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EVOLUÇÃO TECTONO-ESTRATIGRÁFICA DA BACIA DO RIO DO PEIXE, NE DO BRASIL: PORÇÃO NW DO SEMI-GRÁBEN DE SOUSA

Autora:
MARIA CLARA DE MENESES LOURENÇO

Orientador:
PROF. DR. EMANUEL FERRAZ JARDIM DE SÁ

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MARIA CLARA DE MENESES LOURENÇO

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Dissertação apresentada em 16 de dezembro de 2020 ao Programa de Pós-Graduação em Geodinâmica e Geofísica (PPGG), da Universidade Federal do Rio Grande do Norte (UFRN) como requisito à obtenção do Título de Mestre em Geodinâmica e Geofísica, com área de concentração em Geodinâmica.

BANCA EXAMINADORA:

PROF. DR. EMANUEL FERRAZ JARDIM DE SÁ
Presidente e orientador (PPGG/DG/UFRN)

PROFª. DRª. VALÉRIA CENTURION CÓRDOBA
Membro interno (PPGG/DG/UFRN)

DR. PEDRO XAVIER NETO
Membro externo (Pesquisador Associado/PRH-42/UFRN)

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Para ser grande, sê inteiro: nada
Teu exagera ou exclui.
Sê todo em cada coisa. Põe quanto és
No mínimo que fazes.
Assim em cada lago a lua toda
Brilha, porque alta vive.

Fernando Pessoa

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RESUMO

Durante a abertura do Atlântico Sul, no Eocretáceo, bacias tipo grábens e semi-grábens foram desenvolvidas no Nordeste brasileiro, marcando o estágio de rifteamento continental que, posteriormente, evoluiu para as margens passivas no Atlântico Leste. A Bacia do Rio do Peixe está inserida neste conjunto de bacias, cujo preenchimento sedimentar tem sido relacionado ao estágio rifte. Todavia, recentemente foram identificados estratos eodevonianos sotopostos à Sequência Rifte, tornando a Bacia do Rio do Peixe um exemplo diferenciado dentre as demais bacias rifte na região. Utilizando dados de 160 afloramentos, 3 poços exploratórios e sísmica 3D, este trabalho objetiva analisar os aspectos tectono-estratigráficos de superfície e subsuperfície dos intervalos pré- e sin-rifte da bacia, aplicando métodos de campo, de interpretação sísmica, técnicas estruturais e de estratigrafia de sequências. A área de estudo contempla a borda oeste do Semi-gráben de Sousa, bem como a porção leste do Degrau de Santa Helena. Acerca da configuração tectono-estratigráfica da área, verificou-se que o contato do embasamento com o pacote sedimentar, na rampa direcional e na margem flexural do Semi-gráben de Sousa, se dá por falhas. Também se observou em superfície e subsuperfície que o contato entre as sequências pré- e sin-rifte corresponde a uma discordância de baixo ângulo. Na análise tectono-estrutural constatou-se a presença de falhas e dobras de propagação, as quais se relacionam ao evento rifte, caracterizado por uma distensão NW-SE. Em menor expressão um segundo conjunto de estruturas é observado, incluindo falhas de rejeito direcional, relacionado ao evento de abertura da Margem Equatorial, em um regime transtracional dextral. Verifica-se que a Sequência Eodevoniana se desenvolveu a partir de um sistema deltaico, sendo dividida em um trato de sistemas transgressivo, com depósitos de frente deltaica e transição para prodelta, e trato de sistema regressivo, com depósitos de planície deltaica. A caracterização litofaciológica e sismoestratigráfica da região permitiu estabelecer uma nova proposta de delimitação estratigráfica para o remanescente paleozóico. Na Sequência Rifte, atestou-se a relação de interdigitação entre as suas unidades. Esta sequência foi subdividida em tratos de sistemas tectônicos, os quais tanto na região do Degrau de Santa Helena, como no Semi-gráben de Sousa, estão relacionados à momentos da estruturação inicial do evento rifte e à momentos de alta e baixa atividade tectônica. Nesta caracterização, verificou-se que nestes dois setores estruturais os tratos de sistemas iniciais são correlacionáveis, desta forma compartilhando de um mesmo sistema deposicional.

Palavras chaves: Bacia do Rio do Peixe; tectono-estratigrafia; estrutura do rifte eocretáceo; pré-rifte devoniano; estratigrafia de sequências rifte; interpretação sísmica 3D.

ABSTRACT

During the South Atlantic opening, in the Early Cretaceous, interior rift basins were developed in Northeastern Brazil, recording the continental rifting stage that predated the development of the passive margins along the South Atlantic. The Rio do Peixe Basin belongs to this set of basins whose sedimentary fill is related to the rift stage. Recently, Lower Devonian strata were identified underneath the Rift Sequence, making the Rio do Paixe Basin a differentiated example among rift basins in this region. Using data from 160 outcrops, 3 exploratory wells and 3D seismic data, this work aims to analyze the tectono-stratigraphic aspects of the surface and subsurface of the pre- and syn-rift sequences of the basin, applying field methods, seismic interpretation, structural techniques and sequence stratigraphy. The study area includes the western border of Sousa half-graben, as well as the eastern portion of the Santa Helena Step. Regarding the tectono-stratigraphic setting of the area, it was found that the basement contact with the sedimentary package, on the strike ramp and on the flexural margin of the Sousa half-graben is established by faults. It was also observed in surface and subsurface that the contact between the pre- and syn-rift sequences corresponds to a low angle unconformity. In the tectono-structural analysis, it was interpreted faults and propagation folds, which are related to the rift event, characterized by a NW-SE extension. As a minor expression, a second set of structures is observed, including faults of directional displacement, related to the opening of the Equatorial Margin, in a transtensional dextral regime. It was found that the Lower Devonian Sequence developed a deltaic system, being divided into a transgressive system tract, with delta front deposits and transition to prodelta, and a regressive system tract, with delta plain deposits. The lithofaciological and seismic stratigraphic characterization of the region allowed to establish a new suggestion for stratigraphic delimitation for the Paleozoic remnant. In the Rift Sequence, the interdigitation relation between its units was attested. This sequence was subdivided into tectonic systems tracts, which both in the region of Santa Helena Step and in Sousa half-graben, are related to the moments of initial tectonics of the rift event and to episodes of high and low tectonic activities. In this characterization, the initial system tracts of these two structural sectors are correlated, thus sharing the same depositional system.

Key-words: Rio do Peixe Basin; tectono-stratigraphy; Cretaceous rift structures; Devonian pre-rift; rift sequence stratigraphy; 3D seismic interpretation.

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1. INTRODUÇÃO

A presente dissertação representa parte dos requisitos obrigatórios para a obtenção do título de Mestre do Programa de Pós-Graduação em Geodinâmica e Geofísica (PPGG) da Universidade Federal do Rio Grande do Norte (UFRN). O trabalho, intitulado "Evolução Tectono-estratigráfica da Bacia do Rio do Peixe, NE do Brasil: Porção NW do Semi-gráben de Sousa", contou com a orientação do Prof. Dr. Emanuel Ferraz Jardim de Sá e colaboração da Profª. Dra. Valéria Centurion Córdoba, ambos do Departamento de Geologia - UFRN.

1.1. Objetivos e justificativas

No Eocretáceo, a separação do Gondwana e respectiva abertura do Atlântico Sul, foi responsável pela geração de riftes intracontinentais e bacias marginais na Placa Sul-Americana. Na propagação do sistema rifte, foram desenvolvidas bacias interiores no Nordeste brasileiro, contendo registros importantes para a compreensão do rifteamento continental, que precedeu a evolução para margem passiva.

Pertencente ao conjunto de bacias interiores, a Bacia do Rio do Peixe é composta por semi-grábens assimétricos controlados estruturalmente por zonas de cisalhamento pretéritas (Françolin *et al*., 1994; Matos, 1992; Castro *et al*., 2007; Kirkpatrick *et al.*, 2013). Por muito tempo considerou-se que a bacia possuía apenas registros relacionados ao estágio rifte, contudo descobertas mais recentes identificaram uma Sequência Eodevoniana sotoposta à Sequência Rifte (Roesner *et al*. 2011, Silva *et al*. 2014).

No Nordeste brasileiro, apresar de ocorrerem registros de bacias paleozoicas e resquícios sedimentares pré-rifte, ainda são poucos os estudos relacionados a este novo exemplo do Devoniano. Assim, existe a necessidade de mais investigações que integrem esta ocorrência ao contexto tectono-estratigráfico do estágio rifte.

Diante desta lacuna, o presente trabalho tem por objetivo incorporar a ocorrência Devoniana da Bacia do Rio do Peixe à sua evolução tectono-estratigráfica, apresentando novas considerações para o remanescente paleozoico, assim como para a relação entre a tectônica a sedimentação no estágio rifte. Para isto são aplicadas técnicas estruturais e estratigráficas, incluindo métodos de estratigrafia de sequências para bacias rifte, em uma investigação de multi-escala, sendo utilizados dados de 160 afloramentos, 3 poços exploratórios e dado sísmico 3D. A área de estudo está situada na porção NW do Semi-gráben de Sousa, que compreende o local onde aflora o registro pré-rifte devoniano, também abrangendo a porção leste do Degrau de Santa Helena.

1.2. Localização da área de estudo

A Bacia do Rio do Peixe está localizada no NW do Estado da Paraíba, com pequena parte no Estado do Ceará (Figura 1.1). É subdividida em sub-bacias, sendo elas (de oeste para leste) Icozinho, Brejo das Freiras, Sousa e Pombal. A área de estudo situa-se na porção NW da Sub-bacia de Sousa, compreendendo uma área de aproximadamente 70 km² (Figura 1.1).

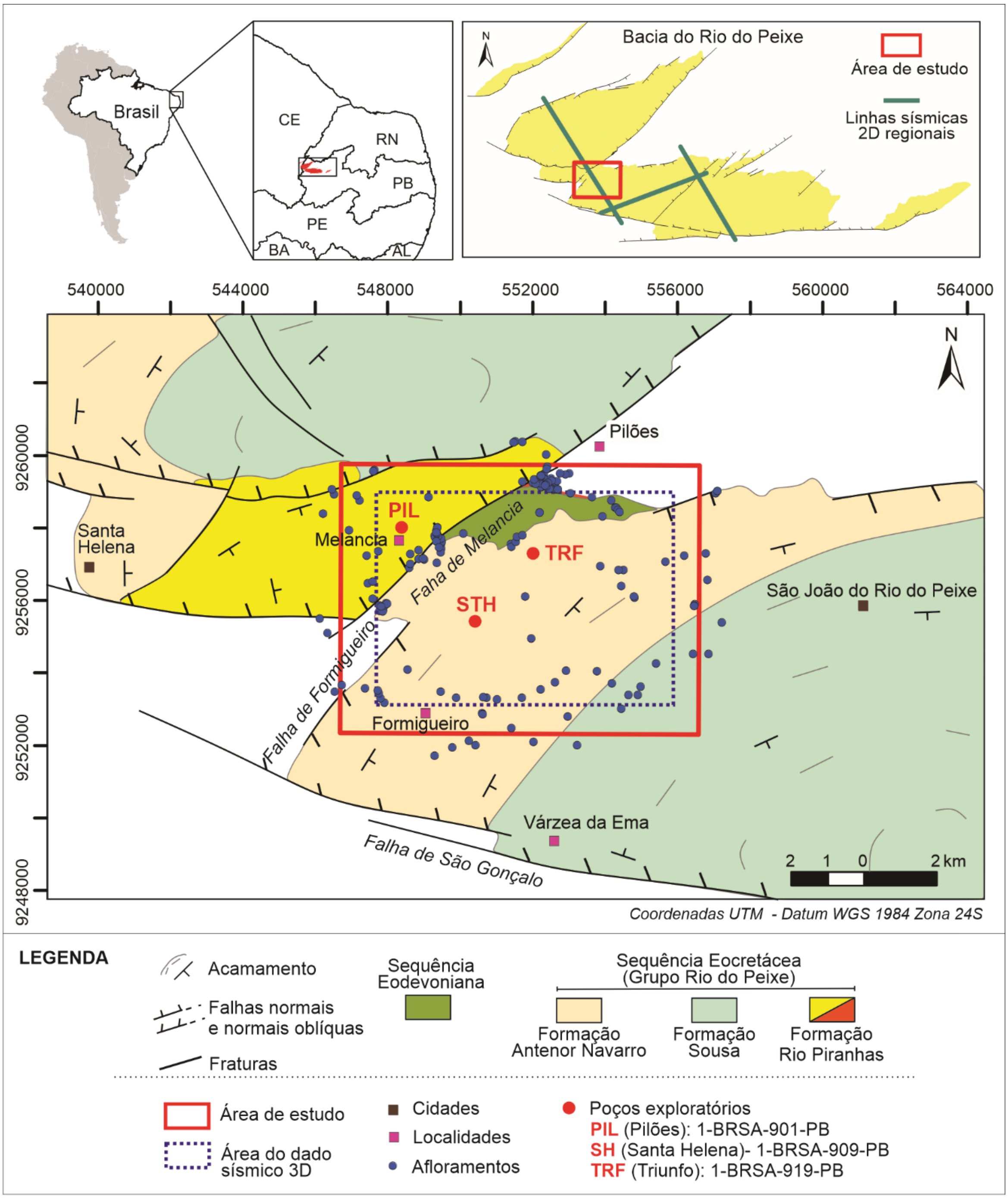


Figura 1.1 – Localização, na Bacia do Rio do Peixe, da área de estudo e dos dados utilizados (afloramentos, sísmica e poços), em mapa geológico simplificado da bacia (compilado de Córdoba *et al*., 2008; Nunes da Silva, 2009; Silva *et al*. 2014 e Mendonça, 2017). A Sequência Eodevoniana apresentada no mapa corresponde à Formação Pilões proposta por Silva *et al*. (2011).

1.3. Materiais e métodos

Para a realização deste trabalho foram usados dados de superfície e subsuperfície, contemplando afloramentos, poços e sísmica 3D situados na área de estudo. Os dados sísmicos e de poços são de domínio público e foram disponibilizados pela Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP). Foram obtidos o volume sísmico 3D do levantamento 0027_3D_RIO_DO_PEIXE e os dados dos poços exploratórios 1-BRSA-901-PB/Pilões, 1-BRSA-909-PB/Santa Helena e 1-BRSA-919-PB/Triunfo (Figura 1.1). A fim de integrar este trabalho ao contexto regional da bacia, o levantamento sísmico regional 0295_RIO_DO_PEIXE_2D também foi utilizado (Figura 1.1).

A seguir, será apresentada a metodologia empregada para a realização desta Dissertação de Mestrado (Figura 1.2).

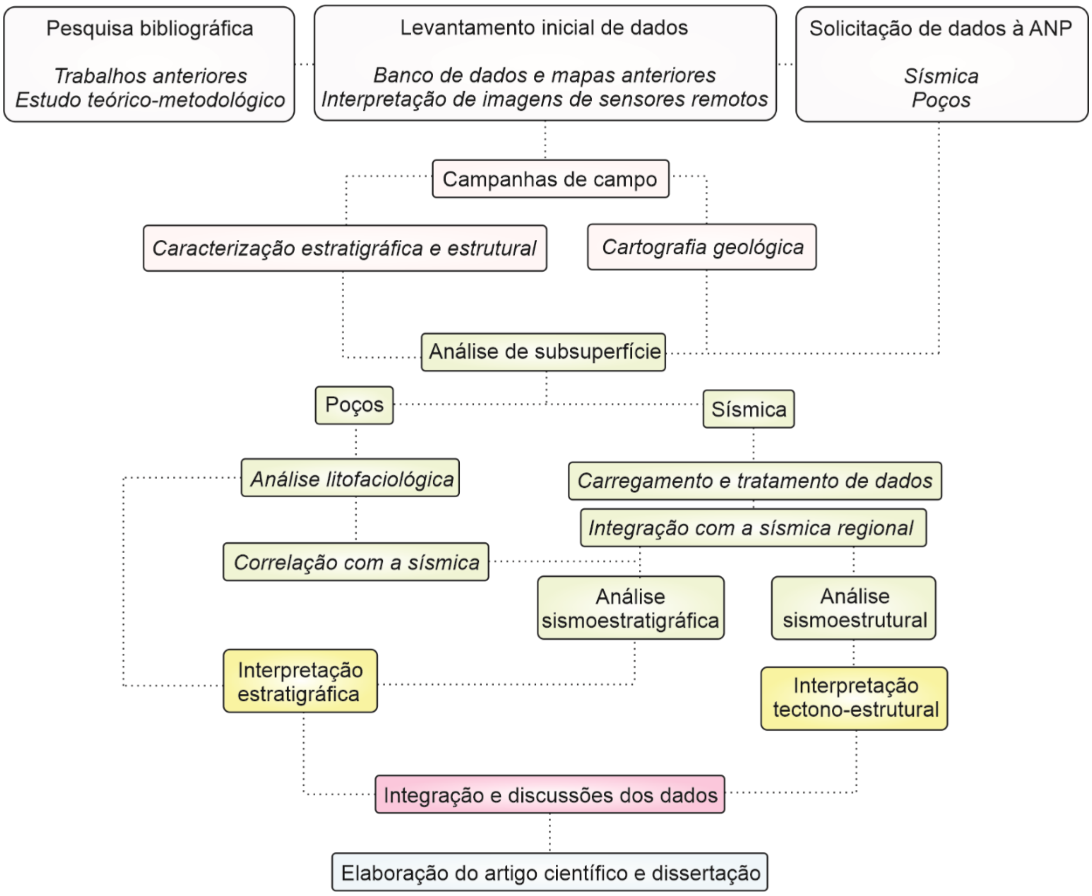


Figura 1.2 – Fluxograma ilustrando as etapas de trabalho realizadas neste estudo.

Para o início deste trabalho, e durante toda sua execução, foram consultados trabalhos prévios relacionados à geologia regional e aos aspectos tectono-estruturais e estratigráficos da Bacia do Pio do Peixe. Estudos bibliográficos sobre os tópicos teóricos e metodológicos que envolvem este estudo também foram realizados.

Numa primeira etapa, antecedendo a campanha de campo, foram levantados dados de mapeamentos pré-existentes e analisadas imagens de sensoriamento remoto (imagem de satélite, imagem topográfica e fotografias aéreas). Paralelamente, foram solicitados à ANP os dados de sísmica e de poços.

O segundo momento deste trabalho consistiu na campanha de campo. Foram visitados um total de 160 afloramentos (Figura 1.1), cuja caracterização comtemplou: relações estratigráficas, descrições litofaciológicas, medidas de acamamento e paleocorrentes e medidas estruturais (foliação, juntas, bandas de deformação e falhas). A partir deste levantamento, para posterior correlação com os dados de subsuperfície, foi confeccionado um mapa geológico da área de estudo, sendo caracterizada as unidades aflorantes.

Uma vez obtidos, os dados de poços foram analisados, sendo utilizados os perfis compostos e perfis de acompanhamento geológico. Convencionou-se como objeto principal de análise os perfis de raio gama associados à descrição litológica, que no geral corroboram com os perfis de densidade, neutrão e de resistividade. A partir dos *trends* e litologias observados, foi possível obter informações acerca das litofácies, energia deposicional e de padrões de empilhamento.

A correlação dos dados de poço com a sísmica se deu a partir da construção de tabelas tampo-profundidade. Na amarração sísmica-poço, não foi disponibilizado pela ANP o arquivo digital do perfil sônico, impossibilitando a criação de sismogramas sintéticos. Assim, a amarração foi obtida a partir da construção de tabelas de tempo-profundidade, com auxílio do *software Engauge* Digitizer 12.0. Para a finalização desta amarração, um último ajuste manual foi feito, com base na interpretação.

O dado sísmico e os perfis digitais dos poços foram carregados no *software OpendTect* (*dGB Earth Science).* No dado sísmico, foram aplicados filtros e atributos, com o objetivo de otimizar a visualização de feições geológicas. Foram analisadas linhas sentido *dip* (*inlines*) e *strike* (*crossline*), linhas arbitrárias e seções horizontais em tempo (*time slices*), possibilitando a interpretação 3D de falhas e horizontes estratigráficos.

Para a interpretação sismoestrutural, as falhas e os traços axiais mais evidentes foram mapeados, buscando-se correlacionar as estruturas à seus eventos tectônicos de origem. Para a interpretação sismoestratigráfica, foram aplicados os conceitos básicos de estratigrafia de sequências, incluindo os modelos para bacias rifte (Kuchle & Scherer, 2010 e Alvarenga, 2016). Nesta análise, os refletores e suas terminações foram rastreados e, a partir dos aspectos de configuração interna, continuidade, amplitude e frequência, foram estabelecidas sismofácies. Com isto, caracterizou-se superfícies e unidades estratigráficas, que permitiram interpretação de tratos de sistemas.

Por fim, a última etapa deste trabalho consistiu na integração e discussão dos resultados obtidos, os quais permitiram estabelecer novas considerações acerca da tectono-estratigrafia das sequências pré e sin-rifte da Bacia do Rio do Peixe. O trabalho desenvolvido foi organizado na forma desta dissertação de mestrado, que contempla o artigo científico "*Multi-scale tectono-stratigraphic analysis of pre- and syn-rift sequences in the Rio do Peixe Basin, NE Brazil*" (*vide* Capítulo 3), submetido na revista "*Marine and Petroleum Geology*".

Capítulo 2

BACIA DO RIO DO PEIXE

2.1. Contexto geotectônico

2.2. Arcabouço estrutural

2.3 Arcabouço estratigráfico

2. BACIA DO RIO DO PEIXE

2.1 Contexto geotectônico

No Juro-Cretáceo, com a separação do Gondwana a abertura do Atlântico Sul, foram formadas bacias sedimentares na margem leste Sul Americana e oeste da África. No Nordeste brasileiro este processo configurou um sistema rifte intracratônico, registrando informações importantes para a compreensão do estágio de rifteamento continental.

A evolução das bacias marginais é dividida em três estágios (Matos, 1992): a fase sin-rifte I (Neojurássico, Figura 2.1A) relaciona-se ao estiramento crustal inicial, com preenchimento de uma ampla depressão; a fase sin-rifte II (Neocomiano-Barremiano, Figura 2.1B), consiste na fase principal de rifteamento, com distensão NW-SE, no qual foram desenvolvidos os *trends* Gabon-Sergipe Alagoas (GSA), Recôncavo-Tucano-Jatobá (RTJ) e Cariri Potiguar (CP); a fase sin-rifte III (Aptiano-Albiano, Figura 2.1C) é associada a uma mudança na direção de distensão, que foi rotacionada no sentido anti-horário, exibindo uma cinemática transcorrente dextral ao longo de um *trend* E-W. Nesta última fase, o *trend* Cariri Potiguar foi abortado e se iniciou a deformação na margem equatorial.

