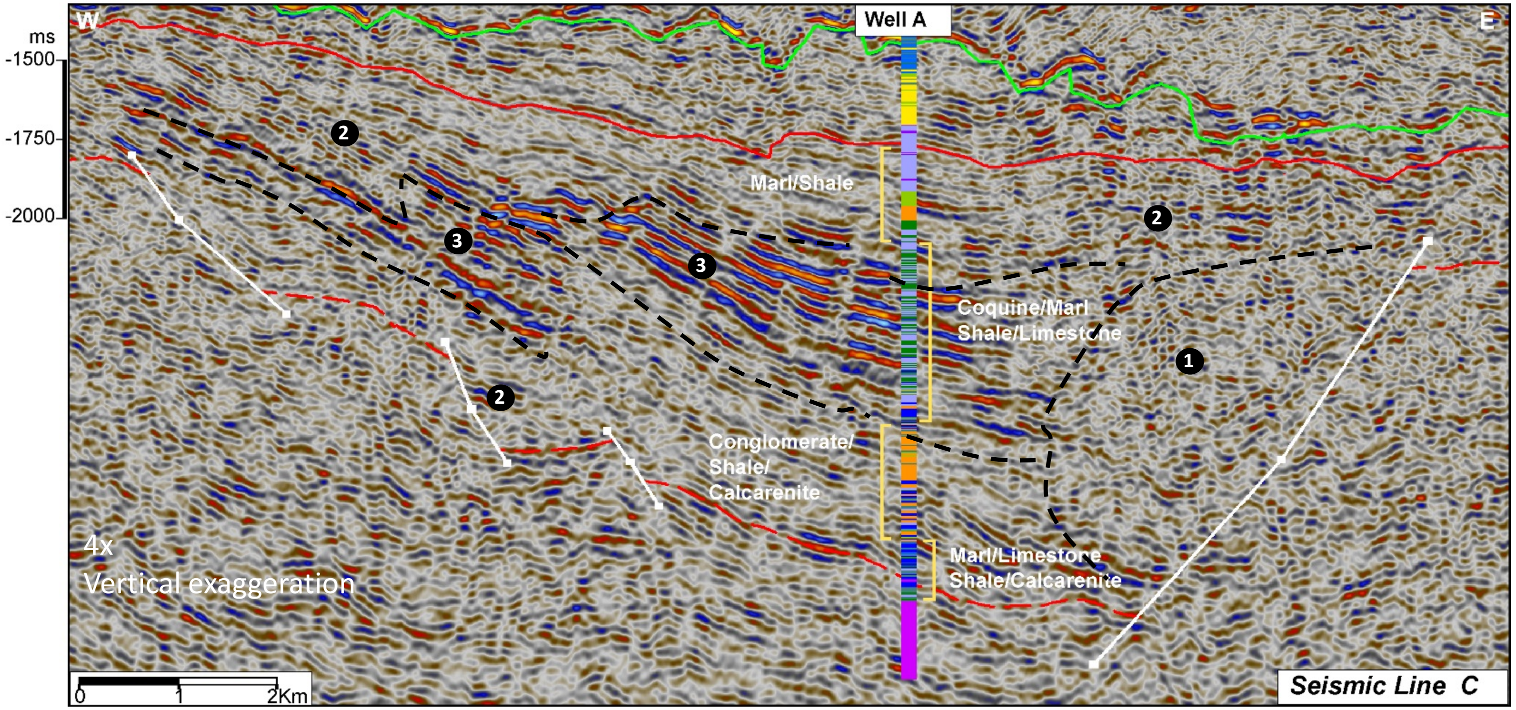