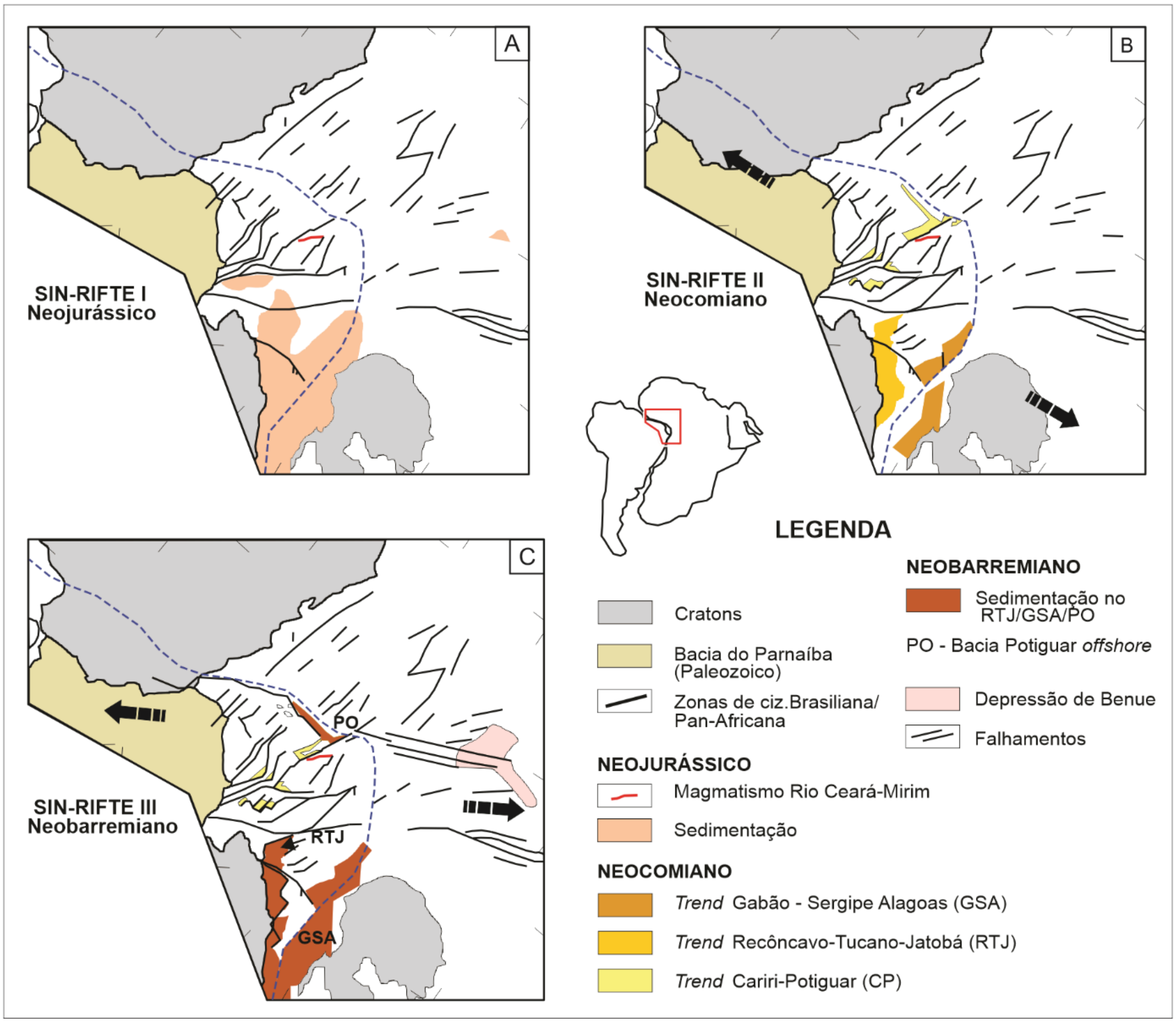


Figura 2.1 – Modelo esquemático para a evolução tectônica das bacias rifte do Nordeste Brasilero (Matos, 1992).

A Bacia do Rio do Peixe pertence ao conjunto de bacias rifte interiores do Nordeste brasileiro (Figura 2.2), situada no *trend* Cariri Potiguar, de origem relacionada a fase sin-rifte II (Figura 2.1). No evento rifte eocretáceo, a instalação das bacias possuiu um controle arquitetural importante das anisotropias do embasamento cristalino, onde a acomodação do *strain* distensional NW-SE nucleou falhas ao longo das faixas miloníticas brasilianas da Província Borborema (Sénant & Popoff, 1991; Matos, 1992,1999; Françolin, 1994; Castro *et al*., 2007; Córdoba *et al*., 2008; Kirkpatrick *et al.*, 2013).

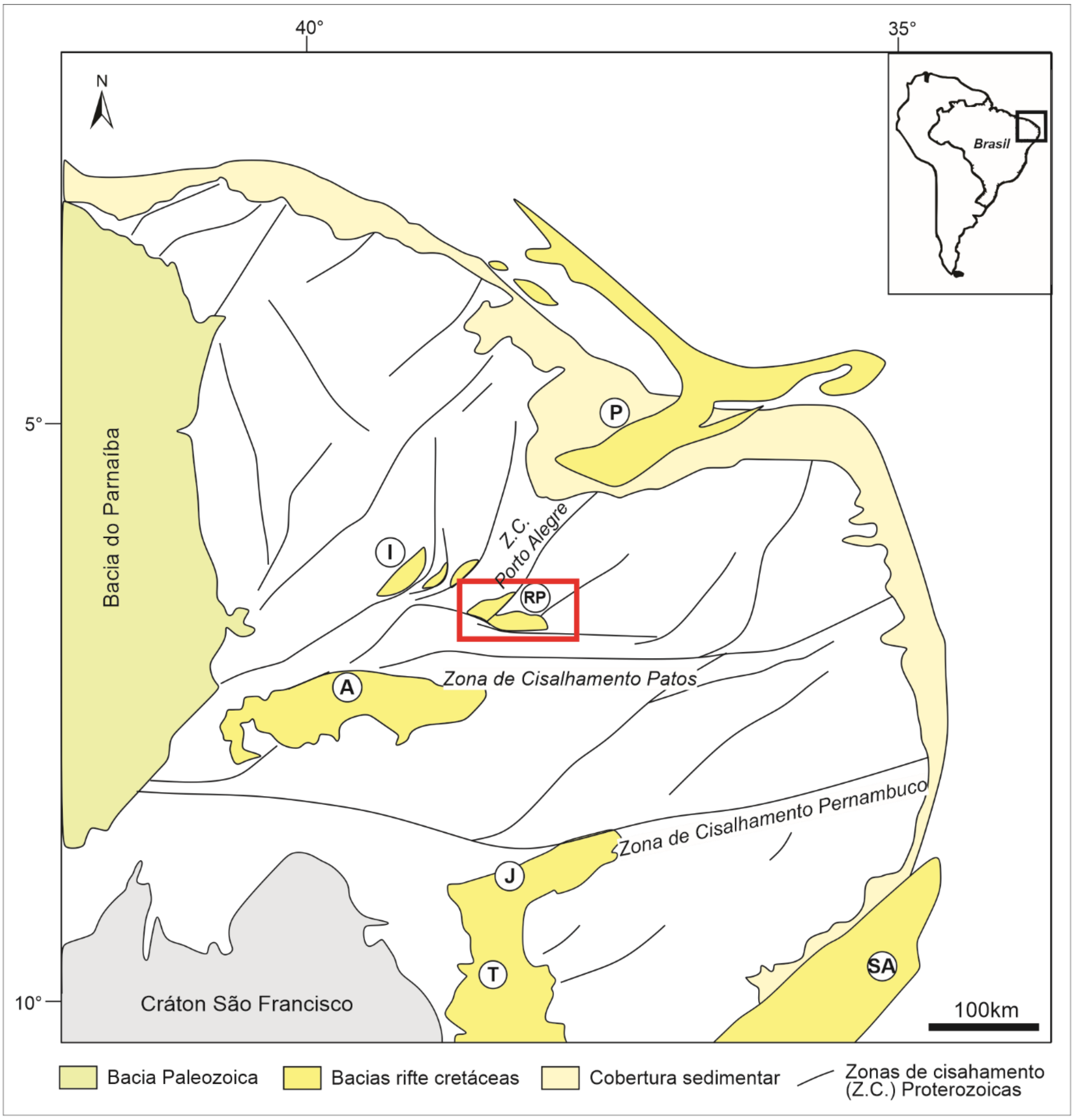


Figura 2.2 – Distribuição das bacias rifte cretáceas do Nordeste brasileiro e das principais zonas de cisalhamento na Província Borborema (Matos, 2012), com destaque para a Bacia do Rio do Peixe (RP). Demais bacias cretáceas: P –Potiguar; I –Iguatú; A – Araripe; J – Jatobá; T – Tucano; SA – Sergipe Alagoas.

A Bacia do Rio do Peixe está localizada no setor setentrional da Província Borborema (Figura 2.2 e 2.3). Seu embasamento a sul e a leste pertence ao Domínio Rio Piranhas-Seridó, e a oeste ao Domínio Jaguaribeano, separados pela zona de cisalhamento Portalegre, também ocorrendo em suas adjacências corpos granitoides brasilianos (Medeiros *et al.*, 2005; Figura 2.3). A zona de cisalhamento Portalegre (direção NE-SW), juntamente com a zona de cisalhamento de Patos (direção E-W), são responsáveis, respectivamente, pela instalação das falhas de Brejo das Freiras e de São Gonçalo (Figura 2.4), que bordejam as duas sub-bacias principais (Brejo das Freiras e Sousa), bem como os grábens de menor porte (Sénant & Popoff, 1991; Córdoba *et al*., 2008; Nunes da Silva, 2009).

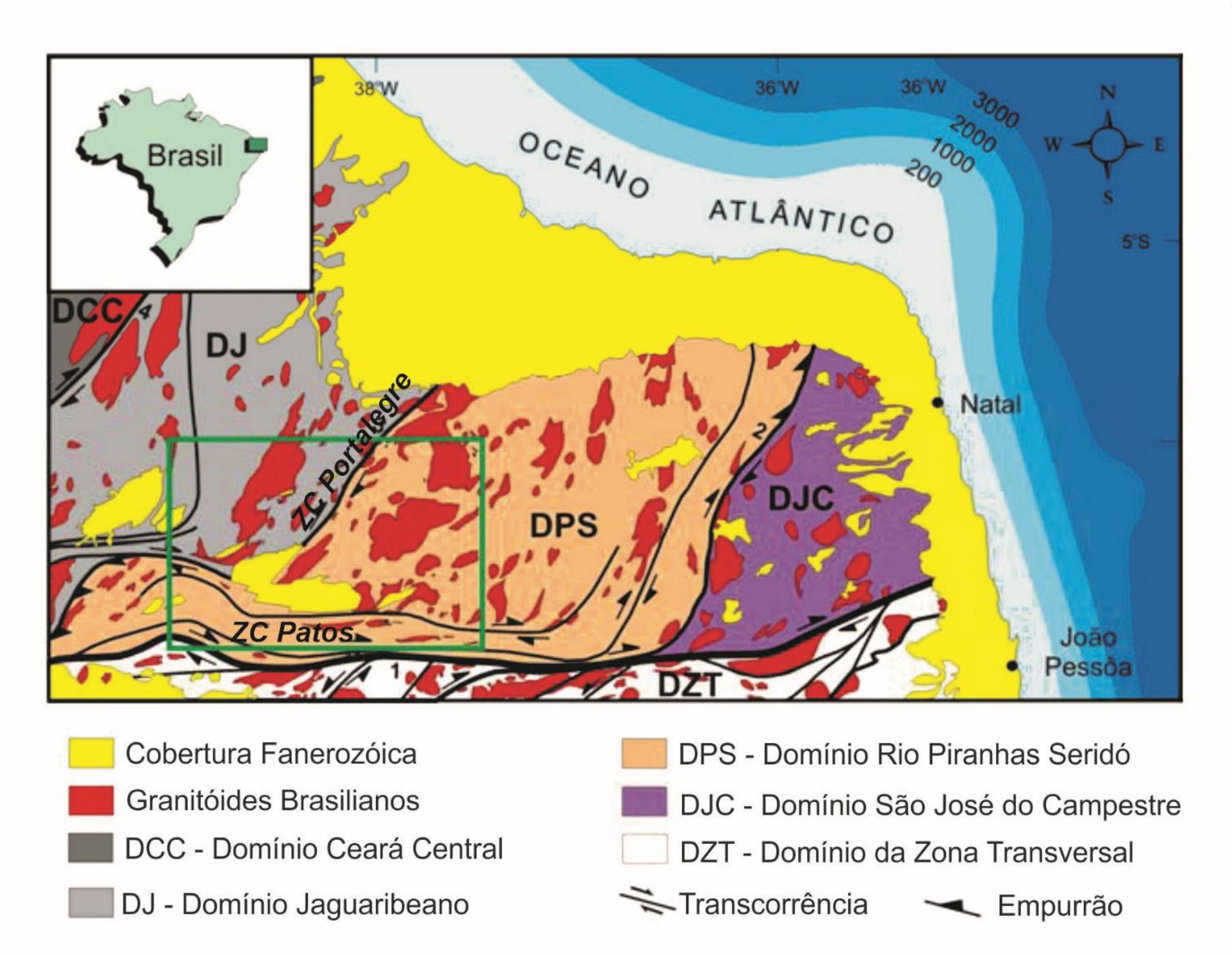


Figura 2.3 – Compartimentação dos domínios tectônicos do embasamento na porção setentrional da Província Borborema, com destaque para a região da Bacia do Rio do Peixe (compilado de Medeiros *et al,* 2005).

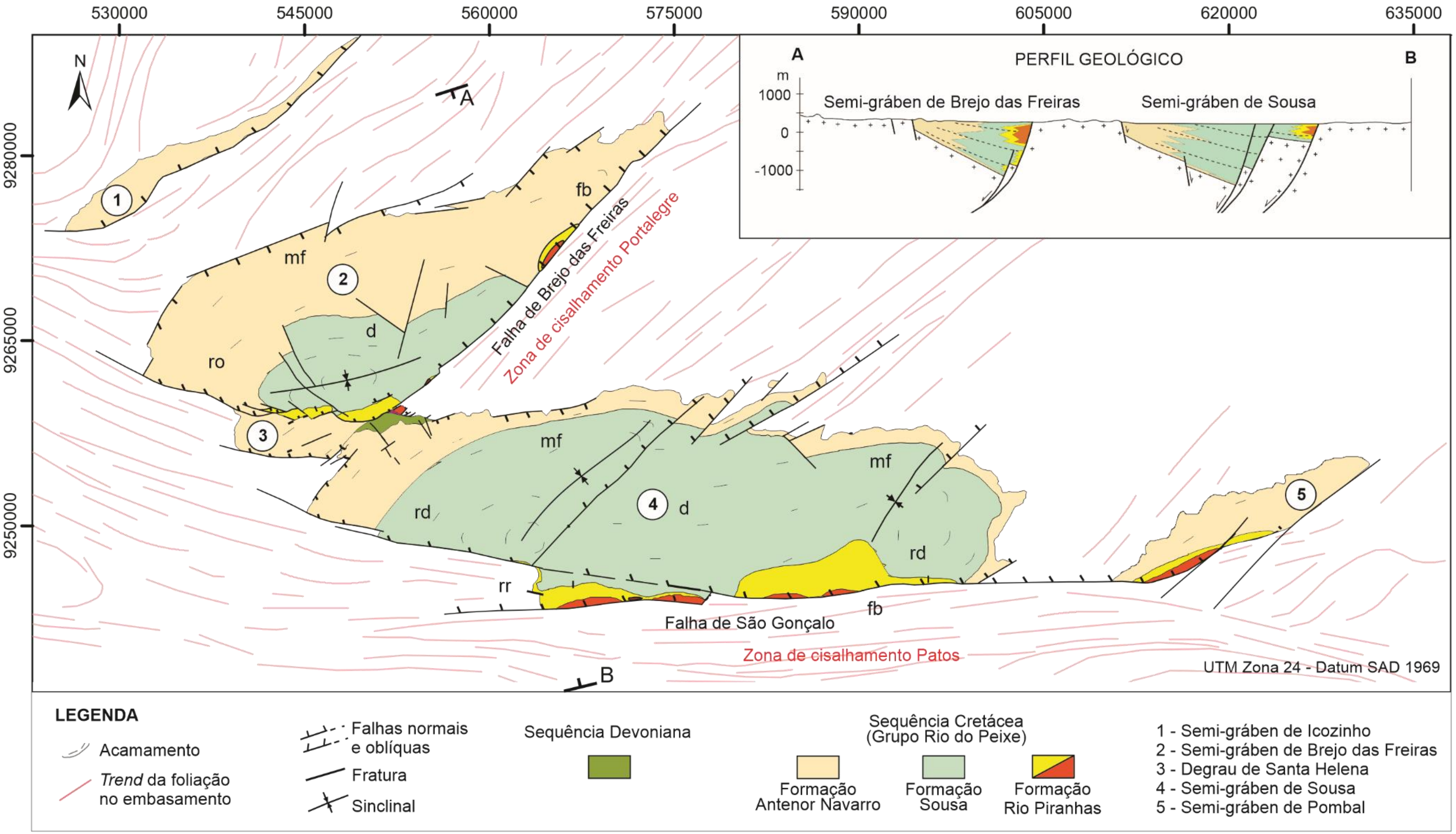


Figura 2.4 – Mapa e perfil geológico simplificado da Bacia do Rio do Peixe (compilado de Córdoba *et al.*, 2008; Nunes da Silva, 2009; Silva *et al.* 2014 e Mendonça, 2017). A Sequência Devoniana apresentada no mapa corresponde a Formação Pilões proposta por Silva *et al.* (2011). Principais compartimentos estruturais dos semi-grábens: fb – falha de borda, d – depocentro, mf – margem flexural, rd – rampa directional, ro – rampa oblíqua, rr – rampa de revezamento.

2.2 Arcabouço estrutural

A Bacia do Rio do Peixe é estruturada em semi-grábens, sendo eles Icozinho, Brejo das Freiras, Sousa e Pombal, compartimentados em suas bordas falhadas, margens flexurais, rampas direcionais e depocentros, além de regiões de altos e de rampas de revezamento (Figura 2.4). Neste sentido, entre os semi-grábens de Brejo das Freiras e de Sousa é compartimentado um setor conhecido como o Degrau de Santa Helena. Até o momento, a compreensão evolutiva desta região não é clara.

Em relação à arquitetura interna da bacia (Figura 2.5), Antunes *et al*. (2007), Córdoba *et al.* (2008) e Nunes da Silva (2009) mostram que suas camadas são basculadas e espessadas para SE ou sul, em direção às margens falhadas. As falhas de borda são estruturadas em degraus, apresentam um perfil lístrico e podem exibir dobras de propagação (arrasto). Os autores também apresentam que no evento distensional eocretáceo foram desenvolvidas estruturas frágeis e hidroplásticas, com duas direções principais, E-W e NE-SW. A primeira é caracterizada por um deslocamento oblíquo normal-sinistral e a segunda por um deslocamento normal. Em menor expressão, falhas de pequeno porte com componentes inversos e falhas NW normais são tentativamente relacionadas à abertura da Margem Equatorial, no Aptiano-Albiano.

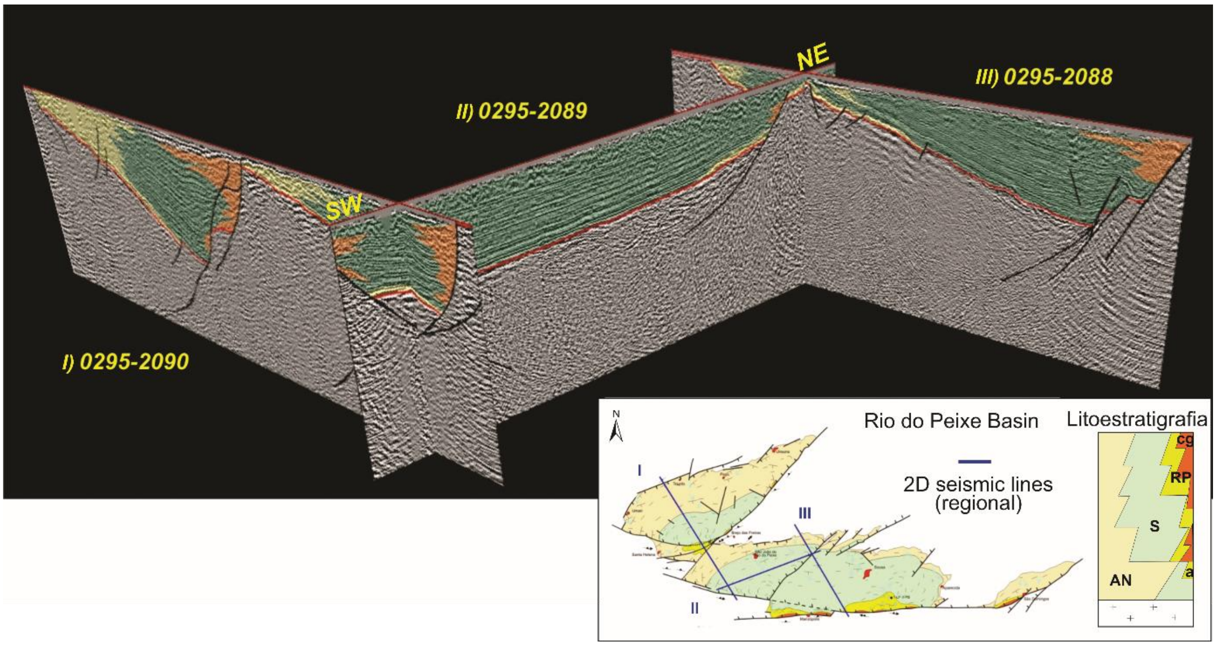


Figura 2.5 - Arcabouço estratigráfico-estrutural da Bacia do Rio do Peixe por meio de linhas sísmicas regionais interpretadas (Córdoba *et al*. 2008).

Um episódio de inversão tectônica mais jovem é abordado por Nogueira *et al.* (2015) e Vasconcelos *et al.* (2020), os quais relacionam este evento a esforços compressivos na Placa Sul Americana, devido ao desenvolvimento da dorsal mesoatlântica (a leste) e da Cadeia Andina (a oeste).

2.3 Arcabouço estratigráfico

2.3.1 Grupo Rio do Peixe

A sequência eocretácea da Bacia do Rio do Peixe consiste no Grupo homônimo, composto pelas formações Antenor Navarro, Sousa e Rio Piranhas (Figuras 2.4, 2.5 e 2.6). Análises bioestratigráficas das rochas deste do grupo sugerem uma deposição eocretácea (neocomiana). Associações paleontológicas de ostracodes e palinomorfos posicionam o grupo nos andares Rio da Serra e Aratu (Ghignone *et al.* 1986; Carvalho, 1989; Regali, 1990; Mabesoone, 1994). As descrições destas unidades, apresentadas abaixo, estão de acordo com os trabalhos de Scherer *et al.* (2007), Córdoba *et al.* (2008) e Nunes da Silva (2009).

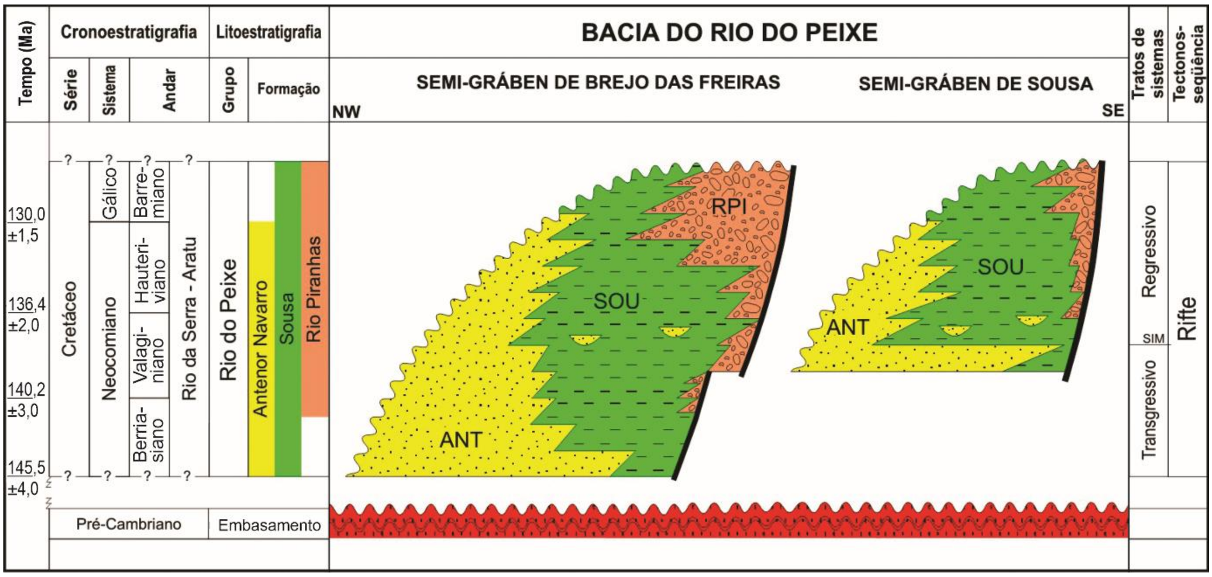


Figura 2.6 - Carta estratigráfica da Bacia do Rio do Peixe para os semi-grábens de Brejo das Freiras e de Sousa, contemplando as unidades cretáceas (Córdoba *et al*., 2008).

A Formação Antenor Navarro é composta por arenitos grossos a médios (ou mesmo finos), por vezes conglomeráticos e, localmente, brechóides. Estão relacionados a sistemas de leques aluviais coalescentes, que evoluem para fluviais entrelaçados ou distributários, associados às margens flexurais e rampas direcionais dos semi-grábens.

A Formação Sousa compreende arenitos finos, siltitos, argilitos e folhelhos, ocorrendo localmente níveis carbonáticos. Associam-se a sistemas de planícies aluviais e/ou lobos terminais, com fácies lacustres em subsuperfície (interpretação sismoestratigráfica).

A Formação Rio Piranhas apresenta brechas, conglomerados e arenitos grossos a médios, frequentemente conglomeráticos e desorganizados. Correspondem a sistemas de leques aluviais em paleoescarpas, associado a sistemas fluviais entrelaçados, com a área fonte na ombreira dos semi-grábens.

Interpretações sismoestratigráficas e cartográficas mostram que os litotipos das unidades do Grupo Rio do Peixe apresentam-se interdigitados, sendo aproximadamente cronoequivalentes (Figuras 2.5 e 2.6; Córdoba *et al.*, 2008; Nunes da Silva, 2009), contrapondo a concepção clássica de um empilhamento regular (Braun, 1969; Mabesoone, 1994).

Córdoba *et al.* (2008) apresentam uma correlação temporal entre os semi-grábens de Brejo da Freiras e de Sousa, em que a origem do semi-gráben de Brejo da Freiras antecede à formação do semi-graben de Sousa. Esta conclusão tem como base o posicionamento da superfície que marca o momento de expansão máxima dos sistemas lacustres entre os semi-grábens (Figura 2.6). Os mesmos autores também inferem dimensões originais mais amplas que as atuais para a bacia, ocorrendo uma expressiva erosão tardi a pós-rifte (pós-Mesobarremiano e pré-Neoaptiano, e continuidade até o Neógeno). Acerca do paleoclima do estágio rifte, estima-se para a bacia climas áridos a semi-áridos (Lima & Coelho, 1987 e Lima Filho, 1991).

2.3.2. Sequência Devoniana

Roesner *et al.* (2011), baseados em associações palinomórficas caracterizadas em testemunhos de poços da PETROBRAS (1-PIL-1-PB, 1-STH-1-PB e 1-TRF-1-PB), identificaram uma nova seção sedimentar siliciclástica abaixo do Grupo Rio do Peixe. Esta seção é relacionada ao Eodevoniano, estimando um hiato deposicional com a Sequência Eocretácea de 265 Ma, cujos organismos sugerem um ambiente de influência marinha com forte influxo de águas continentais. Apesar do intervalo datado não ser especificado, estima-se sua espessura entre 200 e 234m, sendo impreciso o limite superior com a seção cretácea.

A partir da análise de Roesner *et al*. (2011), Silva *et al.* (2014) propuseram duas novas unidades para a Bacia do Rio do Peixe, mapeadas na borda NW do Semi-gráben de Sousa: a formação Pilões (Figura 2.4) e, acima dela, a formação Triunfo, compondo o Grupo Santa Helena. Em sua base este grupo possui relação de não conformidade com o embasamento e em seu limite superior uma discordância angular com o Grupo Rio do Peixe.

Segundo Silva *et al*. (2014), a Formação Triunfo consiste em depósitos fluvio-deltaicos entrelaçados, com arenitos e conglomerados, intercalados a pelitos e arenitos finos. A formação Pilões compreende pelitos e arenitos, com brechas e conglomerados subordinados, relacionados a sistemas de leques deltaicos e fluvio-deltaicos.

2.3.3. Rochas piroclásticas

Na área de interseção entre os Semi-grábens de Sousa (margem flexural) e Brejo das Freiras, Silva *et al.* (2014) caracterizaram ignimbritos e brechas coignimbríticas relacionadas a um evento vulcânico piroclástico até então desconhecido. O depósito, denominado como Brecha vulcânica Poço da Jurema, é colocado como contemporâneo ou anterior à sedimentação devoniana. Deve ser mencionado que Nunes da Silva (2009) descreveu estas unidades como brechas da Formação Rio Piranhas.

Capítulo 3

ARTIGO CIENTÍFICO

MULTI-SCALE TECTONO-STRATIGRAPHIC ANALYSIS OF PRE- AND SYN-RIFT SEQUENCES IN THE RIO DO PEIXE BASIN, NE BRAZIL

MULTI-SCALE TECTONO-STRATIGRAPHIC ANALYSIS OF PRE- AND SYN-RIFT SEQUENCES IN THE RIO DO PEIXE BASIN, NE BRAZIL

Maria Clara de Meneses LOURENÇO [a*,b], Emanuel Ferraz JARDIM DE SÁ [a,c], Valéria Centurion CÓRDOBA[a,c]

[a] Postgraduate Program in Geodynamics and Geophysics, Federal University of Rio Grande do Norte, Natal, Rio Grande do Norte, Brazil.
[b] Department of Petroleum Engineering, Federal University of Rio Grande do Norte, Natal, Rio Grande do Norte, Brazil.
[c] Department of Geology, Federal University of Rio Grande do Norte, Natal, Rio Grande do Norte, Brazil

* Corresponding author. Present address: Laboratory of Petroleum Geology and Geophysics, Federal University of Rio Grande do Norte, University Campus, Lagoa Nova, PO Box 1596, CEP 59078-970, Natal, Rio Grande do Norte, Brazil. Tel.: +55 (084) 3342-2332 (Extension 325). E-mail address: mclaralourenco@hotmail.com (Maria Clara de Meneses Lourenço); emanuel.sa33@gmail.com (Emanuel Ferraz Jardim de Sá)

ABSTRACT

During the Early Cretaceous, interior basins were developed in Northeastern Brazil, recording the continental rifting stage that predated the development of the passive margins along the South Atlantic. The Rio do Peixe Basin is a well exposed example of this set of basins. In this basin, recently, Lower Devonian strata were identified underneath the Rift Sequence, making the Rio do Peixe Basin a differentiated example in the region. Using outcrop, wells and 3D seismic data, this work present new interpretations for the tectono-stratigraphic record of the pre-rift (remnant of a Paleozoic basin) and syn-rift intervals of the Rio do Peixe basin. The study area includes the outcropping and subsurface occurrences of the Lower Devonian (pre-rift) and Lower Cretaceous (rift) sequences, in the western part of the Sousa half-graben and the eastern portion of the Santa Helena step. The basement contact with the sedimentary sequences along the strike ramp and in the flexural margin of the Sousa half-graben is established by normal and oblique slip normal faults. At the surface and subsurface, a low-angle unconformity occurs at the base of the Lower Cretaceous Sequence. The rift structures are characterized by NW-SE extension. As a minor expression, a second deformation event is related to the opening of the Equatorial Margin, in a transtensional dextral regime. The Lower Devonian Sequence corresponds to a deltaic system, divided into transgressive and regressive systems tracts. This sequence presents a chronocorrelate interval in the Parnaíba basin, located further west of the Rio do Peixe Basin. The Rift Sequence displays interdigitated contacts between its coeval stratigraphic units. This sequence is subdivided into tectonic systems tracts, associated to the beginning of extension and episodes of high and low levels of tectonic activity.

Key-words: Rio do Peixe Basin; tectono-stratigraphy; Cretaceous rift structures; Devonian pre-rift; rift sequence stratigraphy; 3D seismic interpretation.

1. Introduction

In the Early Cretaceous, the Gondwana breakup and the consequent opening of the South Atlantic were responsible for the formation of intracontinental rift and marginal basins along South America and Africa. In this process, the propagation of the rift system developed basins in a wide area of Northeast Brazil, located at the intersection between the Eastern and Equatorial margins, bearing important records to understand the Early Cretaceous continental rift phase (Matos, 1992).

Belonging to the so-called Northeast Brazil interior basins, the Rio do Peixe Basin comprises two main half-grabens, named as the Sousa and Brejo das Freiras sub-basins. The Cretaceous faults were structurally controlled by major late Neoproterozoic shear zones (Matos, 1992; Castro et al., 2007; Córdoba et al., 2008). For a long time, it was considered that this basin was essentially comprised by the rift stage sequences. However, more recent work identified a Lower Devonian Sequence underneath the Rift units (Roesner et al. 2011; Silva et al., 2014). Until now it is not clear how this sequence is related to other Paleozoic units in Northeast Brazil, in which the pre-rift Paleozoic record is essentially represented by the Siluro-Devonian Serra Grande Group of the Parnaíba Basin (the Araripe Basin being the most expressive example).

This work aims to analyse the tectono-stratigraphic evolution of the pre- and syn-rift stages of the Rio do Peixe Basin applying structural and stratigraphic techniques integrated in a multi-scale investigation. New insights will be presented for the remnant of the Devonian basin. The structural framework and the relationships between tectonics and sedimentation in course of the rift stage is also a major issue in this paper. In order to accomplish our proposed objectives, outcrop, wells and 3D seismic data were used, integrated with the concepts of sequence stratigraphy and the related tectonic framework.

2. Geological setting

2.1 Geodynamic context

In the Early Cretaceous, the opening of the South Atlantic originated sedimentary basins along the borders of South America and West Africa. In addition to the marginal basins, intracontinental rifts were widely developed along Northeast Brazil, controlled by a NW-SE (according to South America present coordinates) extensional strain field (Matos, 1992).

The evolution of the Northeast Brazil interior rifts is classified into three main stages by Matos (1992; Figure 1). The syn-rift phase I (Late Jurassic; Figure 1A) is characterized by shallow basins, which were filled along a broad depression. The syn-rift phase II (Neocomian-Barremian; Figure 1B) is related to the opening of the South Atlantic Ocean, when three rifting axes were developed, the Gabon-Sergipe-Alagoas (GSA), Recôncavo-Tucano-Jatobá (RTJ) and Cariri-Potiguar (CP). This last trend includes NE and E-W trending basins, such as the Rio do Peixe Basin, the object of this study. Finally, in the syn-rift phase III (Aptian-Albian; Figure 1C), major changes in the plates framework led to the opening of the Equatorial Margin controlled by a dextral transcurrent/transform kinematics roughly along an E-W trend. During this last stage, the Cariri-Potiguar trend was aborted and the opening of the Equatorial margin started.

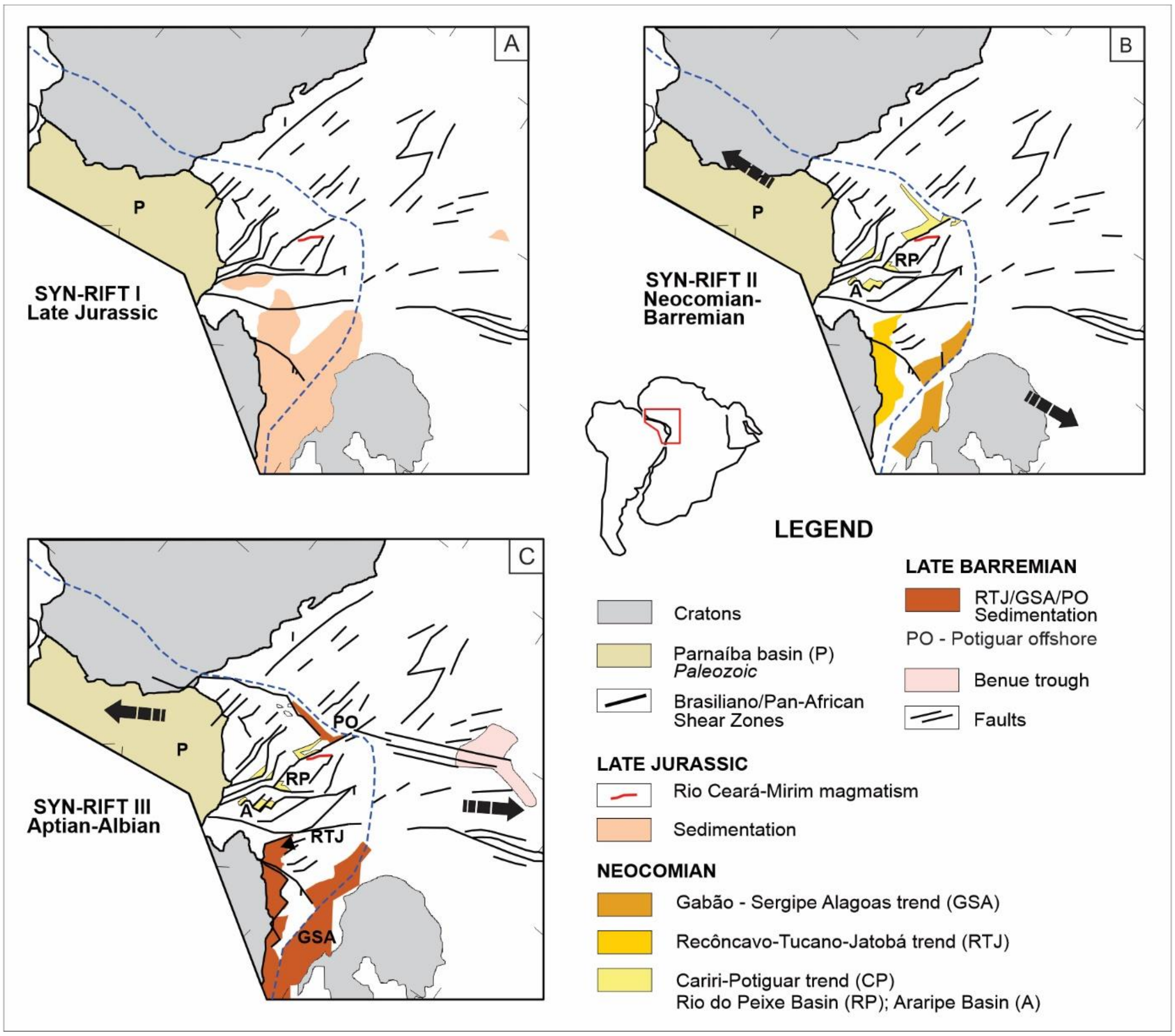


Figure 1 - Schematic model for the tectonic evolution of the Northeastern Brazilian rift basins (Matos, 1992).

The interior basins exhibit an important architectural control by the Late Neoproterozoic basement shear zones. In the Early Cretaceous rift event, the accommodation of the NW-SE extensional strain triggered faults along the Brazilian mylonitic bands of the Borborema

Province (Matos, 1992, 1999; Castro et al., 2007; Córdoba et al., 2008). In the Rio do Peixe Basin, the anisotropies along the NE-trending Portalegre shear zone and the E-W trending Patos shear zone controlled, respectively, the Brejo das Freiras and São Gonçalo faults (Figure 2) which border the two main half-grabens of the Rio do Peixe Basin (Brejo das Freiras and Sousa sub-basins), besides smaller ones (Córdoba et al., 2008; Figure 2).

The basin half-grabens are compartmentalized as their border faults, flexural margins (with secondary faults), strike ramps, relay ramps and depocenters, in addition to regions of basement highs (Figure 2). Between the Brejo das Freiras and Sousa half-grabens there is a compartment with a stepped-shaped geometry, referred in this paper as the Santa Helena step. The evolutionary understanding of this compartment is not yet clear.

Regarding the internal architecture, Córdoba et al. (2008) and Nunes da Silva (2009) shows that the basin strata are tilted and thickened to SE or south, towards the border faults. These authors also show that brittle and hydroplastic structures were developed in the Early Cretaceous event, with two main E-W and NE-SW trends. The first is characterized by a normal-sinistral oblique-slip displacement and the second by normal-slip displacement. Fault propagation folds are remarkable, both in field exposures and in remote sensing imagery. As a minor component, NW-trending normal faults were tentatively related to the Aptian-Albian kinematics further north along the Equatorial Margin. An episode of tectonic inversion was addressed by Nogueira et al. (2015) and Vasconcelos et al. (2020), correlated to a younger stress field.

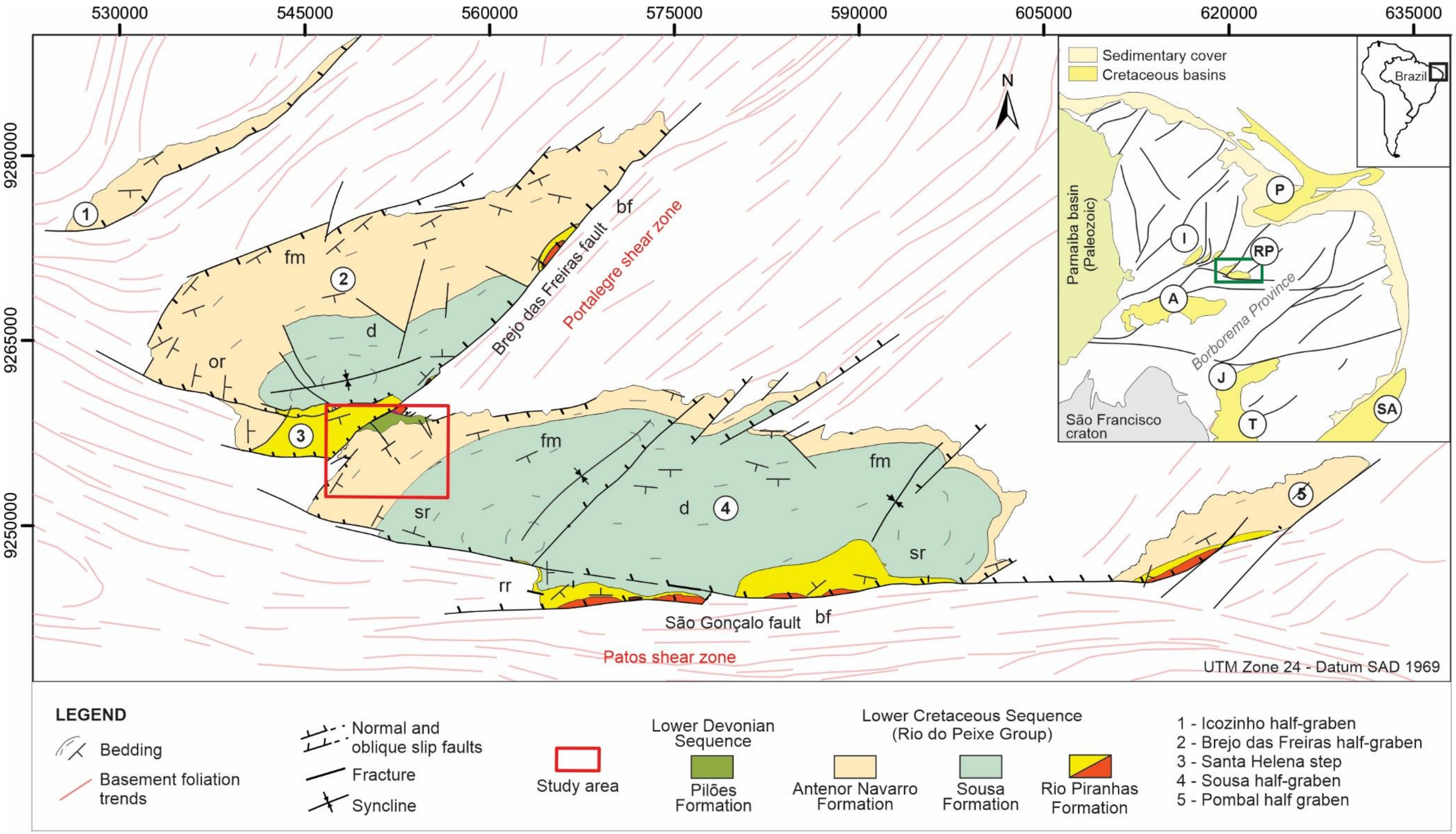


Figure 2 - Simplified geological map of the Rio do Peixe Basin (compiled from Córdoba et al., 2008; Nunes da Silva, 2009; Silva et al. 2014 and Mendonça, 2017). The Devonian Sequence displayed in the map corresponds to the Pilões Formation proposed by Silva et al. (2011). Structural compartments of the main half-grabens: bf - border fault, d - depocenter, fm - flexural margin, sr - strike ramp, or - oblique ramp, rr - relay ramp. In the upper right corner of the figure, the map of the Borborema Province is presented, containing the main basins and shear zones (Matos, 2012). Cretaceous rift basins: P - Potiguar, I - Iguatú, RP - Rio do Peixe (highlighted), A - Araripe, J - Jatobá, T - Tucano and SA - Sergipe Alagoas.

2.2 Lower Cretaceous Sequence

The Lower Cretaceous Sequence of the Rio do Peixe Basin consists of the homonymous group, composed by the Antenor Navarro, Sousa and Rio Piranhas formations (Figure 2 and Figure 3). The descriptions of these units, presented below, are in accordance with the proposal by Córdoba et al. (2008).

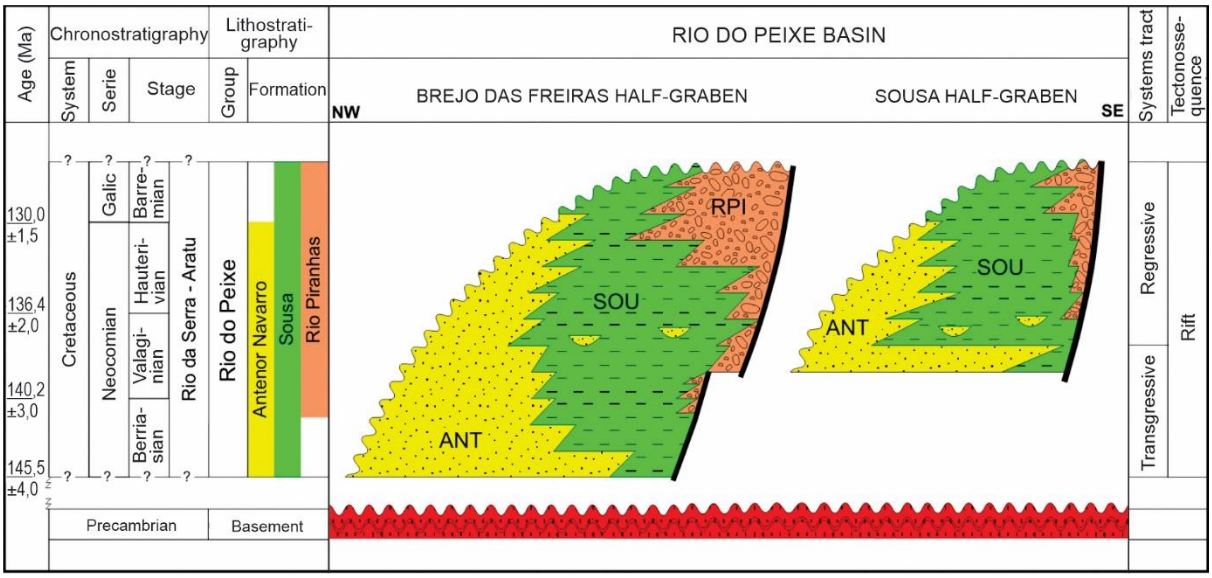


Figure 3 - Stratigraphic chart of the Rio do Peixe Basin, highlighting the Lower Cretaceous Sequence (Córdoba et al. 2008). Note that these authors represent the interdigitation (and thus coeval) of the Cretaceous units, as well as a slightly older age for the beginning of deposition at the Brejo das Freiras half-graben.