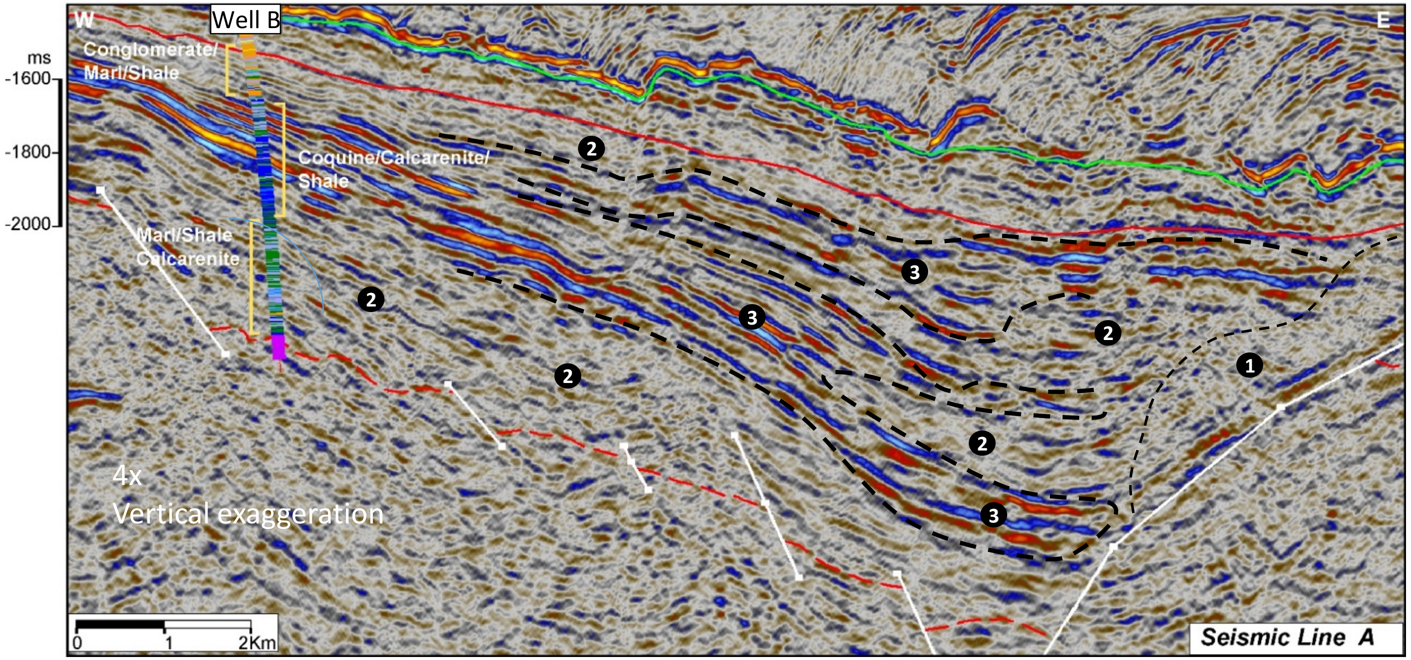