The Antenor Navarro Formation is composed by sandstones with a variable granulometry, sometimes conglomeratic, related to a coalescent alluvial fan system, which evolve into braided or distributary fluvial systems. These deposits are associated with the flexural margins and strike ramps of the half-grabens.

The Sousa Formation comprises fine sandstones, siltstone, claystone and shales, locally with some carbonate levels, associated to alluvial plains and/or terminal lobes of a distributary fluvial system, with lacustrine facies interpreted at the subsurface.

The Rio Piranhas Formation consists of sedimentary breccias, conglomerates and coarse to medium sandstones, often conglomeratic and disorganized, of an alluvial fan system deposited in paleoescarpments, with transitions to a braided fluvial system. Unlike the Antenor Navarro Formation, the Rio Piranhas Formation has its source related to the half-graben structural highs along the border faults.

Some additional points about the stratigraphic framework of the Rio do Peixe Basin are: (i) seismic stratigraphic and field data show that the Lower Cretaceous formations are interdigitated, being thus approximately chrono-equivalent (Córdoba et al., 2008; Nunes da

Silva, 2009; Figure 3); (ii) the paleoclimate of the rift stage was interpreted as arid to semi-arid (Lima Filho, 1991); (iii) it is believed that the original dimensions of the basin were larger than the current ones, with linked main depocenters, implying significant late to post-rift erosion (Córdoba et al., 2008).

2.3 Lower Devonian Sequence

Based on palynological analysis of well samples, Roesner et al. (2011) identified an older siliciclastic sedimentary section below the Rio do Peixe Group. This section is correlated to the Lower Devonian (Lochkovian-Pragian?), being interpreted as an environment of marine influence with a strong influx of continental waters. Although the Devonian interval is not specified, its thickness is estimated between 200 and 234 m.

Silva et al. (2014) proposed the occurrence of two units for the Devonian Sequence of Rio do Peixe Basin, outcropping in the NW border of the Sousa half-graben: the Pilões (Figure 2) and Triunfo formations, assembled in the Santa Helena Group. The Pilões Formation consists of mudstones and sandstones, with subordinate sedimentary breccias and conglomerates, related to a deltaic and fluvio-deltaic system. The Triunfo Formation, which overlies the Pilões Formation, comprises sandstones and conglomerates, interbedded with mudstones and fine sandstones, related to braided fluvio-deltaic deposits.

2.4 Pyroclastic rocks

In the area of intersection between the Sousa half-graben and Brejo das Freiras half-graben, Silva et al. (2014) characterized the local occurrence of ignimbrites and coignimbritic breccias related to an unknown pyroclastic event. The deposit was named by those authors as Poço da Jurema, interpreted as coeval or prior to Devonian sedimentation. The ignimbrite layer is regarded by Nunes da Silva (2009) as intercalated (and locally displaying matrix mixing) within the Cretaceous Rio Piranhas sedimentary breccias and conglomerates, filling a small graben in the western northern border do the Sousa half-graben.

3. Methods

The study area is located in the NW portion of the Sousa half-graben, partially comprising the Santa Helena Step (Figure 4). These two sectors are separated by a NE normal fault, named in this work as Melancia Fault. In the strike ramp border of the Sousa half-graben a NE normal fault is named as Formigueiro Fault. In the study area, field surveys were carried out and the available seismic and well data were reinterpreted.

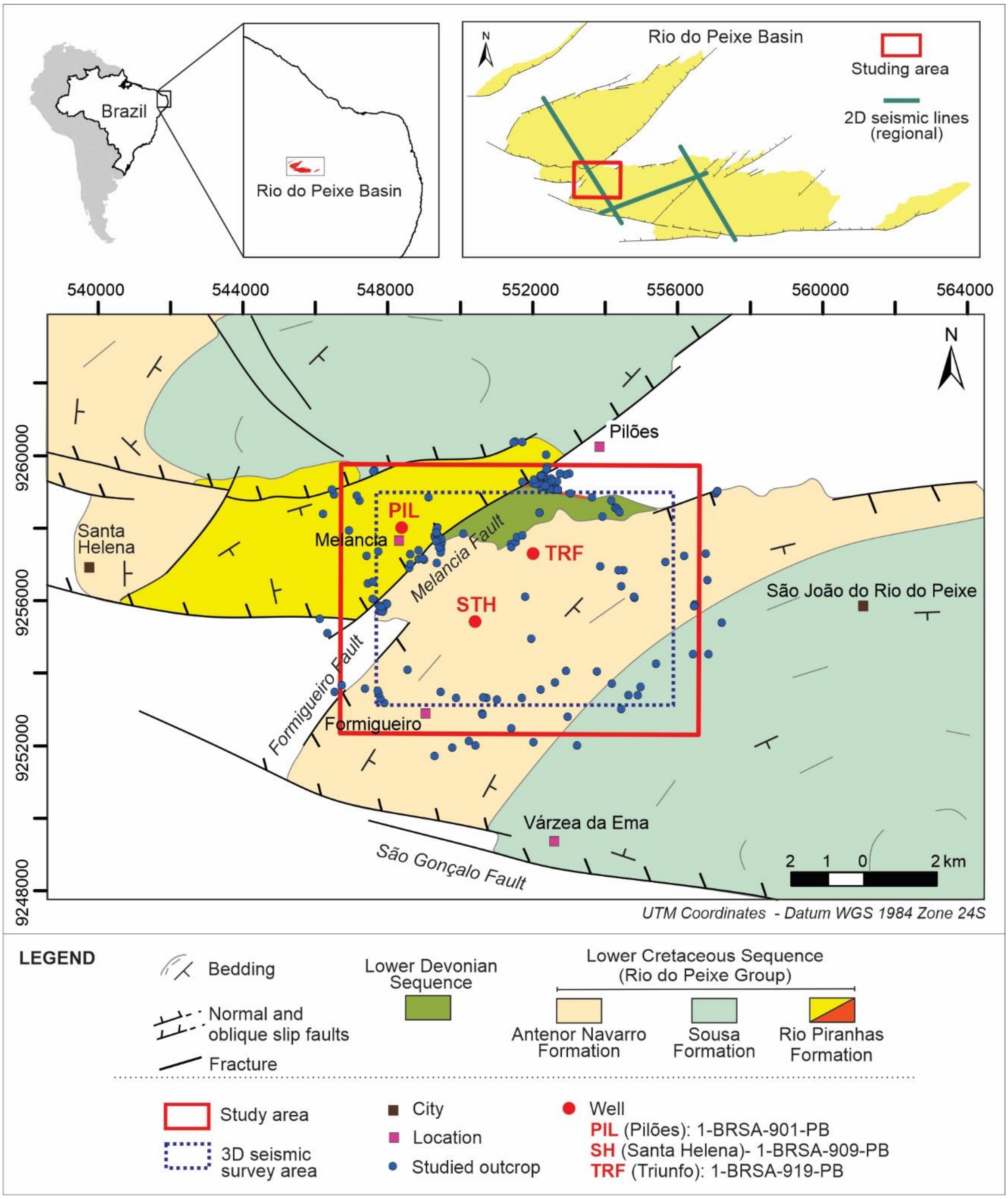


Figure 4 - Study area location in the Rio do Peixe basin, including studied outcrops, seismic data and wells. The geologic map presented was compiled from Córdoba et al. (2008), Nunes da Silva (2009), Silva et al. (2014) and Mendonça (2017). The Devonian Sequence corresponds to the Pilões Formation proposed by Silva et al. (2011).

A total of 160 outcrops were visited (Figure 4), in which were carried out sampling, lithofacies descriptions, stratigraphic sections, contact relations, paleocurrents and bedding measurements, as well structural data (basement foliation, joints, deformation bands and faults).

Subsurface data was provided by the Brazilian Agency of Oil and Gas (ANP). The 3D seismic volume 0027_3D_RIO_DO_PEIXE and the exploratory wells 1-BRSA-901-PB/Pilões, 1-BRSA-909-PB/Santa Helena and 1-BRSA-919-PB/Triunfo were used (Figure 4). In order to integrate the interpretation within a regional framework, the 2D regional seismic survey 0295_RIO_DO_PEIXE_2D was also required (Figure 4). Previous interpretation by Córdoba et al. (2008), Souza (2016) and Rapozo (2020) were maintained.

For well analysis, the gamma ray log profiles and the lithologic columns were used as reference to obtain information about lithofacies, depositional energy and stacking patterns. The seismic-well correlation was performed by time-depth tables and some manual adjustments. As the digital file of the sonic profile was not available, it was not possible to use synthetic seismograms.

The seismic data was manipulated and interpreted using the OpendTect software (dGB Earth Science), in which the inlines, crosslines, time slices and arbitrary lines were analysed. Filters and attributes were applied in order to optimize the visualization of reflectors and highlight geological features (Figure 5). The filters used were the Dip-Steered Median Filter (DSMF) and the Vertical Centered Derivative (VCD; Figure 5B). A pseudo-relief attribute (Amplitude Volume Technique; Bulhões and Amorim, 2005) was also used. This combination of filters and attributes has been applied by previous works (Pichel, 2014; Souza, 2016; Rapozo, 2020).

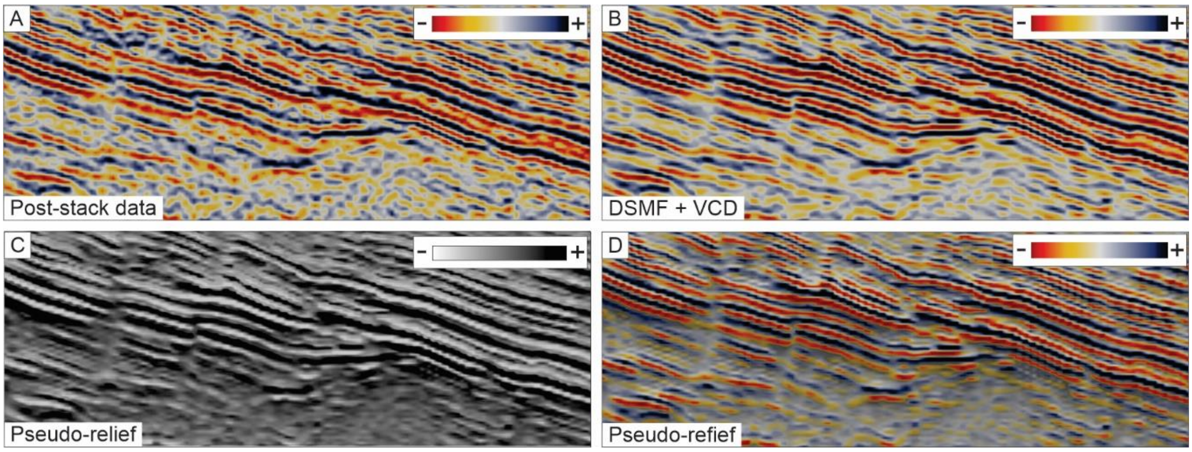


Figure 5 - Filters and attributes applied to the post-processing seismic data in order to optimize the interpretation. A) Post-processed seismic data (initial data). B) image with the Dip-Steered Median Filter (DSMF) and Vertical Centered Derivative (VCD) filters applied; reference for the seismic stratigraphic analysis. C) image with the mentioned filters and the pseudo-relief attribute in a "grayscale" color table, adopted for the structural analysis. D) image with the mentioned filters and the pseudo-relief attribute in a "seismic" color table, used in the seismic stratigraphic analysis.

The DSMF has as input the Steering Cube, which stores information about strike and dip from the reflectors. The amplitudes are collected within a circumference and the central value is replaced by the median of the values. After applied this filter, the VCD filter highlights coherent high frequency events and mitigates inconsistent events with high and low frequency. The pseudo-relief attribute (Bulhões and Amorim, 2005) was obtained using the Hilbert transform on the Root Mean Square (RMS) amplitude attribute, this one calculated during the VCD application.

For the seismic structural interpretation, the important faults and fold hinge traces were mapped. The chosen image for this analysis contains the pseudo-relief attribute in "grayscale" color table (Figure 5C).

For the seismic stratigraphic interpretation, stratigraphic units and surfaces were defined based on tracking reflectors, recognizing their terminations and characterizing seismic facies. The concepts of sequence stratigraphy were applied in this analysis. For the Lower Devonian Sequence, the base level changes were observed. For the Lower Cretaceous Sequence, tectonic system tracts were classified according to Kuchle & Scherer (2010) and Alvarenga (2016). In seismic stratigraphic interpretation, the color table "seismic" was adopted (Figure 5B), also using the pseudo-relief effect (Figure 5D).

4. Surface geology of the study area

The study area is located in the flexural margin and strike ramp in the western part of the Sousa half-graben and also includes the eastern portion of the Santa Helena step (Figure 4 and 6). These two sectors are separated by the Melancia Fault, a main NE trending normal fault. In the Sousa half-graben, the northern flexural margin and the western strike ramp (in the basement contact) are bordered by second order normal faults. This latter compartment fault is referred in this work as the Formigueiro Fault.

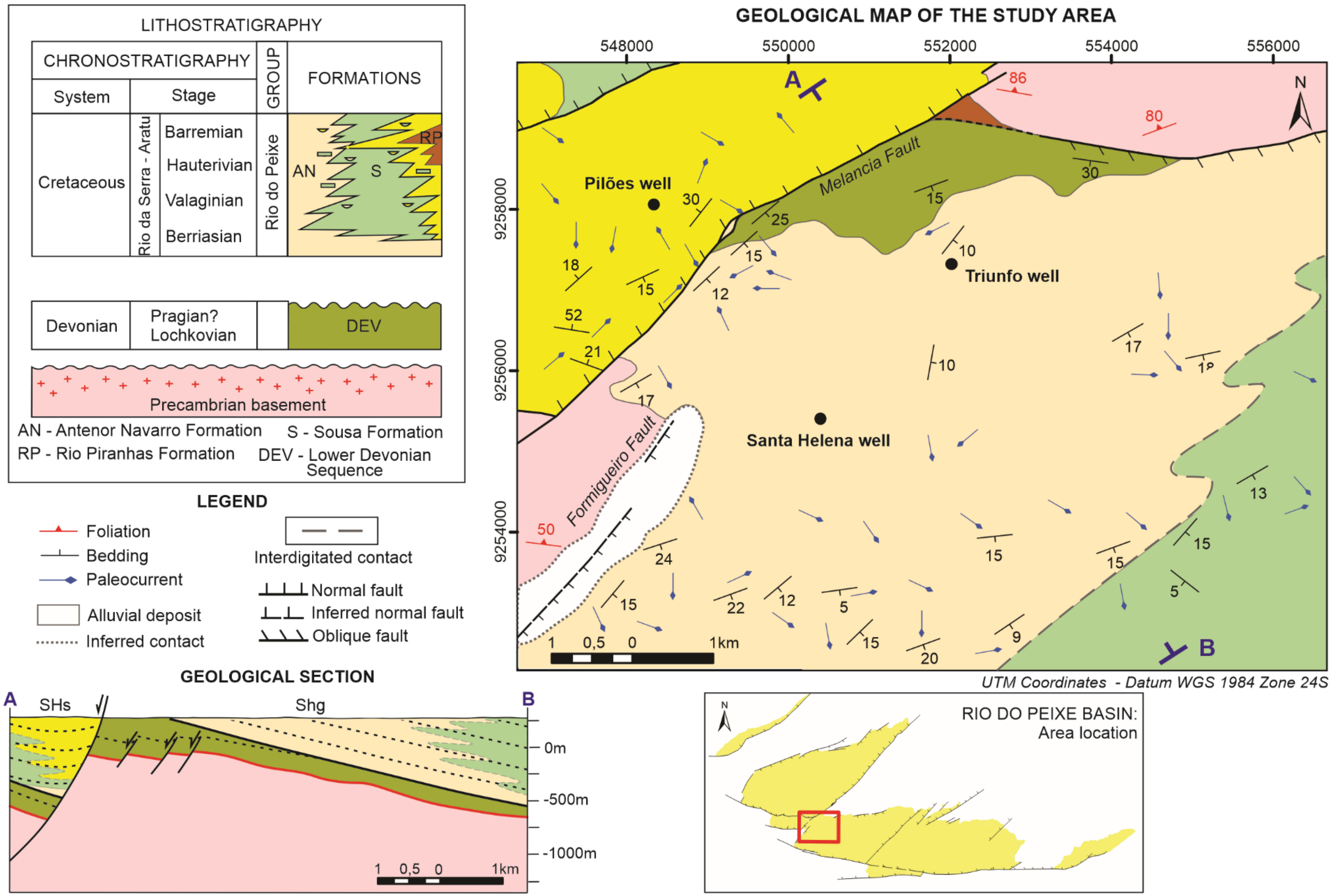


Figure 6 - Geological map of the study area, including a schematic section and a diagram with the litho and chronostratigraphic relationships between the different units. The interdigitation between the Antenor Navarro e Sousa formations is schematically represented. In the section note the angular unconformity between the Lower Devonian and the Lower Cretaceous sequences. SHs - Santa Helena step; Shg - Sousa half-graben.

The Rio Piranhas Formation outcrops in the Santa Helena step (Figure 6). It is worth mentioned that the Antenor Navarro Formation outcrops in the west border of this compartment (Figure 2 and Figure 4). In the Sousa half-graben, the interdigitation between the lithotypes of the Antenor Navarro and Sousa formations is observed (and schematically represented in the map; Figure 6), with beds dipping predominantly towards SE, against the main fault of the Sousa half-graben. Underneath the Antenor Navarro Formation, separated by a low angle unconformity (Figure 7A), mudstones and sandstones of the Lower Devonian Sequence were identified. The Devonian strata is in contact with the Rio Piranhas Formation through a Melancia fault contact. In a restricted sector in the north of the area (Pilões locality - Figure 4), ignimbrites locally occur interbedded with the Rio Piranhas Formation in a small graben.

4.1.1 Antenor Navarro Formation

In its lower basal levels near the basement rocks, the Antenor Navarro Formation exhibits matrix-supported conglomerates. However, medium to coarse grained sandstones, conglomeratic or with conglomeratic levels, with trough cross-stratification, are dominant (Figure 7A and 7B). Less frequently, there are sandstones with tabular cross-stratification. In the transition to the Sousa Formation, there are sandstones with parallel stratification and low-angle cross-stratifications.

This lithofacies association is interpreted as distributary fluvial channels and their marginal deposits, related to a proximal fluvial system (Córdoba et al., 2008). The measured paleocurrents have a dominant sense towards SE (Figure 6), indicating the origin of the fluvial system from the flexural margin and strike ramp of the Sousa half-graben. Despite the overall pattern of paleocurrents, in the NW portion of the strike ramp this formation locally exhibits distinct paleocurrents, pointing to a west to NW flow sense (Figure 6).

4.1.2 Sousa Formation

The Sousa Formation consists of sandstone and mudstone lithofacies (Figure 7C), and may exhibit carbonate cement. Medium to fine sandstones occur with trough cross-stratification, low-angle trough cross-stratification and parallel cross-stratifications, as well as some massive sandstones. Sometimes, associated with sandstones, there are mudstones with parallel- and cross-laminations. In the area, the formation also shows ripple marks and very fine sandstones to siltstones, presenting a massive structure.

Figure 7 - Main lithofacies recognized in outcrops of the Lower Cretaceous and Lower Devonian sequences. A) Unconformity (surface indicated by arrows) between the Antenor Navarro (AN, upper unit) and the Devonian Sequence (DEV, lower unit). In this place, the Antenor Navarro Formation consists of a light gray, coarse quartz sandstone (illustrated in B), while the Devonian strata are dominated by a beige micaceous, finer-grained sandstone; B) Antenor Navarro Formation: conglomeratic sandstone with trough cross-stratification; C) Sousa Formation: fine sandstone with parallel lamination; D) Rio Piranhas Formation: conglomeratic sandstone, with trough cross-stratification; E) Devonian Sequence: sandstones and mudstones interstratified with parallel lamination - in the detail image is shown a centimetric level of poorly sorted sandstone, including granules and pebbles; F) Devonian Sequence: medium to fine grained sandstone with parallel stratification.

This lithofacies association allows to interpret distal fluvial channels, floodplains and crevasse splay deposits (Córdoba et al., 2008). The SE-trending paleocurrents (Figure 6), like in the Antenor Navarro Formation, suggest source areas from the flexural margin and strike ramp of Sousa half-graben.

4.1.3 Rio Piranhas Formation

The Rio Piranhas Formation outcrops along the Santa Helena step, exhibiting red, commonly coarse and conglomeratic sandstones (Figure 7D). These levels are matrix supported and may exhibit sandstone intraclasts. The lithotypes usually display trough cross-stratification, and sometimes massive structure. This set of facies is compatible with braided fluvial and alluvial fan systems (Córdoba et al., 2008).

More restrict occurrences of the Rio Piranhas Formation are additionally observed in the study area: (i) just north of the Sousa half-graben, sedimentary breccia, related to proximal alluvial fan deposits, are preserved by faults in a small structural low (small graben; Figure 6); (ii) in a not mappable scale, minor occurrence of sandstones of the Rio Piranhas Formation are interdigitated with the Antenor Navarro Formation.

In the Santa Helena step, the paleocurrent pattern is variable (Figure 6), but SE/ESE trends dominate. This direction is the same observed for bedding (further shown by the seismic images), which is tilted towards the NE-trending normal Melancia Fault. In the vicinity of this structure, NE-trending paleocurrents (axial flow) also occur.

4.2 Pyroclastic Rocks

In the northern part of the study area, there is a local occurrence of ignimbrites interbedded with sedimentary breccias of the Rio Piranhas Formation. This occurrence is preserved in a small, triangular graben bordered by two faults bearing NE (Melancia) and E-W trends, close to the Pilões locality (Figure 4). These rocks, named as the Poço da Jurema deposit, were regarded to be coeval or prior to the Devonian Sequence by Silva et al. (2014). Bearing the same petrographic and mesoscopic features, as well as their control by the rift faults, this paper maintains the previous correlations of these rocks with the Rio Piranhas Formation (Nunes da Silva, 2009), here included the ignimbrite bed.

4.3 Lower Devonian Sequence

Concerning the Devonian strata, the most common lithofacies observed in outcrops comprise interstratified (milimetric to centimetric alternation) sandstones and mudstones, with parallel lamination (Figure 7E; Figure 8). The sandstones display varied granulometry and generally exhibit levels with angular and subangular granules and pebbles (Figure 7E).

To a lesser extent, there are also facies of medium and fine grained sandstones, with good to moderate selection, presenting massive structure, incipient stratification or low angle cross-stratification (Figure 7F; Figure 8).