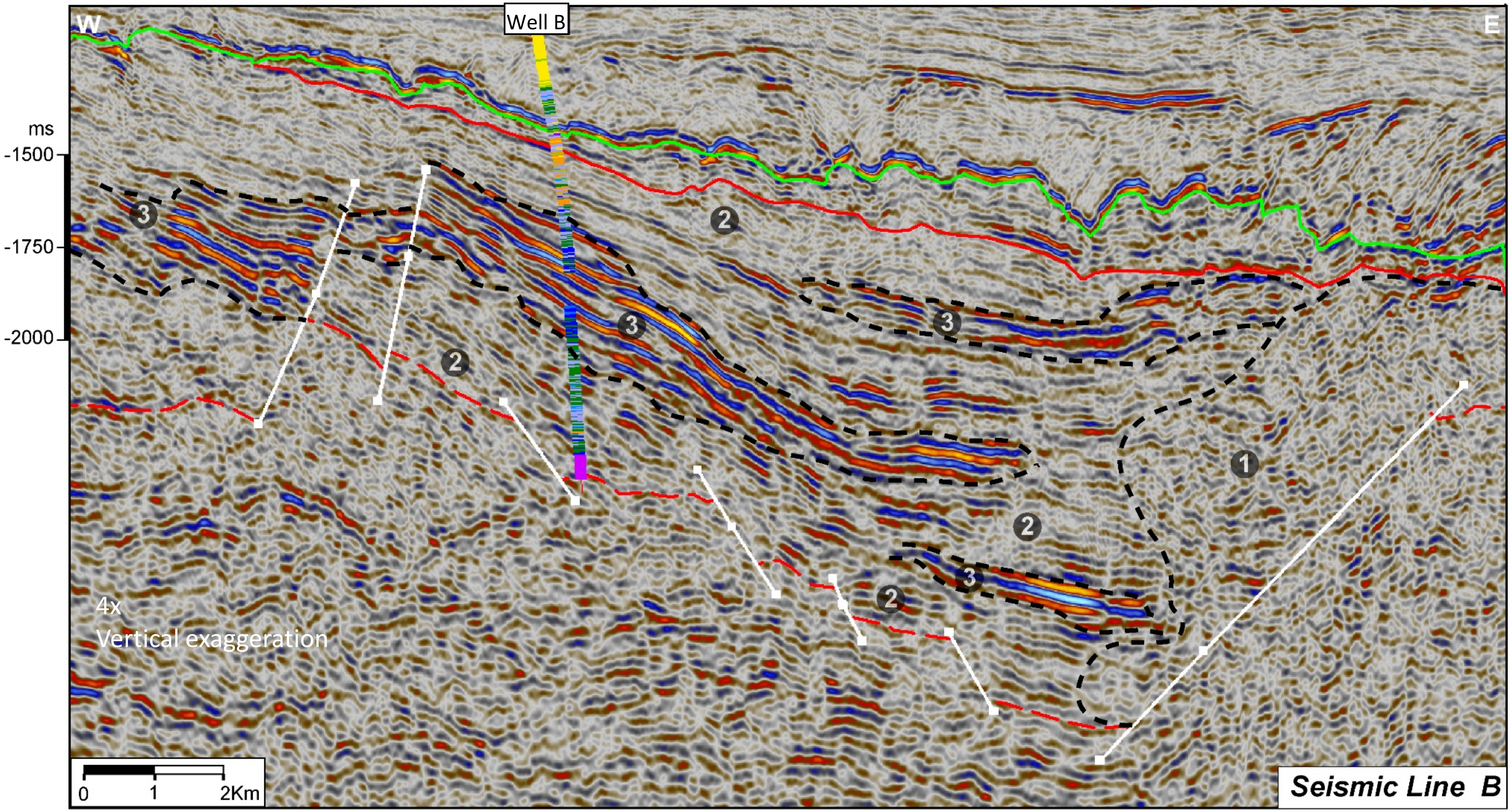