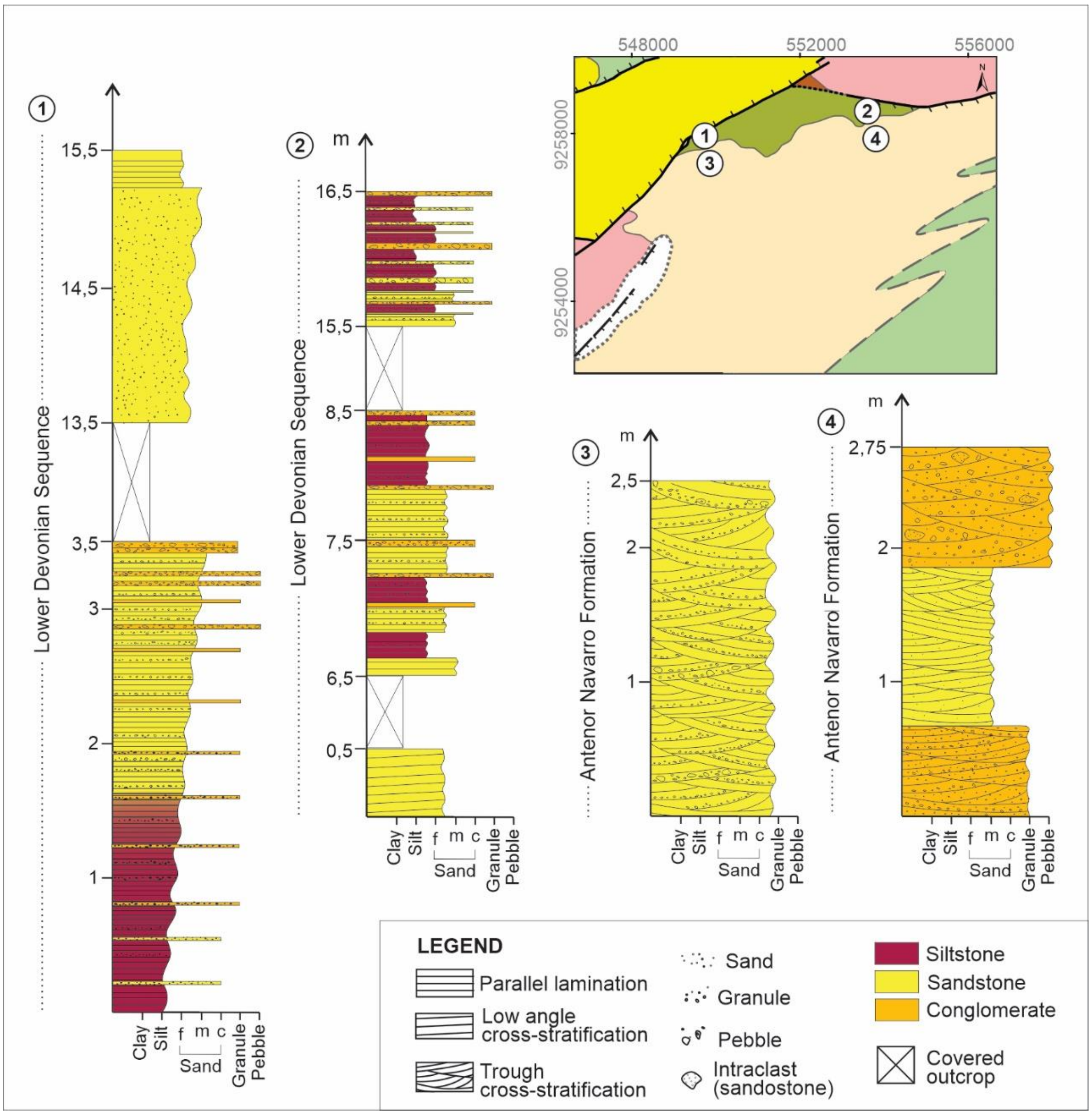


Figure 8 - Columnar sections based on outcrop data located near the unconformity between the Lower Devonian and Lower Cretaceous sequences; see the sections location in the map inset. The Devonian lithofacies show interstratified sandstone-mudstone with parallel lamination and fine to medium grained sandstones with variable structure (massive, parallel lamination or low angle cross-stratification). The Cretaceous lithotofacies (Antenor Navarro Formation) exhibits sandstones and matrix supported conglomerates with trough cross-stratifications, highlighting the lithofaciological contrast between these sequences.

Both interstratified and sandstone facies have a considerable micaceous content (biotite and muscovite). Biotite and other ferromagnesian minerals are sometimes intensely oxidized, cementing the rocks.

The lithofacies observed in the outcrops of the Lower Devonian Sequence suggest hyperpicnal deposits, whose characteristics are compatible with intermediate and distal underwater deposits for the Pilões Formation (Silva et al., 2014).

In this work, the sandstones of the Triunfo Formation, recognized as Devonian by Silva et al. (2014), present the same lithofaciological features of the Antenor Navarro Formation (Figure 8), being interpreted as such. These sandstones directly overlies the Pilões Formation through an angular unconformity (Figura 7A). Like expected for the sandstones of the Antenor Navarro Formation, there rocks are also characterized by their quartz content and by fluvial trough cross-stratifications. They present lateral continuity and a wide distribution throughout the study area and in the whole Rio do Peixe Basin, sharing the characteristic interdigitation with the lithotypes of the Sousa and Rio Piranhas formations.

5. Subsurface tectono-stratigraphic setting

The framework of the structural domains of the Rio do Peixe Basin was built along the Early Cretaceous rifting event. The study area includes the western part of the strike ramp and the flexural margin of the Sousa half-graben, as well as the eastern area of the Santa Helena step (Figure 9). In order to introduce this structural framework, the general subsurface tectono-stratigraphic features will be presented in this topic, and initially illustrated in Figures 9 and 10.

The Melancia Fault, the main structure of this area, represents a NE-trending splay of the Brejo das Freiras fault, which is segmented in a piggyback evolution (Córdoba et al., 2008; Rapozo, 2020). The Melancia Fault separates the Santa Helena step from the Sousa half-graben, with a NE-trending basement high between these two domains.

Both in the Santa Helena step and in the Sousa half-graben, bedding in the units and the basement top are tilted to SE/SSE. The basement and overlying strata in the Santa Helena step dip towards the Melancia Fault and, in the Sousa half-graben, towards the São Gonçalo Fault (the main fault of this half-graben, located to the south of the study area; Figure 2 and Figure 4). Local changes in bedding orientation may occur, within the fault damage zone. The dips of the pre-rift sequence presents a low angular difference with the overlying rift strata (Figure 10), which can be related to tilting and fault propagation folds associated to the major Early Cretaceous faults; however, a component of a poorly known pre-Cretaceous geometry cannot be excluded.

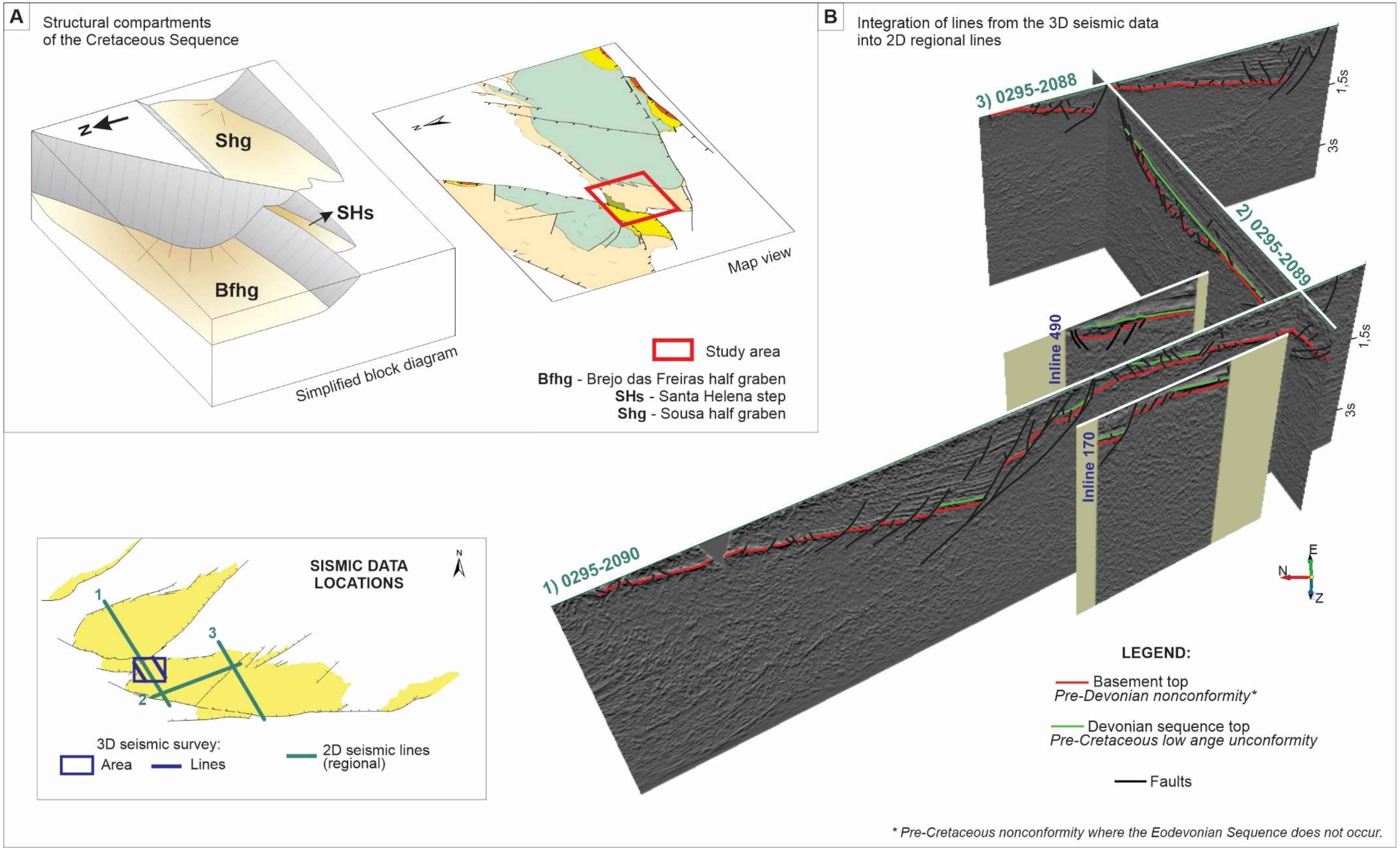


Figure 9 - Tectono-stratigraphic context of the study area. Seismic lines taken from the 3D seismic data are integrated with regional 2D lines (labeled as 1, 2 and 3), these ones previously interpreted by Córdoba et al. (2008), Souza (2016) and Rapozo (2020); observe the location of the 3D data in the regional subsurface tectono-stratigraphic context, including the geometry of the pre-rift sequence.

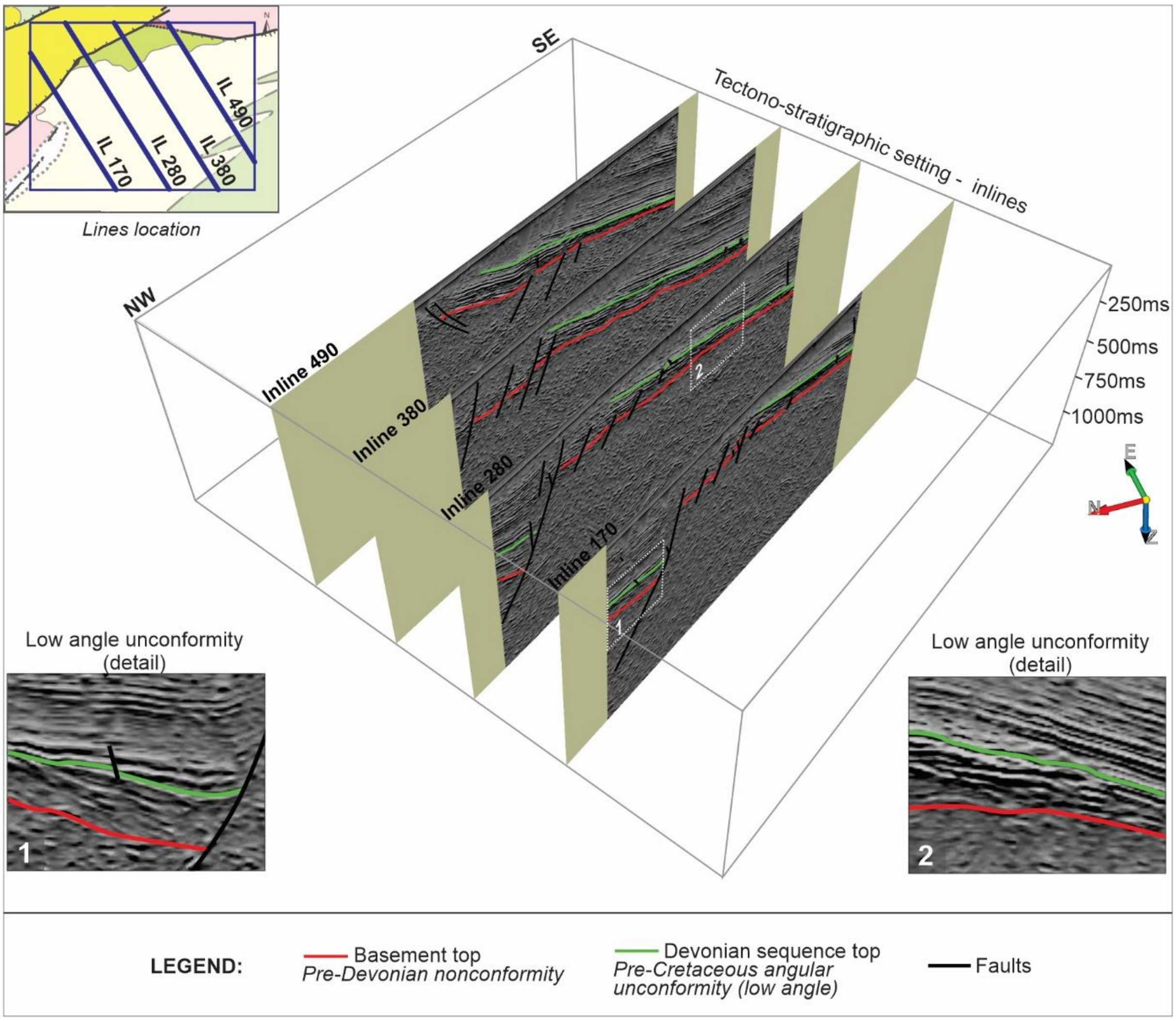


Figure 10 - Tectono-stratigraphic setting of the study area in the 3D seismic data. Observe the structural sectors of the area, as well as the geometry of the pre- and syn-rift sequences. The details in 1 and 2 highlight the low angle of the pre-Cretaceous unconformity.

The basement contact with the pre-rift sequence (Lower Devonian Sequence) outlines a pre-Devonian nonconformity. Where the pre-rift is not preserved or does not occur, the nonconformity follows the base of the Lower Cretaceous sequence (Figure 9). A pre-Cretaceous low angle angular unconformity occurs at the top of the pre-rift sequence (Figure 10).

6. Structural analysis of the seismic data

6.1 Neocomian structures

As introduced, the main structure in the area is the Melancia Fault, a normal listric fault displaying NE-SW strike and dipping to NW (Figure 10 and Figure 11). Associated with the Melancia Fault, secondary structures occur, such as second order splays and minor synthetic and antithetic faults. Synclines produced by the fault propagation effect (bending mechanism) combined with the regional tilting is a common and important feature along the whole basin.

Rotation of strata during tilting and fold growth can also produce pseudo-inverse faults (Figure 11A).

In the footwall of the Melancia Fault, secondary faults occur in the NW border of the Sousa half-graben. They are medium-sized, predominantly synthetic, and arranged in a step configuration (Figure 11B).

In the Sousa half-graben, the basement contact with the sedimentary sequences at the flexural margin is affected by second order faults striking WNW-ESE to WSW-ENE and S/SE dipping (Figure 12). At the western termination of the strike ramp, the Formigueiro Fault is a NE-striking secondary normal fault dipping to SE (Figure 13).

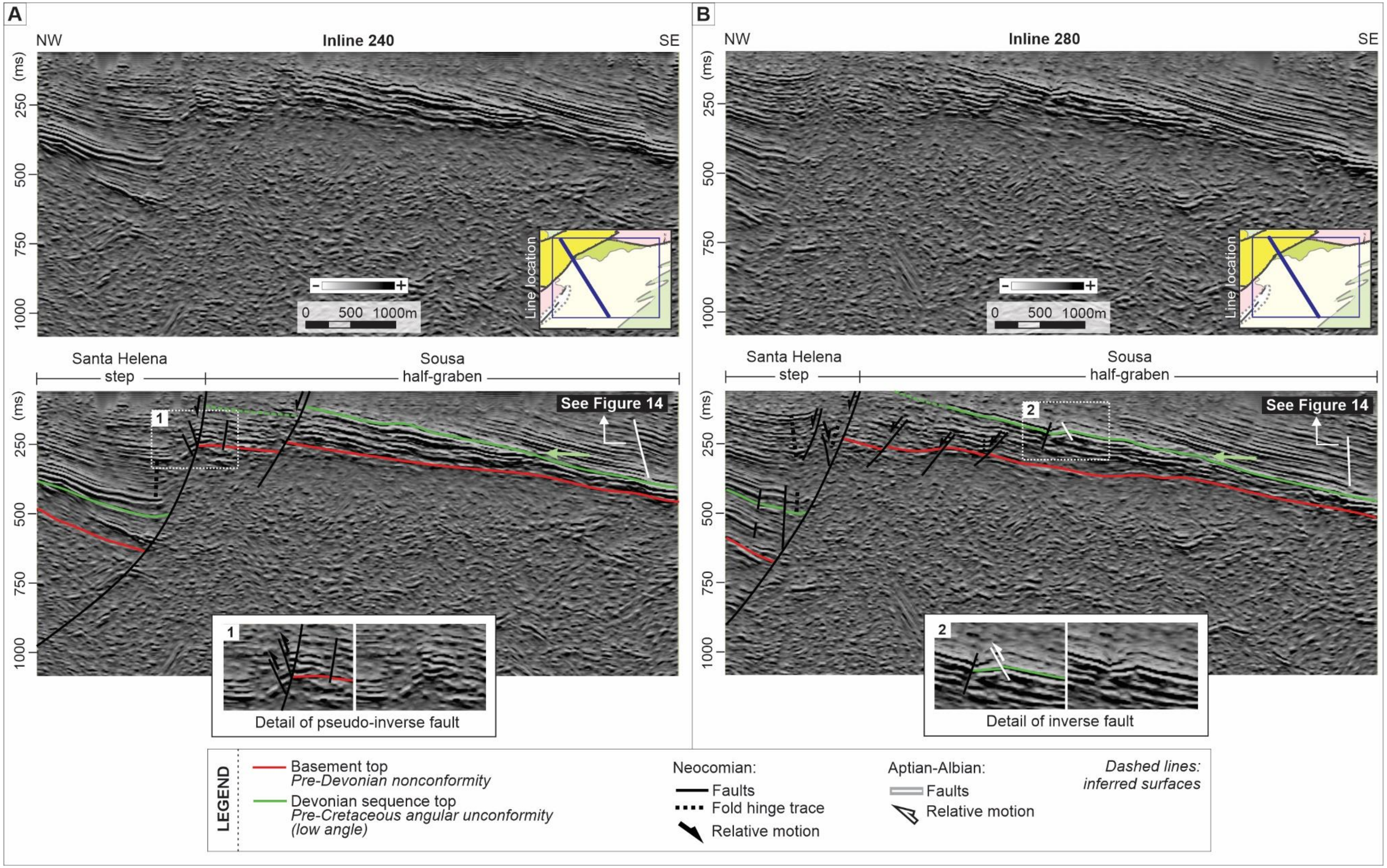


Figure 11 - Seismic structural interpretation for the 3D seismic data (uninterpreted lines at the top): inlines 240 (A) and 280 (B). Melancia Fault is the major fault of the dataset, separating the Santa Helena step from the Sousa half-graben. Associated with it, second order splays are observed and, due to strata rotation during tilting and fault propagation, pseudo-inverse faults are observed (A - detail 1). The propagation effect also generates synforms in the hangingwall close to the Melancia fault. In the footwall of this fault, a stepped-shaped structure is formed (B). Minor high angle faults are also identified. For instance, in the SE side of the two lines, there is a high angle fault which, when observed in a time slice (see Figure 14), displays a WNW-ESE strike and a dextral strike-slip component; this kinematics is not compatible with the Early Cretaceous extension and fits well in the Aptian-Albian dextral transtension along the Equatorial

Margin, further north. In B), a small fault with an inverse dip-slip component along its NE-SW inferred strike is also related to the Aptian-Albian kinematics (B - detail 2). The green arrow indicates the angular Pre-Cretaceous unconformity.

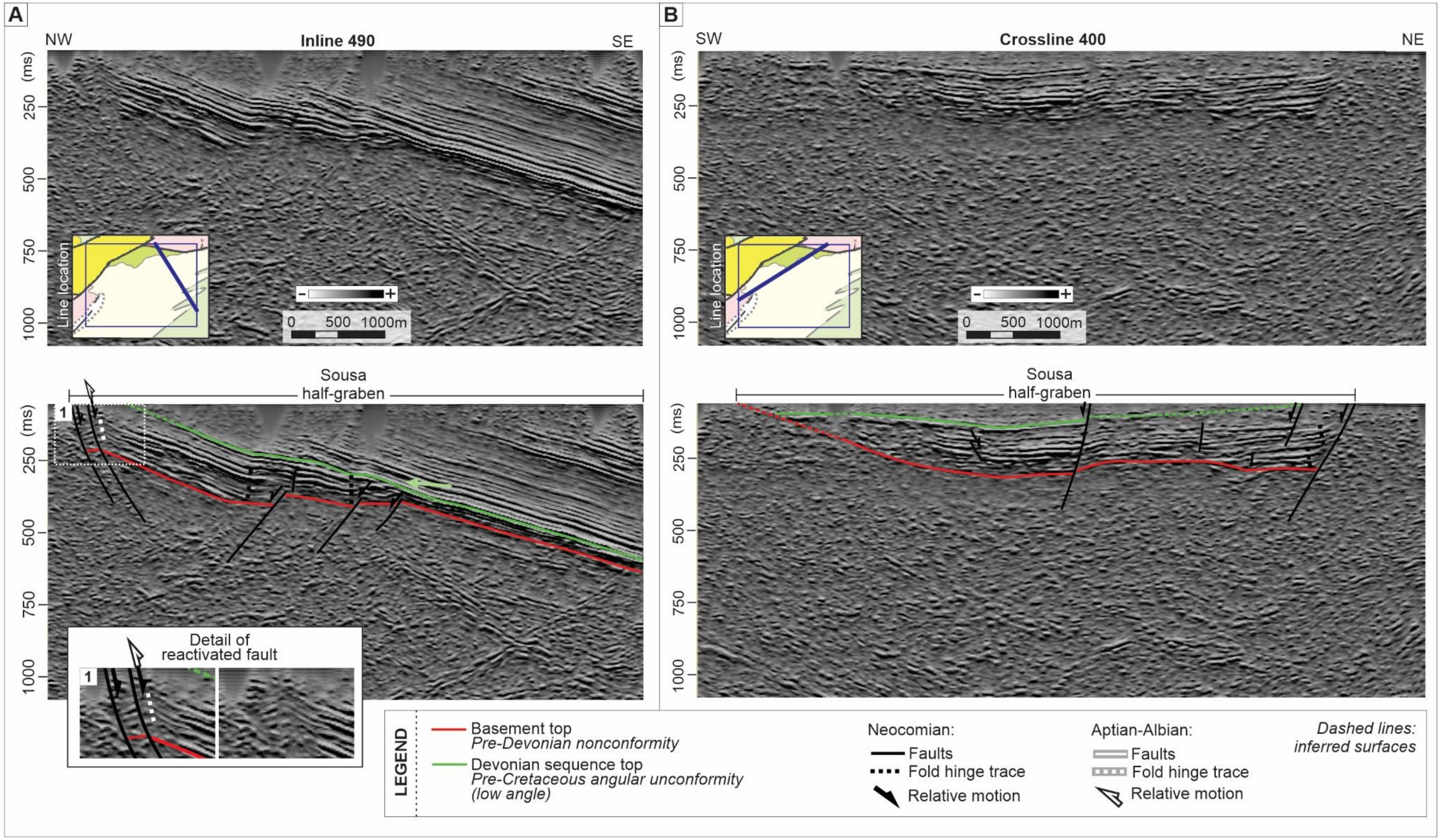


Figure 12 - Seismic structural interpretation for the 3D seismic data (uninterpreted lines at the top): inline 490 (A) and crossline 400 (B). South-dipping fault contact between the sedimentary sequences and the basement in the flexural margin of the Sousa half-graben. Both lines have synthetic and antithetic faults. Basement is down faulted and a sinistral strike-slip component is interpreted from field data, along this structure. A fault propagation anticline is observed in a normal fault, suggesting its inversion (A – detail 1). Propagation folds, in this case synclines, also occur in secondary faults. In the SW portion of the crossline 400 (B), the contact of the sedimentary package with the basement occurs by an unconformity. The green arrow in A indicates the angular character of the Pre-Cretaceous unconformity.