W
E
Well A
ms
-1500
-1750
-2000
2
3
3
2
2
1
Marl/Shale
Coquine/Marl
Shale/Limestone
Conglomerate/
Shale/
Calcarenite
Marl/Limestone
Shale/Calcarenite
4x
Vertical exaggeration
0
1
2Km
Seismic Line C

Fig 8



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

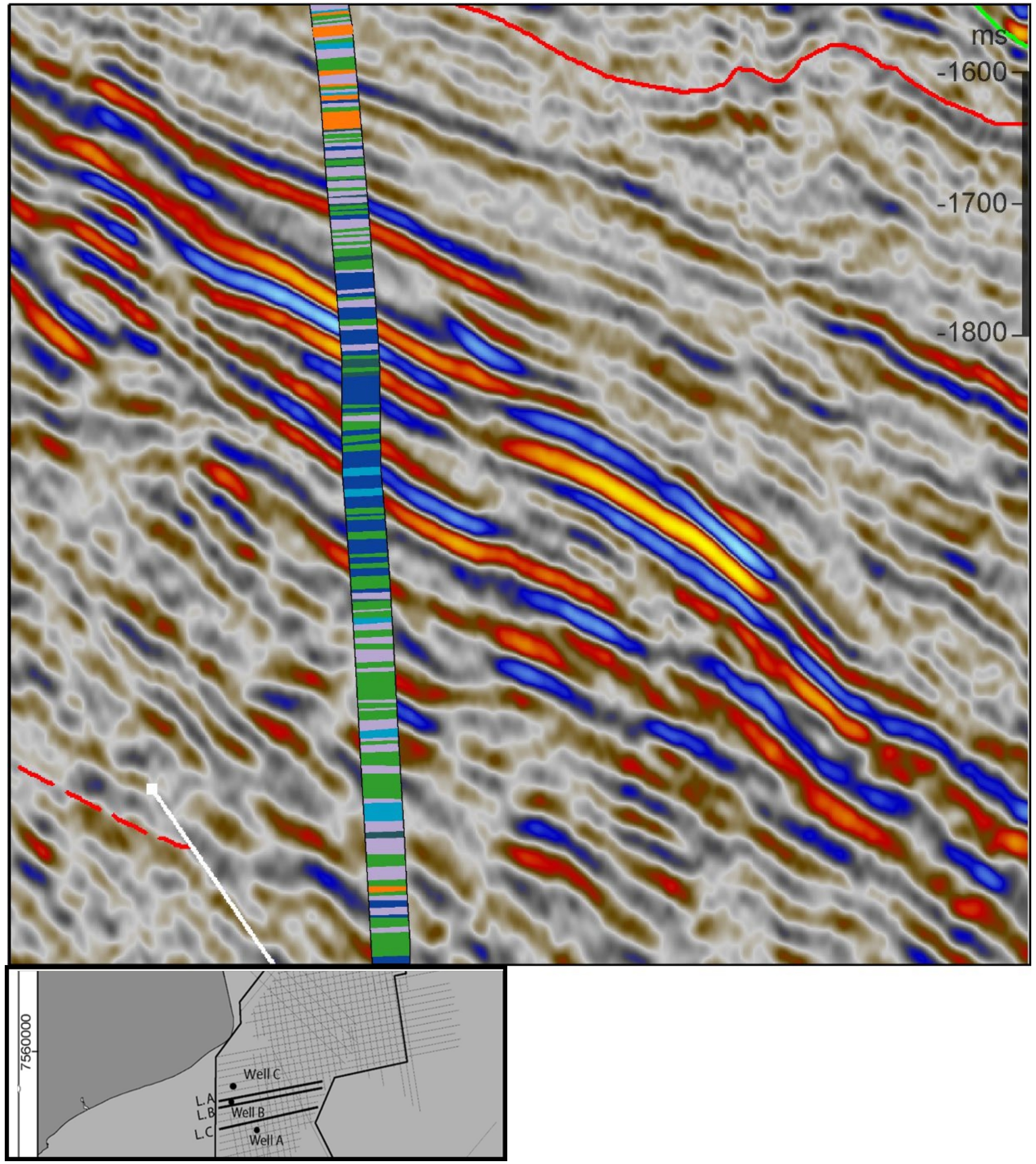
Fig 9



W
Well B
E
ms
-1500
-1750
-2000
3
2
3
2
3
1
2
3
2
4x
Vertical exaggeration
0
1
2Km
Seismic Line B

Fig 10

Seismic Line A - Well B



Legend

- Silty-argillite
- Conglomerate
- Shale
- Arenite
- Basalt/diabase
- Calcilutite
- Calcarenite
- Coquina
- Gypsum/Salt
- Marl

Fig 11

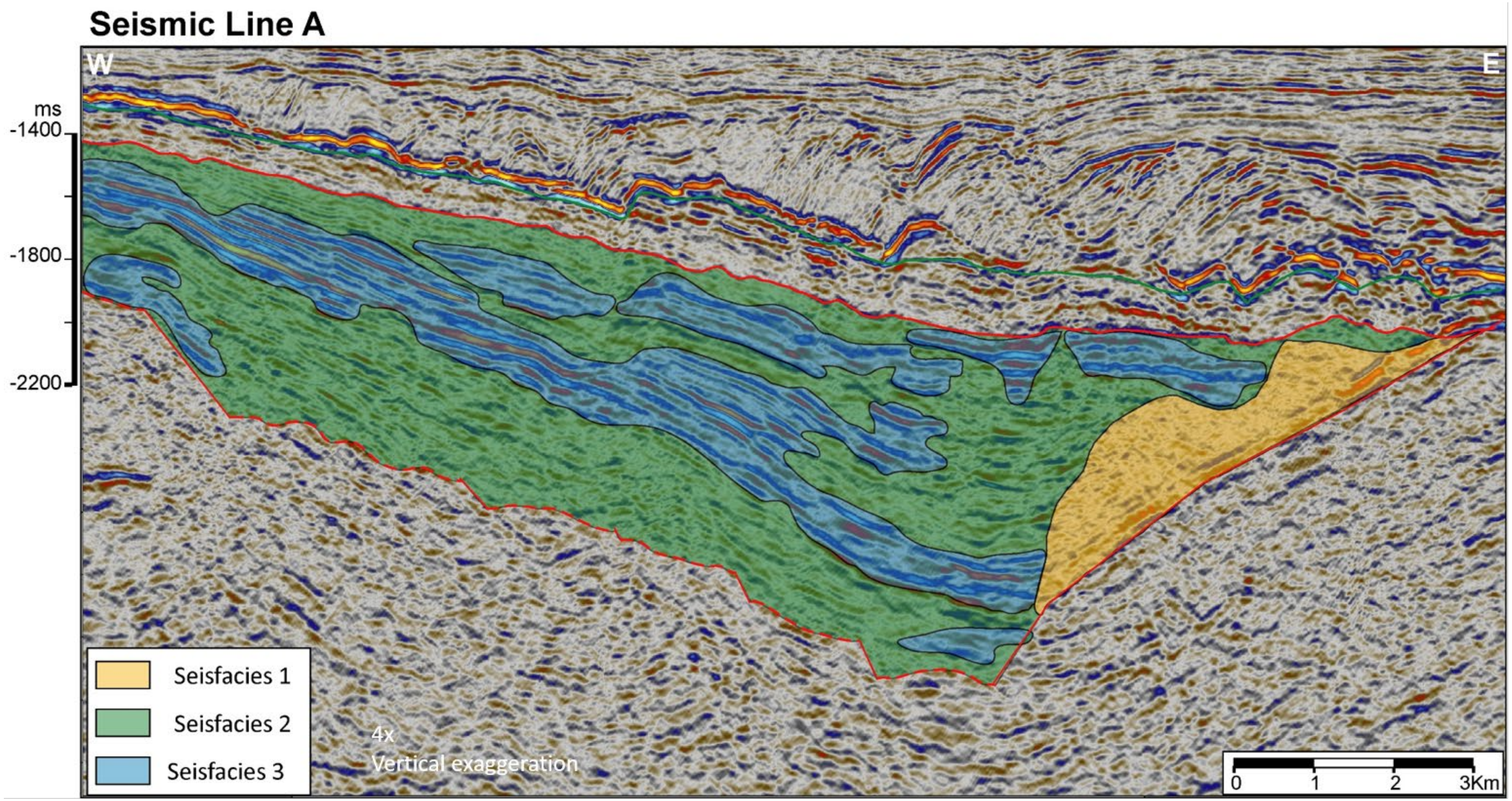