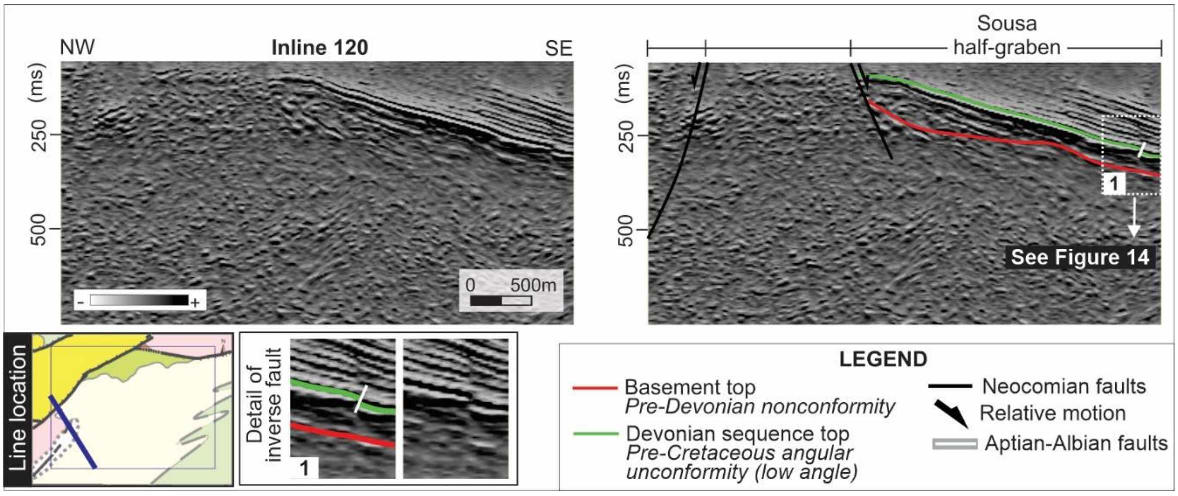


Figure 13 - Uninterpreted (left) and seismic structural interpretation (right) for the 3D seismic data: inline 120. On the northwest side is the Melancia Fault, and to the southeast is the strike ramp of the Sousa half-graben, where the basement contact with the sedimentary package is also affected by a SE-dipping second order normal fault, named as Formigueiro Fault. In the SE portion of the line there is a minor fault with an inverse component, interpreted as an Aptian-Albian structure. In time slices observation (Figure 14), this fault has a WNW-ESE strike, presenting a dextral strike-slip component not coherent with the Early Cretaceous NW extension.

High-angle faults identified in the seismic lines can be related either to a strike-slip kinematics or as normal faults rotated by tilting beds; in this latter case the rotation can also produce pseudo-inverse faults.

Most of the faults described above start from the basement, extending upwards reaching the Devonian Sequence and frequently continuing in the Cretaceous Sequence. Due to the geometric and the NW-extension kinematic setting of these faults, they are related to the Early Cretaceous (Neocomian) rifting event.

6.2 Aptian-Albian structures

Although subordinate as regards to the older ones above described, a distinct group of structures was also characterized in the seismic (as well as in field) data, with an incompatible kinematics in relation to the NW-SE Early Cretaceous extension. These structures are dispersed throughout the area, and the better examples were observed in the Sousa half-graben. Below, some of their particular characteristics are pointed:

- Small-sized high angle faults with inverse slip component (Figures 11B and 13);
- Anticlines (fault-propagation folds) associated to normal faults (Figure 12A) are indicative of positive inversion;
- In the south of the area, there is an expressive WNW-ESE oblique slip fault, with dextral strike-slip and inverse dip-slip components (Figures 14A, A1);

- Some contractional style folds display a gently plunging hinge and a steep-dipping NE-SW trending hinge surface (Figures 14B, B1, B2). These folds are better interpreted as related to a dextral strike-slip component along the WNW to E-W-trending oblique slip faults, which occur especially in the south of the study area. This strike is parallel to the fault border of the Sousa half-graben (São Gonçalo Fault).

Although these structures are not the dominant ones in our dataset, they record an episode of reactivation and inversion associated to an E-W dextral kinematics. It would be compatible to relate this younger event to the opening of the Brazilian Equatorial Margin during the Aptian-Albian time interval. This second episode can be correlated with the transtensional regime recognized (Syn-rift phase III) by Matos (1992). Clearly, this is not compatible with the normal-sinistral kinemicatics for the main E-W trending faults of the Rio do Peixe Basin. 57

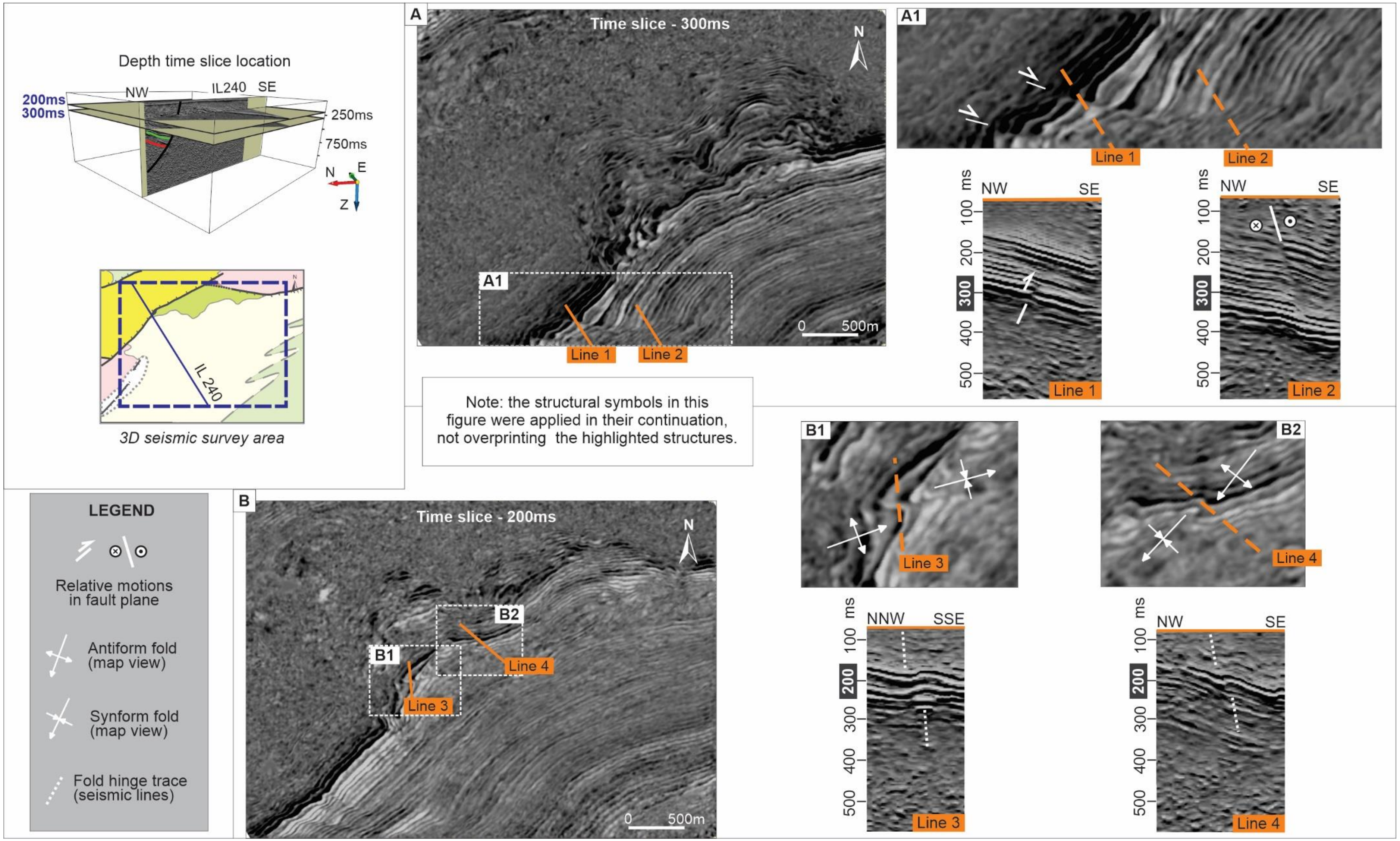


Figure 14 - Seismic structural interpretation of Aptian-Albian structures from the observation of 300ms (A) and 200ms (B) time slices. In the upper left corner of the figure is showed the coverage area of the seismic data and the time slices location (inline 240 for reference). In the southern border of the 300ms slice (A), it is observed a WNW-ESE fault with a dextral strike-slip component. In line 1 this fault shows an inverse dip-slip component and in line 2 a high dip angle (see correlation with Figures 11 and 13). In the 200ms slice (B), is showed a set of gently dipping contractional folds with NE-SW hinge traces. These folds are shown in lines 3 and 4. Note that the folds in line 4 display a faulted flank.

7. Well and seismic stratigraphic analysis

The subsurface stratigraphic study was based on the analysis of the three exploratory wells in the area (location in Figure 4 and Figure 6) and in the seismic stratigraphic interpretation of the 3D seismic data (location in Figure 4). For the Lower Cretaceous Sequence, the Santa Helena step and the Sousa half-graben were analysed separately, since they probably have moments of distinct tectono-stratigraphic evolutions during the rift event.

The two major sequences here concerned are: the Lower Devonian (pre-rift) Sequence and the Lower Cretaceous (syn-rift) Sequence, the latter recognized both in the Santa Helena step and in the Sousa half-graben. In the system tracts interpretation for the Lower Cretaceous Sequence, applying the rift sequence stratigraphy model (Kuchle & Scherer, 2010 and Alvarenga, 2016), the Pre-Cretaceous unconformity bears the connotation of a "Syn-rift Surface", meaning in this model the beginning of the rift phase.

In the seismic data, a total of 5 seismic facies was identified: parallel – seismic facies 1, parallel to subparallel – seismic facies 2, subparallel – seismic facies 3, shingled progradational – seismic facies 4, and chaotic – seismic facies 5. The characterization and description of these seismic facies are presented in Figure 15.

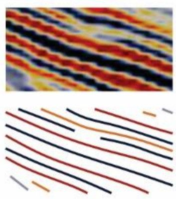
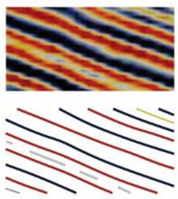
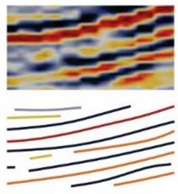
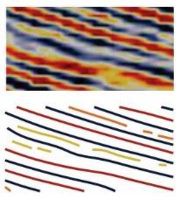
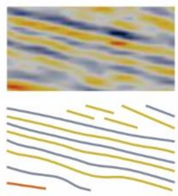
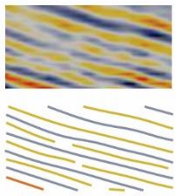
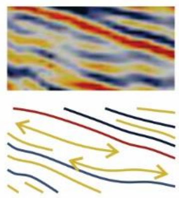
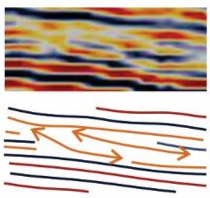
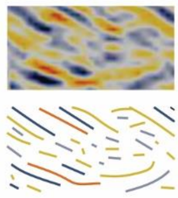
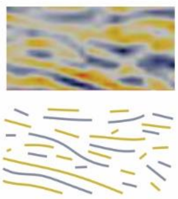
	SEISMIC EXAMPLES		DESCRIPTION AND INTERPRETATION
SEISMIC FACIES 1			**Parallel** *high continuity and amplitude* Continuous strata with systematic lithological variation, with few changes in thickness and deposited under a uniform sedimentation rate, on a stable or uniformly subsident surface. Sometimes, lenticular intercalations occur. This seismic facies is associated with low energy environments, related to alluvial plain, lacustrine or prodeltaic deposits, with a limited occurence of fluvial channels or terminal lobes.
SEIMIC FACIES 2			**Parallel to subparallel** *variable continuity and amplitude* Continuous strata, with discontinuous and sometimes lenticular levels, deposited under a uniform sedimentation rate, on a stable or uniformly subsident surface. This seismic facies is associated with alluvial plain deposits or, depending on the association, a deeper environment of the basin, with intercalations of fluvial channels or terminal lobes.
SEISMIC FACIES 3			**Subparallel** *variable continuity and low amplitude* Continuous and discontinuous strata, sometimes lenticular, deposited under a uniform sedimentation rate, on a stable or uniformly subsident surface. This seismic facies is associated with alluvial fans and braided fluvial deposits, identified for the Lower Cretaceous Sequence.
SEISMIC FACIES 4			**Shingled Progradational** Prograding strata in shallow water depths, under a low accommodation rate, related to the arrival of fluvio-deltaic deposits. In seismic, it is identified by toplap and downlap terminations, the latter indicating a component of the progradation direction. In the examples, there are progradation towards the right (in tilted strata) and the left .
SEISMIC FACIES 5			**Chaotic** Irregular and discontinuous arrangement of reflectors, usually with low amplitude. They indicate landslide processes and gravitational flows, associated with the front of alluvial fans or deltas.

Figure 15 - Examples, descriptions and interpretations for the seismic facies identified in this study. The location of the examples used are shown in Figures 18 to 21.

7.1 Lower Devonian Sequence

Three stratigraphic units were identified for the Lower Devonian Sequence, named D1, D2 and D3. This sequence has an external basin fill geometry, with the basement top displaying features of erosional troughs (Figure 16). The well data is the most consistent for delimitation of these stratigraphic units, which when tied in the seismic, allowed a better seismic stratigraphic characterization. A particular feature observed in the wells is that the Devonian units sometimes exhibit lithotypes with a considerable mica and pyrite content, corroborating the outcrop observations.

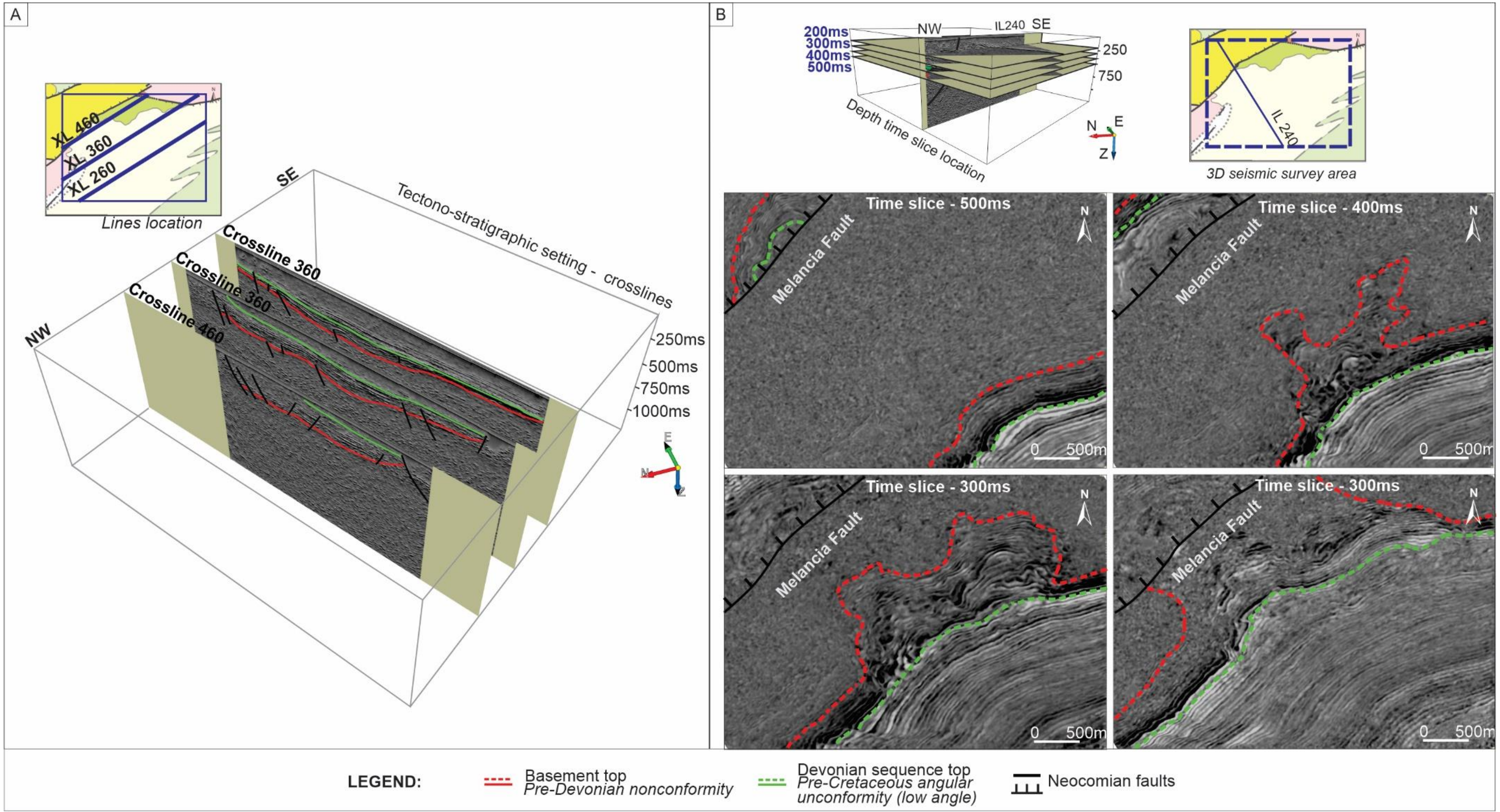


Figure 16 - Basin fill external geometry of the Lower Devonian Sequence by a crossline view (A) and in time slices view (B, at different depths). Observe in B the contrast between the geometries of the pre- and syn-rift sequences; note in the southern border of the time slices the WNW-ESE fault with dextral strike-slip component, presented in figure 14. The images at the top illustrate the area covered by the seismic data and the location of the lines and time slices. In this last one, the inline 240 is used as reference.

It is worth mentioning that the well data are an important reference for the interpretation of the basement top, because in the seismic data this limit is not always clear. Another point to consider is that the Lower Devonian Sequence is significantly affected by faults interpreted as of Neocomian age and related to the rift event (Topic 6.1).

7.1.1 D1 and D2 Units

The D1 unit in the Pilões well has a symmetrical gamma ray trend, characterized by sedimentary breccias, conglomerates and sandstones, with interbedded siltstones (Figure 17A). In the Triunfo well, this unit has at the base a thin (just a few meters thick) conglomerate, followed by shales, displaying an irregular and symmetrical gamma ray trends (Figure 17C). In the Santa Helena well there is also a basal conglomerate interval, followed by shales, with a dirtyning-up gamma ray profile (Figure 17B).

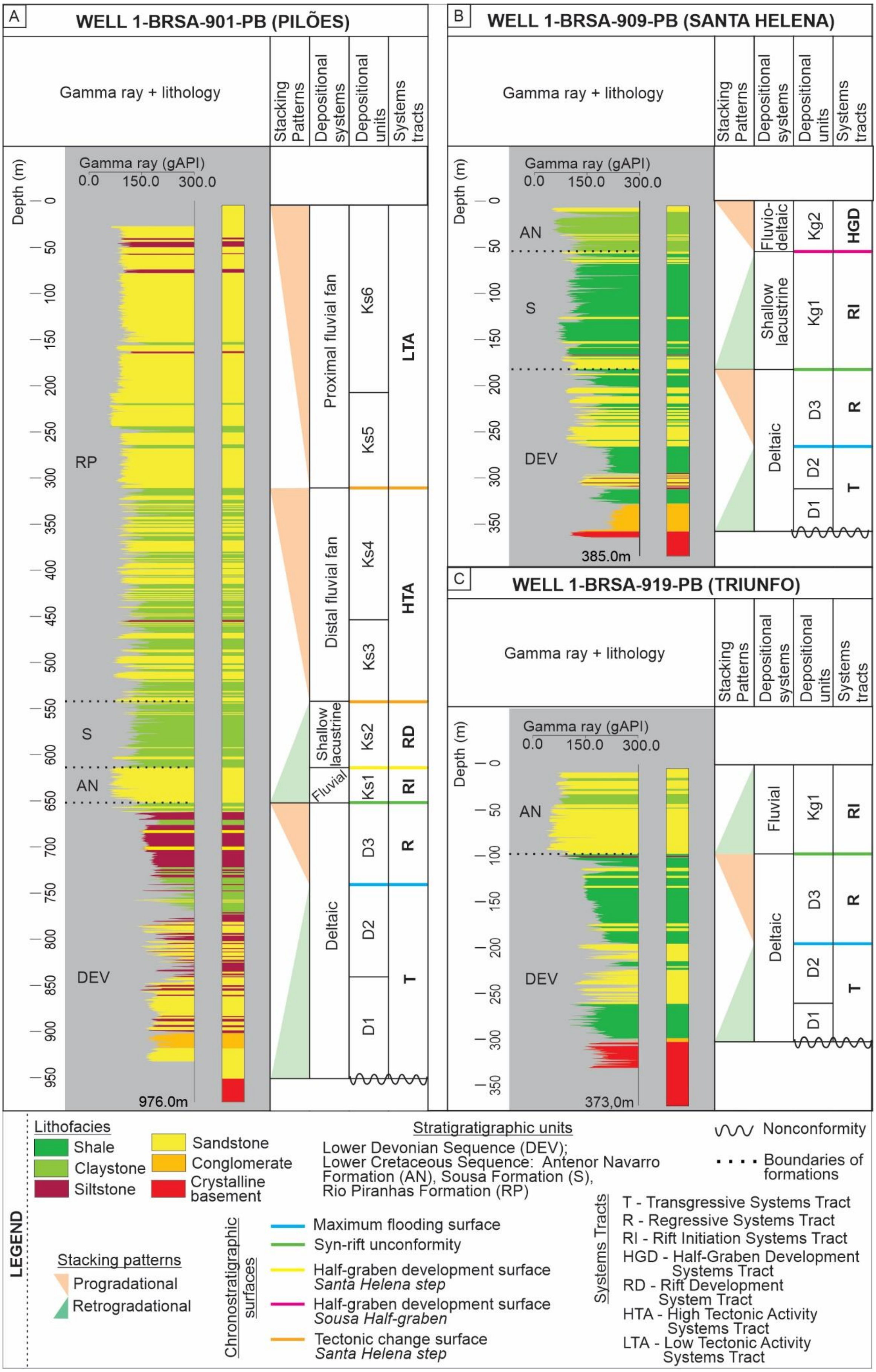

A
WELL 1-BRSA-901-PB (PILÕES)
Gamma ray + lithology
Stacking Patterns
Depositional systems
Depositional units
Systems tracts
Depth (m)
Gamma ray (gAPI)
0.0 150.0 300.0
RP
S
AN
DEV
976.0m
Proximal fluvial fan
Distal fluvial fan
Shallow lacustrine
Fluvial
Deltaic
Ks6
Ks5
Ks4
Ks3
Ks2
Ks1
D3
D2
D1
LTA
HTA
RD
RI
R
T
B
WELL 1-BRSA-909-PB (SANTA HELENA)
Fluvio-deltaic
Shallow lacustrine
Deltaic
Kg2
Kg1
HGD
385.0m
C
WELL 1-BRSA-919-PB (TRIUNFO)
Fluvial
Kg1
373,0m
LEGEND
Lithofacies
Shale
Claystone
Siltstone
Sandstone
Conglomerate
Crystalline basement
Stratigratigraphic units
Lower Devonian Sequence (DEV);
Lower Cretaceous Sequence: Antenor Navarro Formation (AN), Sousa Formation (S), Rio Piranhas Formation (RP)
Nonconformity
Boundaries of formations
Stacking patterns
Progradational
Retrogradational
Chronostratigraphic surfaces
Maximum flooding surface
Syn-rift unconformity
Half-graben development surface Santa Helena step
Half-graben development surface Sousa Half-graben
Tectonic change surface Santa Helena step
Systems Tracts
T - Transgressive Systems Tract
R - Regressive Systems Tract
RI - Rift Initiation Systems Tract
HGD - Half-Graben Development Systems Tract
RD - Rift Development System Tract
HTA - High Tectonic Activity Systems Tract
LTA - Low Tectonic Activity Systems Tract

Figure 17 - Well analysis (see well location in Figures 4 and 6) using gamma ray log associated with lithology. The following interpretations are shown: stacking patterns, depositional systems, depositional units, stratigraphic surfaces and systems tracts. This analysis was carried out for the Lower Devonian Sequence (in the three wells) and for the Lower Cretaceous Sequence of the Santa Helena **S**tep (Pilões well) and the Sousa half-graben (Triunfo and Santa Helena wells). The well to seismic ties is presented in Figures 18, 19 and 21.