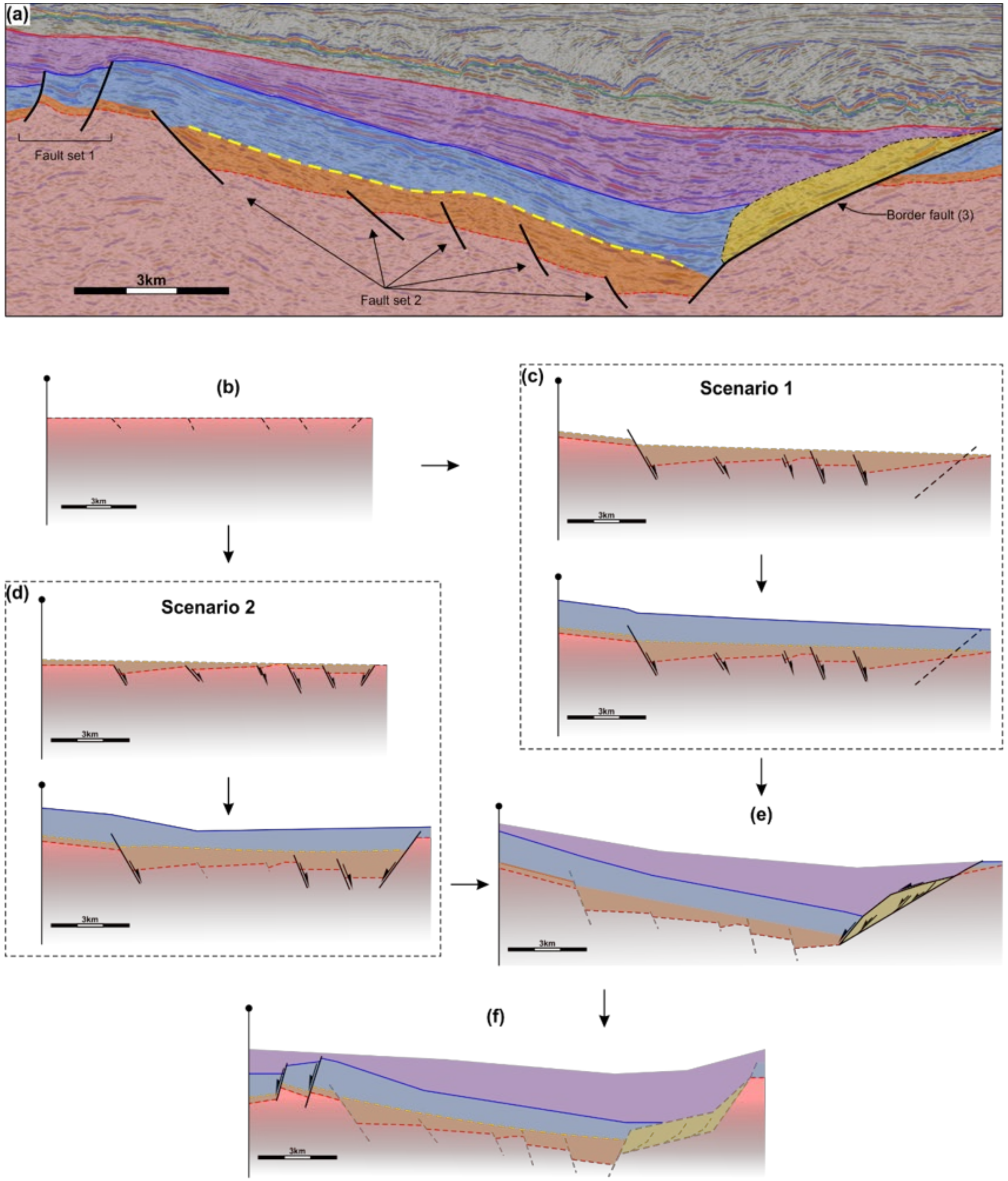
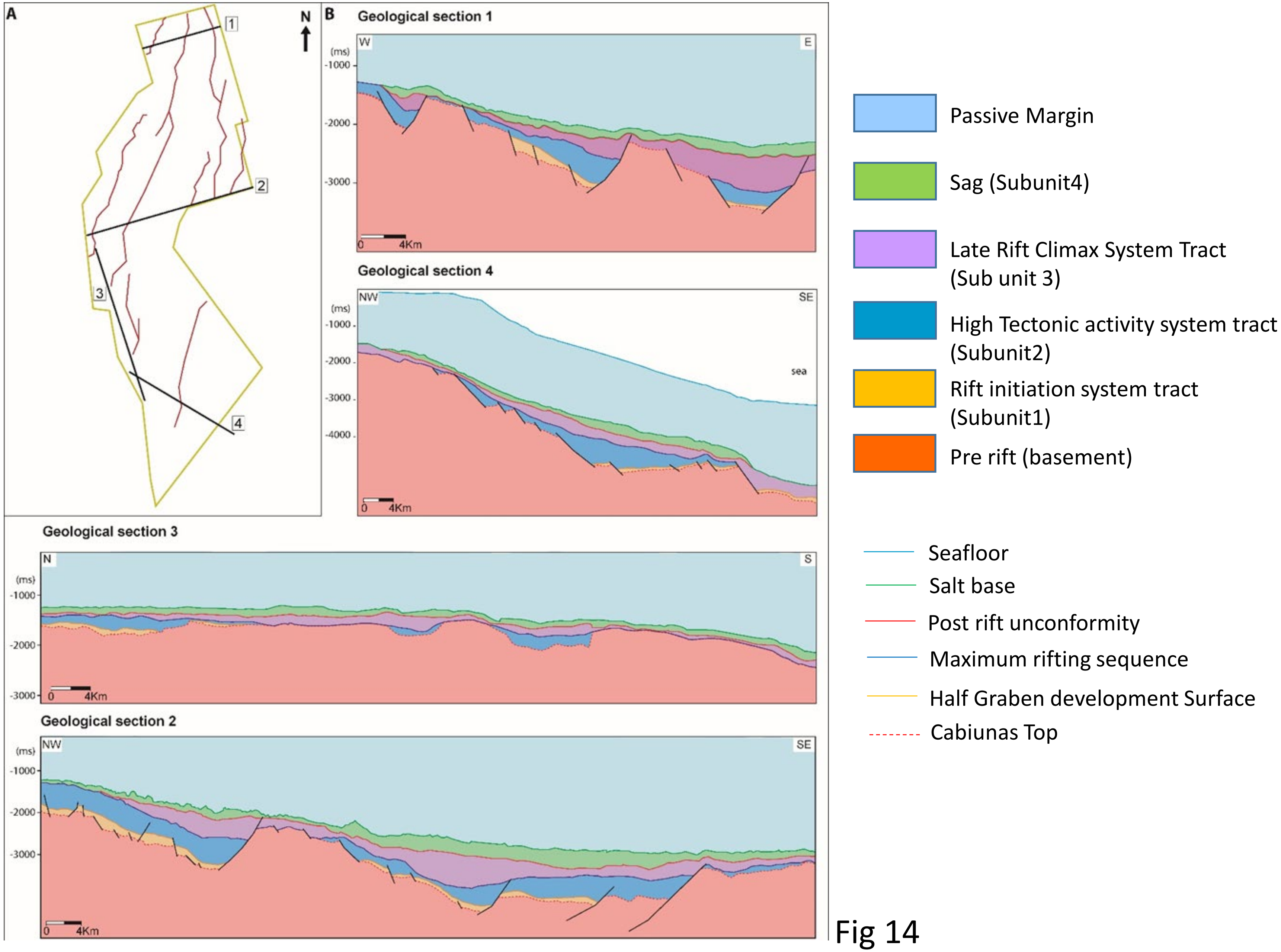