In contrast to D1, the D2 unit exhibits in the Pilões well a very irregular gamma ray trend, reaching its maximum values (exceeding the profile scale), characterized by intercalated sandstones and siltstones (Figure 17A). In the Triunfo well, this unit also has an irregular gamma ray trend, showing sandstones with a mudstone level (Figure 17C). In the Santa Helena well the gamma ray is less irregular than in the others, with intercalated sandstones and siltstones, and shales at the top (Figure 17B). In all wells, a carbonaceous content is recorded to the unit D2.

In seismic data (Figures 18, 19, 20 and 21), D1 and D2 have similar seismic facies. In the west portion of the data, chaotic seismic facies (seismic facies 5) dominates, with some few non-systematic lateral variations of parallel and parallel to subparallel seismic facies (seismic facies 1 and 2). These two are more common in the eastern portion of the data. Shingled progradational seismic facies (seismic facies 4) also occur, very dispersed, indicating a progradation component to NW. Compared with D1, chaotic seismic facies is less frequent in D2. In D1 and D2, the presence of mound-shaped internal geometry was verified (Figure 22).

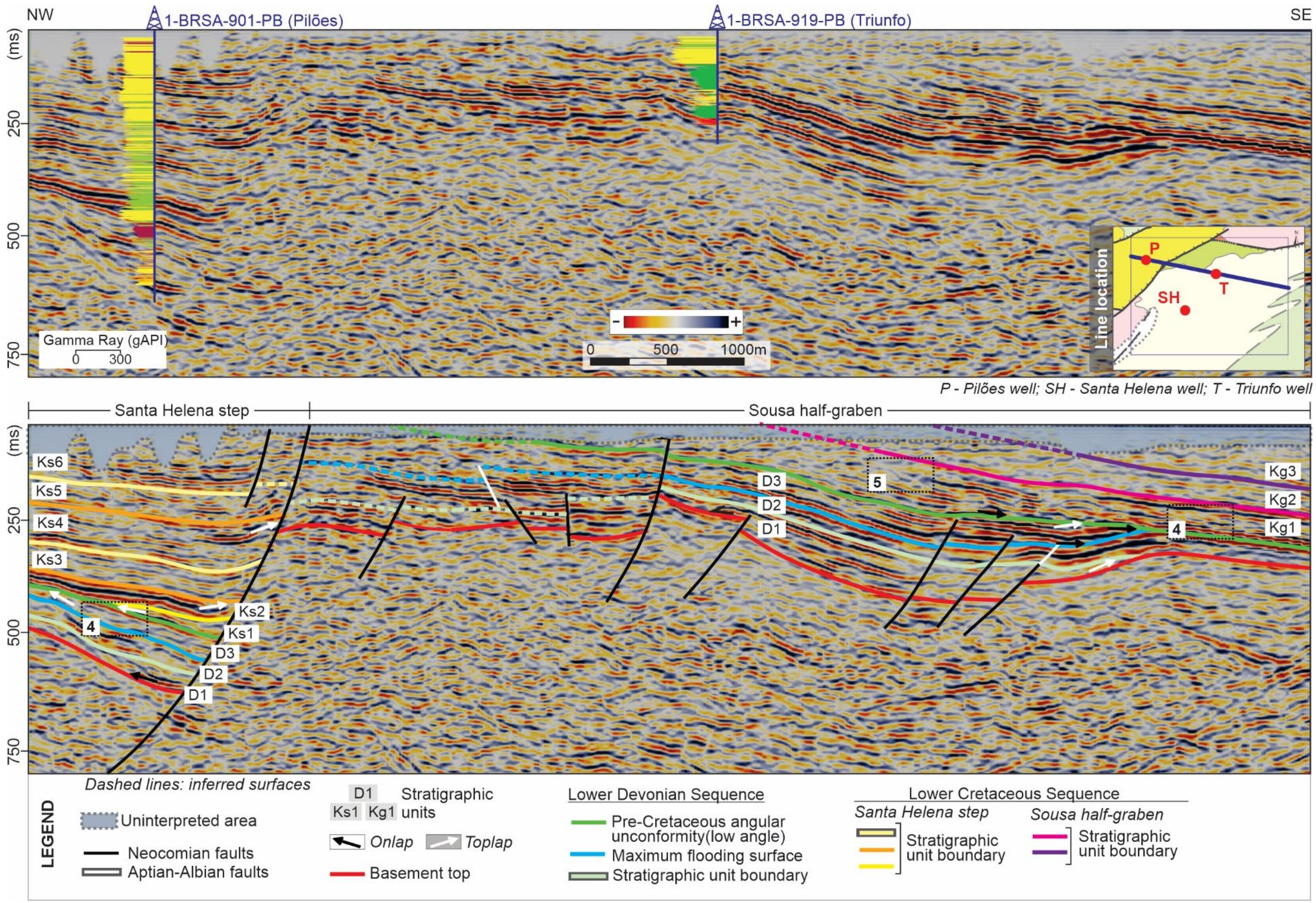


Figure 18 - Seismic stratigraphic interpretation: line passing through the Pilões and Triunfo wells (Pilões-Triunfo line). In the upper image, the well to seismic tie is displayed in a uninterpreted line. Stratigraphic units and stratigraphic surfaces (chronostratigraphic) are presented for the Lower Devonian Sequence and for the Lower Cretaceous Sequence of the Santa Helena Step and Sousa half-graben. The examples used in Figure 17 for shingled progradational seismic facies (4) and chaotic seismic facies (5) are indicated.

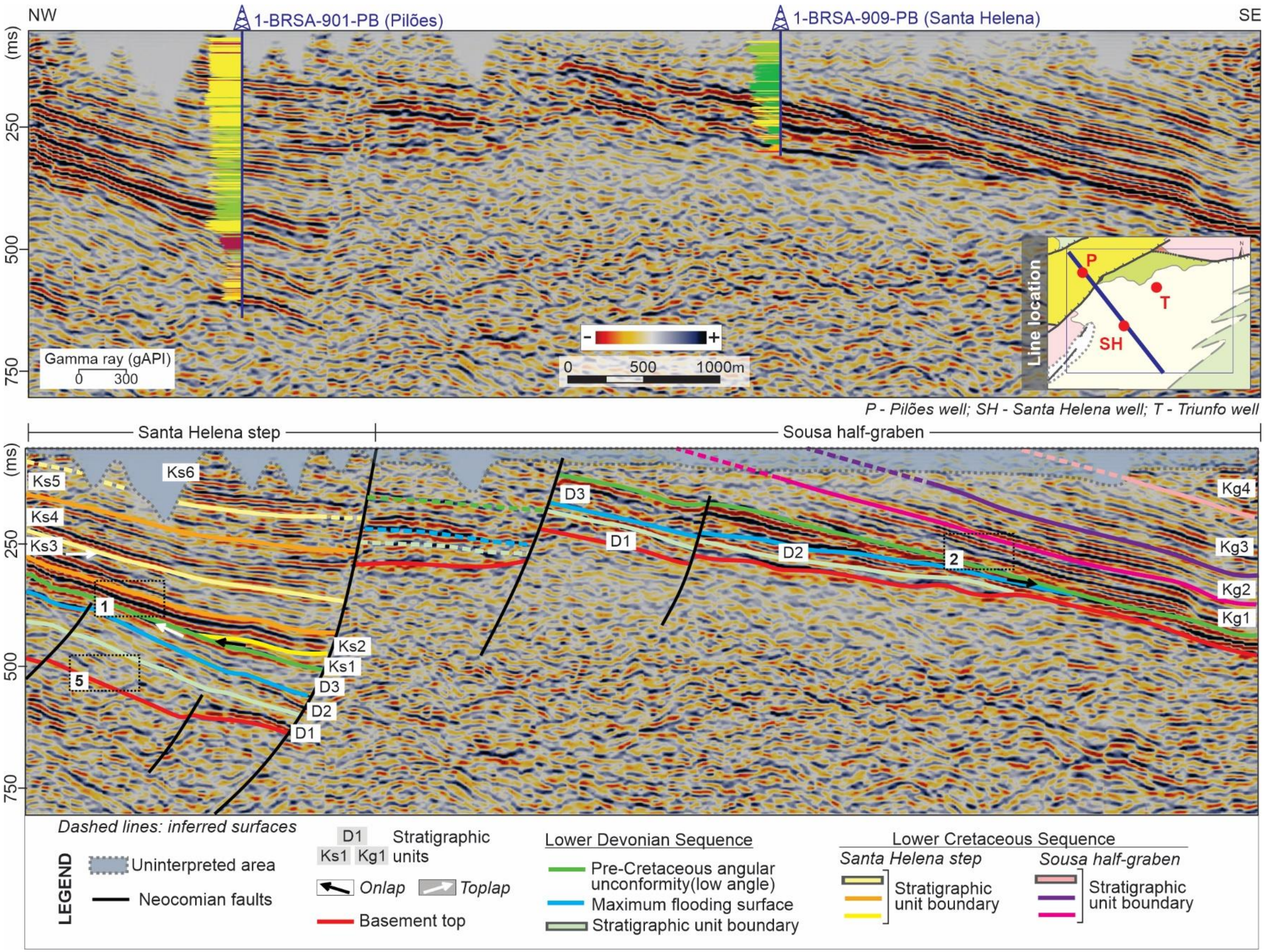


Figure 19 - Seismic stratigraphic interpretation: line passing through the Pilões and Santa Helena wells (Pilões-Santa Helena line). In the upper image, the well to seismic tie is displayed in a uninterpreted line. Stratigraphic units and stratigraphic surfaces (chronostratigraphic) are presented for the Lower Devonian Sequence and for the Lower Cretaceous Sequence of the Santa Helena Step and Sousa half-graben. The examples used in Figure 17 for parallel seismic facies (1), parallel to subparallel seismic facies (2) and chaotic seismic facies (5) are indicated.

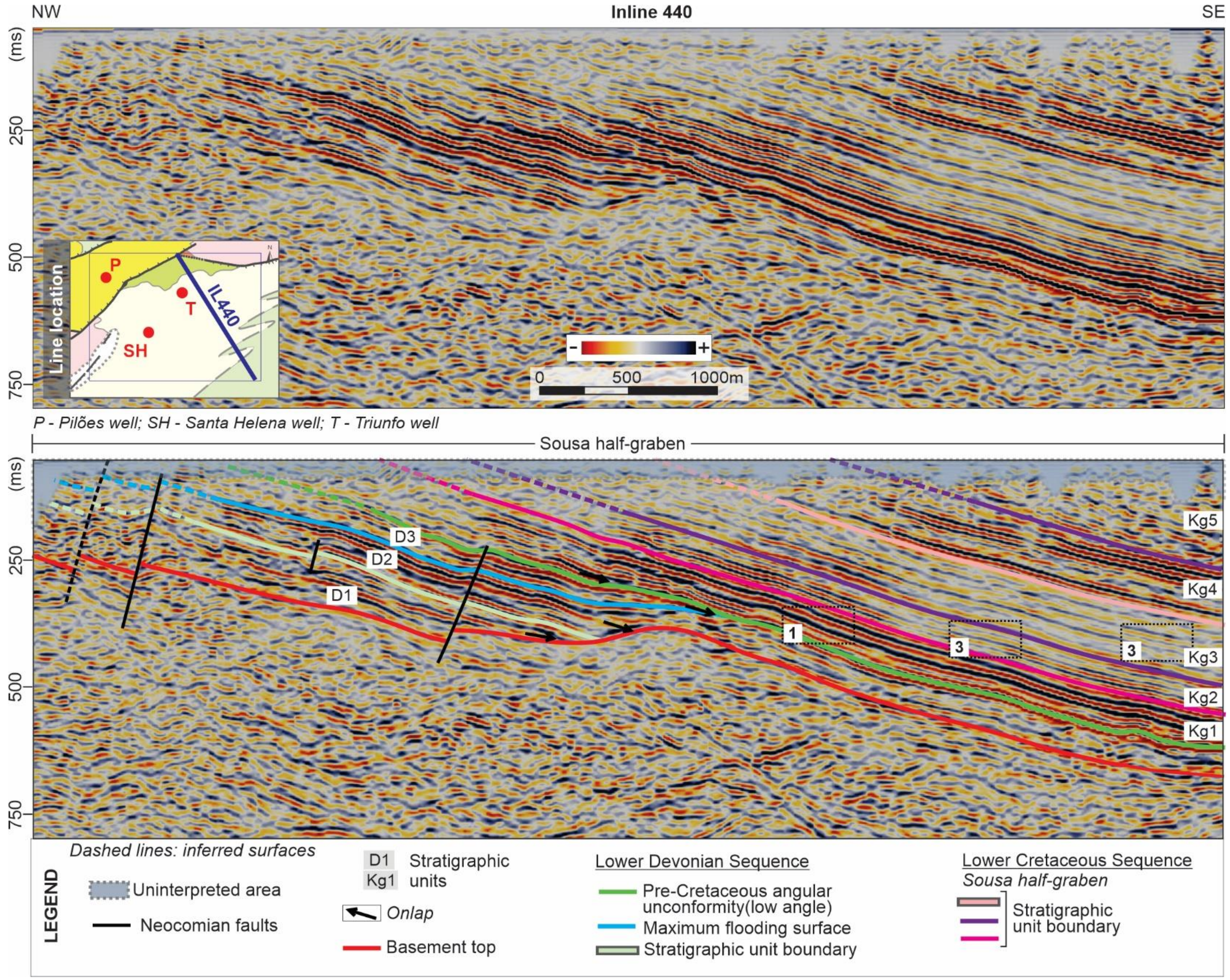


Figure 20 - Seismic stratigraphic interpretation: inline 440. In the upper image an uninterpreted line is displayed. Stratigraphic units and stratigraphic surfaces (chronostratigraphic) are presented for the Lower Devonian Sequence and for the Lower Cretaceous Sequence of the Sousa half-graben. The stratigraphic units of this sequence are best seen in this section, since the half-graben exhibits the highest sedimentary thicknesses. The examples used in Figure 17 for parallel seismic facies (1) and subparallel seismic facies (3) are indicated.

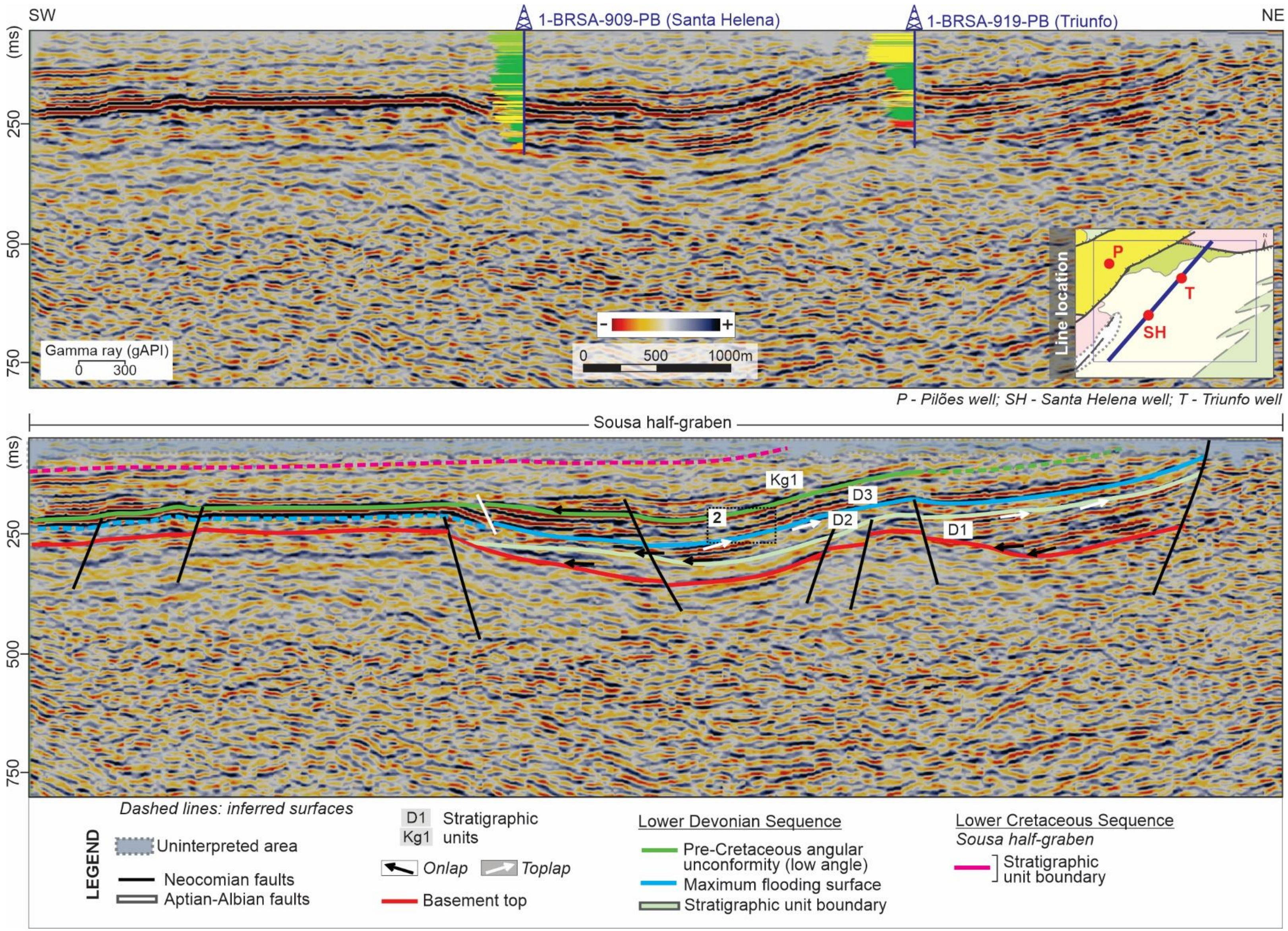


Figure 21 - Seismic stratigraphic interpretation: line passing through the Santa Helena and Triunfo wells (Santa Helena-Triunfo line). In the upper image, the well to seismic tie is displayed in a uninterpreted line. Stratigraphic units and stratigraphic surfaces (chronostratigraphic) are presented for the Lower Devonian Sequence and for the Lower Cretaceous Sequences of the Sousa half-graben (only Kg1). The examples used in Figure 17 for parallel to subparallel seismic facies (2) are indicated

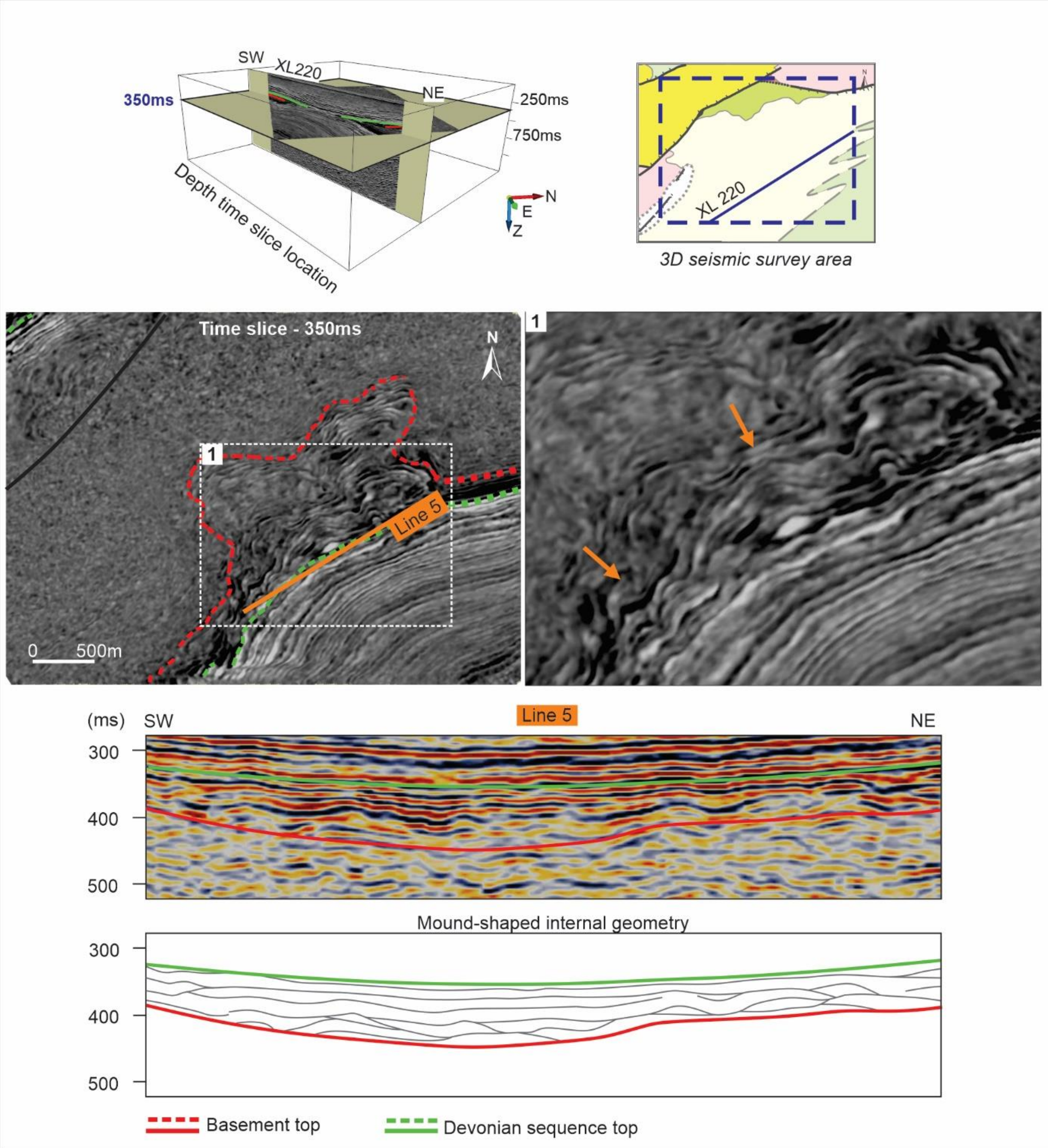


Figure 22 - Internal mound-shaped geometry for the Lower Devonian basal units (D1 and D2). In the 350ms slice are exemplified curvilinear features (semicircles) in map view, highlighted in 1 and indicated by arrows. In line 5, which cuts across these features, a mound-shaped internal geometry is verified and related with coalescent lobes. The images at the top show the coverage area of the seismic data and the location of the time slice level, using the crossline 220 as reference.