Seismic Line A
W
E
ms
-1400
-1800
-2200
Seisfacies 1
Seisfacies 2
Seisfacies 3
4x
Vertical exaggeration
0
1
2
3Km

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
Passive Margin
Sag (Subunit4)
Late Rift Climax System Tract
(Sub unit 3)
High Tectonic activity system tract
(Subunit2)
Rift initiation system tract
(Subunit1)
Pre rift (basement)
Seafloor
Salt base
Post rift unconformity
Maximum rifting sequence
Half Graben development Surface
Cabiunas Top

Fig 14

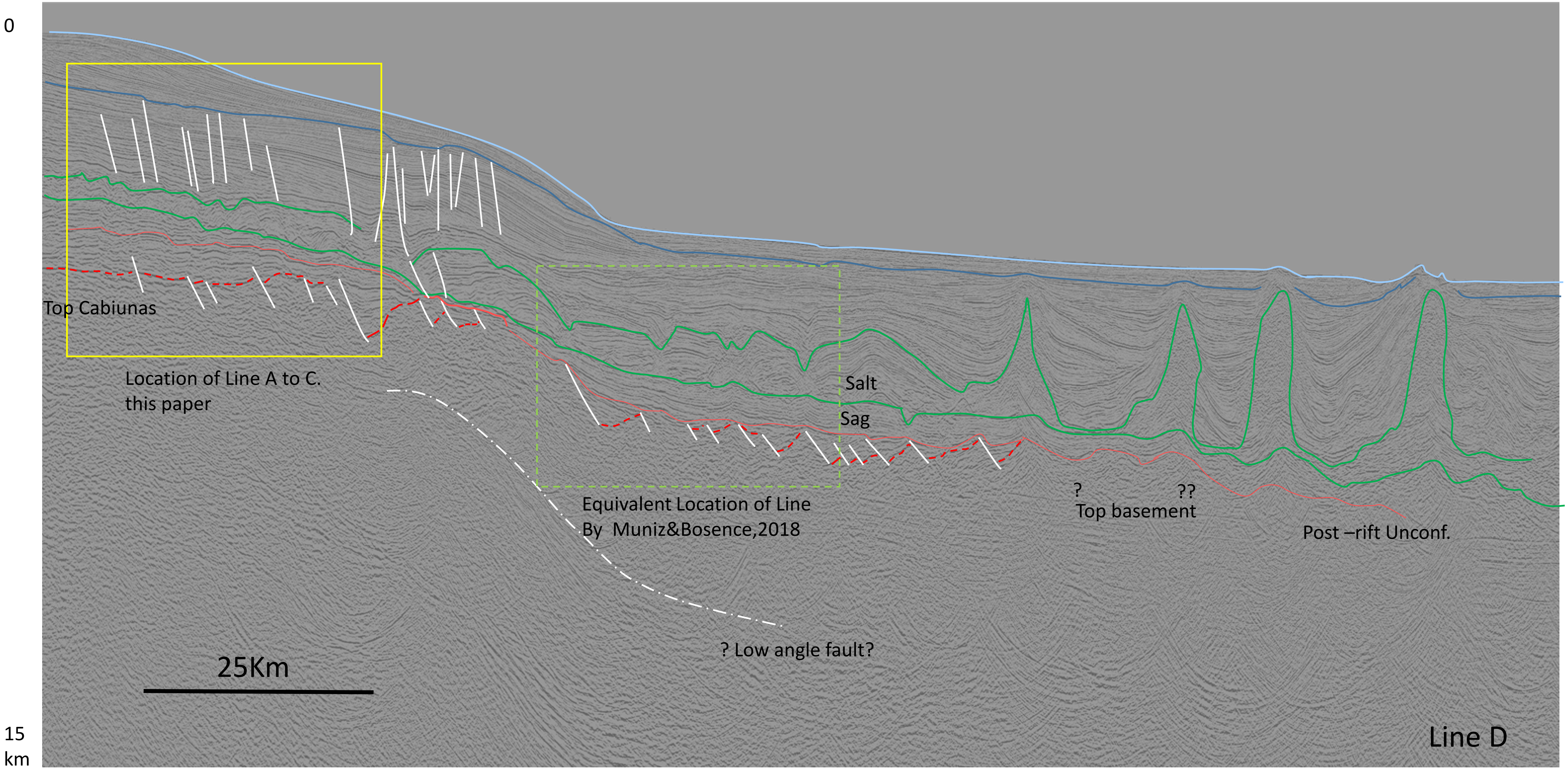

0
15
km
Top Cabiunas
Location of Line A to C.
this paper
Salt
Sag
Equivalent Location of Line
By Muniz&Bosence,2018
?
??
Top basement
Post –rift Unconf.
? Low angle fault?
25Km
Line D

Fig 15