7.1.2 D3 Unit

In the Pilões well, D3 unit is predominately composed by siltstones, interbedded with sandstones and presenting claystones at the base and top. The gamma ray profile exhibits a smooth cleaning up trend, which at the top becomes more prominent (Figure 17A). In the Triunfo well, shales predominate, with sandstones intercalated, exhibiting the same gamma ray pattern (Figure 17C). In the Santa Helena well, dominate sandstones, with shales intercalated, exhibiting an irregular gamma ray trend which shows at the top a cleaning up trend (Figure 17B).

The D3 unit is differentiated in the seismic data from the previous units because it has a higher volume of parallel and parallel to subparallel seismic facies (seismic facies 1 and 2). As in the other units, progradational shingled seismic facies (seismic facies 4) occur with NW progradation component. Chaotic seismic facies (seismic facies 5) are also observed (Figures 18, 19, 20 and 21).

7.1.3 Systems tracts

In D1 unit, the occurrence of debris flow in an underwater environment is interpreted, where mound-shaped internal geometry is consistent with delta-front lobes. In D2, the spikes in the gamma-ray and the carbonaceous content indicate a base-level rise, suggesting a transition from the deltaic front to prodeltaic deposits. High frequency systematic lithological intercalations are related to turbiditic flows. It is noticed that the lithofaciological characteristics observed in the Pilões well, and the seismic facies of its surroundings are more proximal when compared to the other wells.

From these observations, D1 and D2 units configure the Transgressive Systems Tract, where the upper limit of D2 unit represents the Maximum Flooding Surface (Figure 23).

After the maximum flooding, D3 unit is interpreted as a shallow underwater deposit of a delta plain, presenting an increase in depositional energy to the top. Thus, there is a regressive phase, in which the D3 unit represents the Regressive Systems Tract (Figure 23).

7.1.4 Discussions

The Lower Devonian Sequence described in this work corresponds, in litostratigraphic terms, only to the Pilões Formation, as defined by Silva et al. (2014), in which deltaic facies and the occurrence of a transgression and regression episodes were also recognized by those authors. It is worth mentioning that Roesner et al. (2011) characterizes for this interval a marine influence with a strong influx of continental waters, in transitional to coastal marine environment.

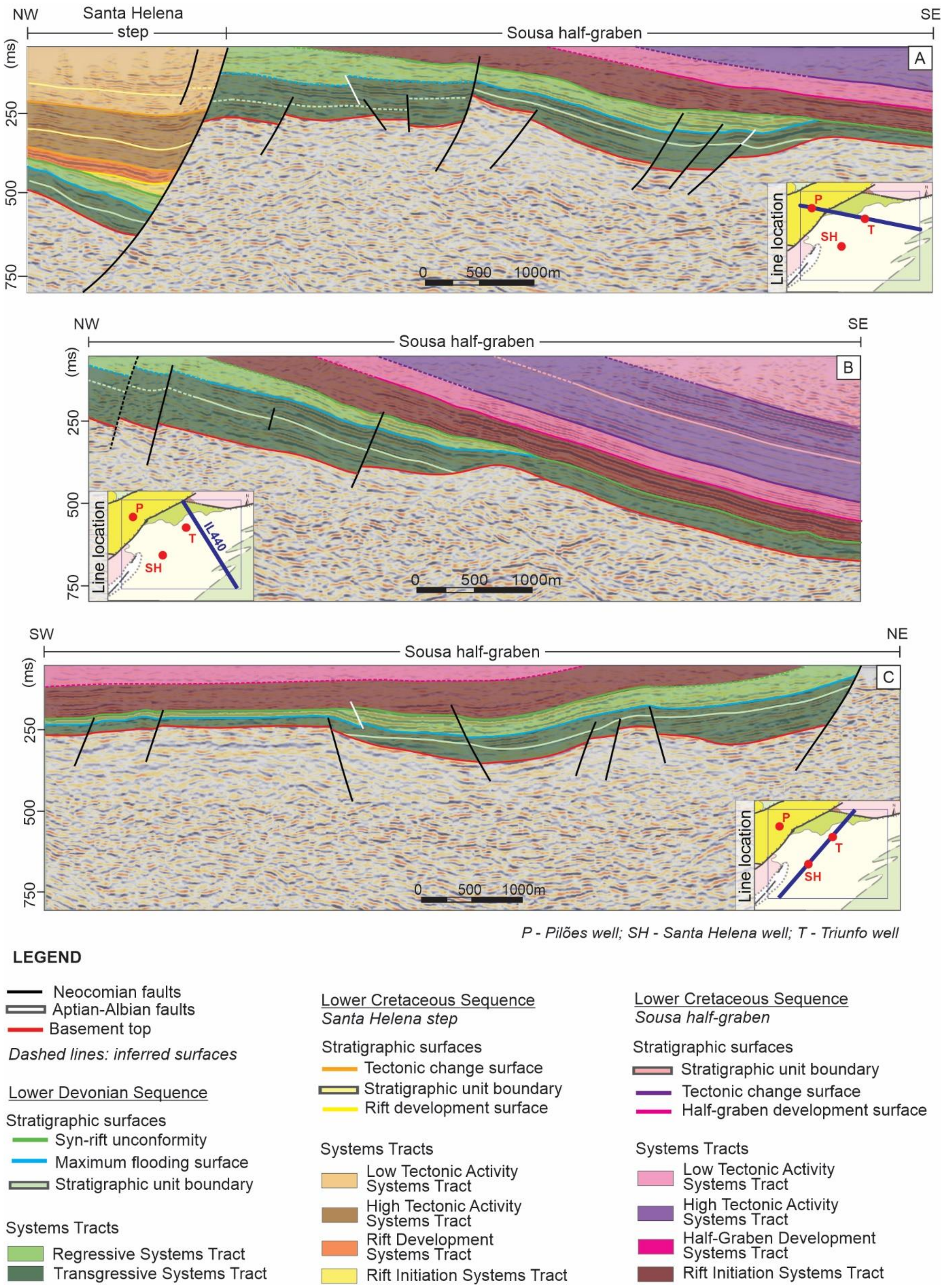


Figure 23 - Lower Devonian and Lower Cretaceous Systems Tracts distribution in the 3D seismic data, exemplified in the Pilões-Triunfo line (A), inline 440 (B) and Santa Helena-Triunfo line (C). Stratigraphic surfaces interpretations are presented for the Lower Devonian Sequence and for the Lower Cretaceous Sequence (Santa Helena step and Sousa half-graben).

In this paper, the Triunfo Formation, proposed by Silva et al. (2014), is not accepted as the upper part of the Devonian Sequence, but rather to the lower part of the Antenor Navarro Formation, that immediately overlies the Pilões Formation. Besides data from field mapping, this interpretation considers its typical distributary fluvial lithofacies and its seismic stratigraphic pattern, which clearly place it at the basal interval of the Lower Cretaceous Sequence.

In this way, the term Santa Helena Group is not sustainable as it would be composed by only one formation. Therefore, our suggestion at this moment is to keep the term Lower Devonian Sequence or, alternatively, to consider just the Pilões Formation as the lithostratigraphic expression of this sequence.

In Northeast Brazil, the Devonian record of largest geographical expression and geographically closer to the Rio do Peixe Basin occurs in the Parnaíba Basin (Vaz *et al*., 2007; Figure 1, Figure 2 and Figure 24). Roesner et al. (2011) suggests that the Lower Devonian Sequence of the Rio do Peixe Basin is potentially chronocorrelated with the upper part of the Jaicós Formation and possibly the lower part of the Itaim Formation of the Parnaíba Basin.

In Northern Brazil there are other Lower Devonian strata chronocorrelated with the Rio do Peixe basin (Figure 24), as the upper part of the Jutaí Formation, in the Solimões Basin (Grahn et al., 2003; Rubinstein et al., 2005; Filho et al., 2007), and the Manacapuru Formation and the lower part of the Jatapu Formation (Grupo Trombetas) in the Amazonas Basin (Azevedo-Soares & Grahn, 2005; Cunha et al., 2007).

In the northern Tucano and Jatobá basins (Figure 24), southern of the Rio do Peixe Basin, a Siluro-Devonian Sequence is estimated, correlated with the Parnaíba Basin, in which the upper part of the Tacaratu Formation is also chronocorrelative intervals in NE Brazil (Costa et al., 2007; Carvalho et al., 2018).

Despite the chronocorrelated examples mentioned above, in the light of current knowledge, we consider a need for a better Early Devonian paleobiogeographic characterization of this region, which is important for the correlations between these basins. In this work, it was decided not do a correlation based on the comparison of depositional systems, since they are susceptible to local variations within the same regional context.

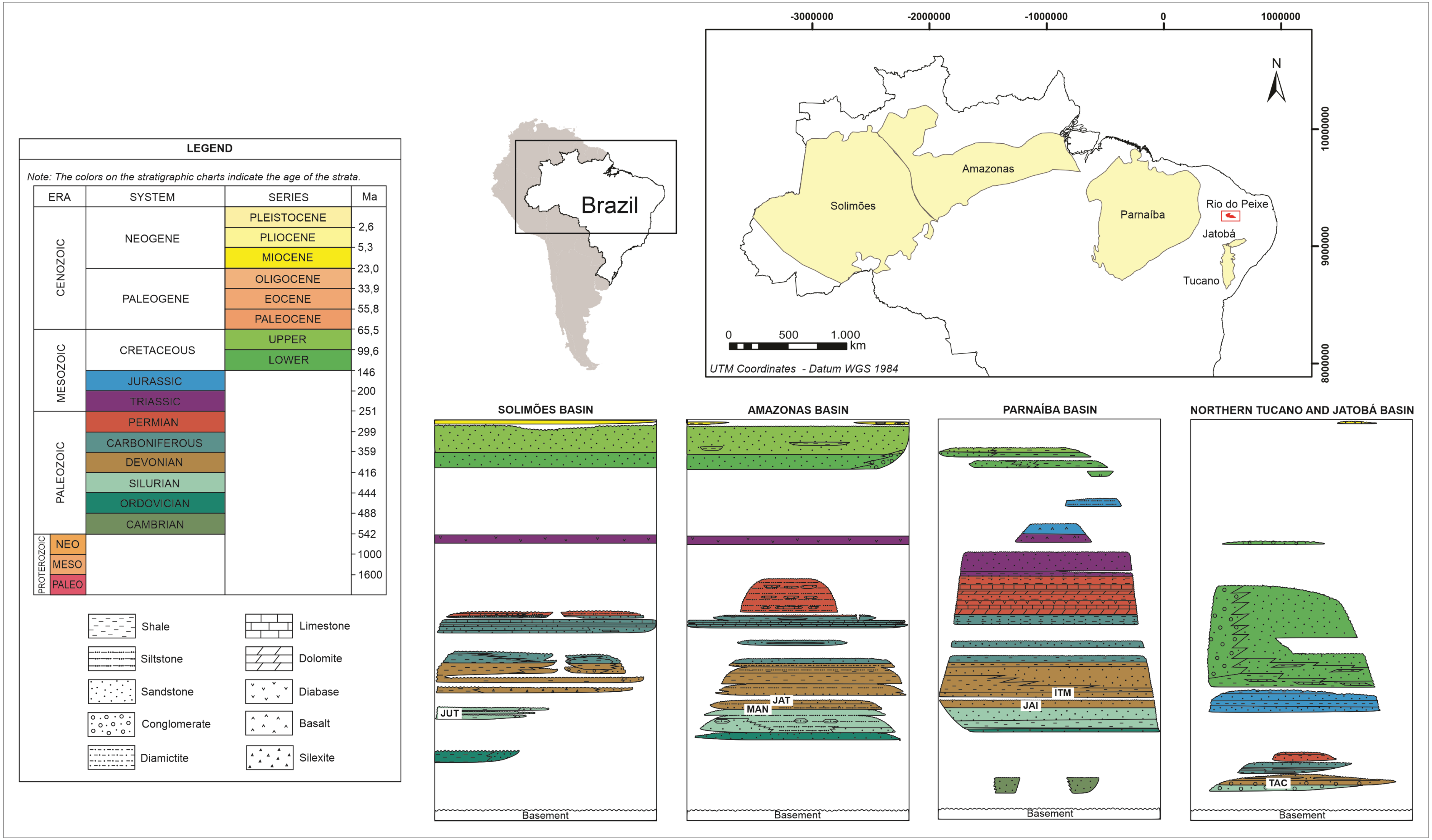


Figure 24 - North and Northeast brazilian sedimentary basins with Early Devonian deposition and their simplified stratigraphic charts (Milani et al, 2007). Possible chronocorrelated Siluro-Devonian formations with the Rio do Peixe basin are indicated: JUT – Jutaí, MAN – Manacapuru, JAT – Jatapu, JAI – Jaicós, ITM – Itaim, TAC -Tacaratu.

7.2 Lower Cretaceous Sequence – Santa Helena step

In the Lower Cretaceous Sequence of the Santa Helena step, 6 stratigraphic units were identified, named as Ks1 to Ks6. Subsurface lithostratigraphy is registered only in the Pilões well, thus being the only one to be described for these units. In the seismic data, with the exception of Ks1, these units exhibit a smooth wedge-shaped external geometry, delimited by changes in the characteristics of reflectors and their terminations.

7.2.1 Ks1 unit

The Ks1 unit is represented in the well by a sandstone interval, with a cylindrical gamma ray trend (Figure 17A). This unit exhibits parallel to subparallel seismic facies (seismic facies 2) and a wedge-shaped external geometry (Figures 18 and 19). This thin wedge occurs restricted to the vicinity of the Melancia Fault.

7.2.2 Ks2 unit

This unit corresponds to an interval with an irregular gamma ray trend, where claystone dominates, being interdigitated with some sandstone levels (Figure 17A). Parallel seismic facies predominate in it (seismic facies 1; Figures 18 and 19).

7.2.3 Ks3 and Ks4 units

In Ks3 unit, an irregular gamma ray trend occurs, showing intercalated mudstones and sandstones. The Ks4 unit is similar, but with an increase in the amount of sandstone intercalations (Figure 17A). The Ks3 and Ks4 units exhibit parallel, parallel to subparallel and subparallel seismic facies (seismic facies 1, 2 and 3), in which the first is less frequent. In Ks4 the reflectors generally have higher amplitudes when compared to Ks3. In the vicinity of the Melancia Fault, some chaotic seismic facies (seismic facies 5) are observed. Shingled progradational seismic facies (seismic facies 4) occurs in some localities, with a NW progradational component, thus originated from the main fault (Figures 18 and 19).

7.2.3 Ks5 and Ks6 units

In the Ks5 and Ks6 units sandstone predominate, intercalated with some levels of mudstones and siltstones, displaying a cylindrical gamma ray trend (Figure 17A). In seismic data (Figures 18 and 19), parallel to subparallel (seismic facies 2) and chaotic seismic facies (seismic facies 5) are observed. Shingled progradational seismic facies (seismic facies 4) locally occur, with a flow component towards SE, to the main fault.

7.2.4 Systems tracts

In the Santa Helena step, the concepts of tectonic systems tracts, originally designed for half-graben (Kuchle and Scherer, 2010), were adapted for a step-shapped compartment. The Melancia Fault was considered as the main fault of this domain and the terms “Half-graben Development Systems Tract” and “Half-graben Development Surface” were renamed to “Rift Development Systems Tract” and “Rift Development Surface”.

The Ks1 unit is interpreted as the Rift Initiation Systems Tract (Figure 23A). In this tract a wide fluvial system (Antenor Navarro Formation) occurred in the whole basin, related to the initial crustal stretching (Córdoba et al., 2008). In the region of the Santa Helena Step, a minor part of this system is preserved.

The Ks2 unit comprises the Rift Development Systems Tract, separated from the previous tract by the Rift Development Surface (Figure 23A). In this tract an initial step geometry was developed, where a shallow lake system is characterized (Sousa Formation), without the development of alluvial fans.

Above the Ks2 there is a Tectonic Change Surface, in which sequences Ks3 and Ks4 correspond to the High Tectonic Activity Systems Tract (Figure 23A). In this tract there is a relative increase in tectonic activity in the step and, consequently, a relative increase in the accommodation space. It appears that the relief contrast was not high enough to generate expressive clastic wedges in the border fault. Thus, a distal fluvial fan system is characterized, with braided fluvial channels (Rio Piranhas Formation) and terminal lobes in alluvial plains and/or lakes relatively deeper (Sousa Formation), with sedimentary input from the Melancia Fault.

The Ks5 and Ks6 units correspond to the Low Tectonic Activity Systems Tract (Figure 23A), with another Tectonic Changing Surface at its base. In this tract, there is a relative decrease in tectonic activity and thus, more limited creation of accommodation space and sedimentary input. A proximal fluvial fan system (Rio Piranhas Formation) is interpreted, starting from the border fault, with braided fluvial channels and alluvial plains.

7.2.4 Discussion

In the eastern portion of Santa Helena step, is identified that a restricted wedge of the Antenor Navarro Formation occurs in subsurface, overlying the Devonian Sequence and followed by the interdigitated, Sousa and Rio Piranhas formations. This relation is in accordance with the descriptions of Córdoba et al. (2008). In the study area, the Rio Piranhas Formation predominates both in subsurface and outcrops.

The alluvial fans mentioned above, for the Santa Helena step, are classified as fluvial fans. Theorical aspects for this type of classification are presented by Assine (2008). In the wells and in the seismic data, evidence of gravity flows is not common, unlike what is expected for high scarpments in border faults of half-grabens. The existence of an arid to semi-arid paleoclimate (Lima Filho, 1991) also supports the occurrence of fluvial fans, with a reduction in water recharge.

The tectono-stratigraphic characterization presented for the Santa Helena step contributes to its better understanding, so far not much explored. However, the regional evolutionary understanding of this region still deserves further studies.

7.3 Lower Cretaceous Sequence – Sousa half-graben

For the Lower Cretaceous Sequence of the Sousa half-graben, 5 stratigraphic units were identified, named as Kg1 to Kg5. In this sector, the lithostratigraphic subsurface characterization was obtained from the Triunfo and Santa Helena wells. These wells are not located in the deeper basement compartments, so they do not include all the sequences recognized in the seismic data.

In the scale of this study, concerning the seismic data, the stratigraphic units present a sheet-shaped external geometry. In general, for each unit, there is a predominance of one seismic facies. Their limits are marked by changes in the characteristics of the reflectors, and also by their terminations. In the seismic stratigraphic analysis, previous interpretations of 2D regional seismic lines, which include the entire half-graben, were also considered (Córdoba et al., 2008; Pichel, 2014; Souza, 2016).

7.3.1 Kg1 unit

The Kg1 unit consists of the only Cretaceous interval recorded in the Triunfo well. It is characterized by sandstones and, at the top, claystones intercalated, exhibiting a cylindrical gamma ray trend (Figure 17C). In the Santa Helena well shales predominate, with subordinate sandstone levels. The gamma ray displays a cylindrical trend at the base, which becomes more irregular towards the top (Figure 17B).

In the seismic data (Figures 18, 19, 20 and 21), parallel seismic facies (seismic facies 1) predominates, also presenting a parallel to subparallel seismic facies (seismic facies 2). On the half-graben boundaries, where the basement top is shallower, occur a decrease in the continuity of the reflectors, displaying a transition to chaotic seismofacies (seismofacies 5). At the base of the unit, shingled progradational seismic facies (seismic facies 4) with a progradation component for SE are also observed.

7.3.2 Kg2 unit

Only the Santa Helena well registers the Kg2 unit, being the last record of this well. The interval is characterized by claystones, with some sandstone intercalations, presenting an irregular and cleaning up gamma ray trend (Figure 17B).

In the seismic data (Figures 18, 19, 20), parallel to subparallel seismic facies (seismic facies 2) predominate, contrasting in some places with the lower unit due to the difference in amplitude and frequency of the reflectors, which in Kg2 are lower. In the transition from the strike ramp to the flexural margin, the reflectors decrease their amplitude and in part their continuity. As in the Kg1 unit, chaotic seismic facies (seismic facies 5) are observed in the border of the half-graben.

7.3.3 Kg3 unit

The Kg3 unit (Figures 18, 19, 20) presents parallel to subparallel, and subparallel seismic facies (seismic facies 2 and 3), but exhibiting chaotic seismic facies in some points (seismic facies 5). In the east portion of the seimic data, this unit contrasts with the adjacent ones because it has lower amplitude reflectors (seismic facies 3).

7.3.4 Kg4 unit

The Kg4 unit is best seen where basement top is deepest (Figure 20). The reflectors present higher amplitude in relation to the previous unit. At the base, shingled progradational seismic facies (seismic facies 4) with NW progradation component are observed. In this unit, parallel seismic facies (seismic facies 1) predominate, also presenting parallel to subparallel seismic facies (seismic facies 2). As in the other units, chaotic seismic facies (seismic facies 5) are observed in the border of the half-graben.

7.3.5 Kg5 unit

Above the Kg4 unit, at the upper limit of the seismic data, a change in the comportment is identified, with chaotic and parallel to subparallel seismic facies (seismic facies 5 and 2; Figure 20). Despite the small volume, this characteristic suggests the existence of another stratigraphic unit, named Kg5.

7.3.6 Systems Tracts

The Kg1 unit comprises the Rift Initation Systems Tract (Figure 23). This tract is related to an incipient depression, result of initial crustal stretching. The occurrence of a fluvial system (Formation Antenor Navarro) is interpreted, where fluvial channels and alluvial plains intercalate, in depth, to a shallow lake system (Sousa Formation). The progradation component for SW agrees with the depocenter of the Sousa half-graben.

Above the Kg1 unit, the Half-graben Development Surface is identified, so that the Kg2 unit corresponds to the Half-graben Development Systems Tract (Figure 23). In this tract, an initial geometry of half-graben was developed. In the study area, this tract is similar to the previous one, however with a relatively deeper fluvio-deltaic system. In the Kg1 and Kg2 units is interpreted higher depths in the strike ramp and, towards the flexural margin, the basin becomes shallower.

Kg3 and Kg4 units configure the High Tectonic Activity Systems Tract (Figures 23A and 23B), limited at the base by the Tectonic Change Surface. In this tract, an increase in tectonic activity finally developed the configuration of a half-graben. The observation of a progradational component towards NW indicates a retrogradation related to the higher accommodation space. There is an increase in the sedimentary input from the flexural margin, related to the late deposition in this margin in response of high tectonic activity. In this tract, an alluvial fan system (Antenor Navarro Formation) is interpreted, considering the possibility of a distal alluvial plain and/or lakes that tends to be deeper (Sousa Formation).

Finally, the characteristics of the Kg5 unit suggest another Tectonic Change Surface, with the upwards beginning of a Low Tectonic Activity Systems Tract (Figure 23B).

7.3.7 Discussions

The stratigraphic interpretation presented for the Lower Cretaceous Sequence in the west portion of Sousa half-graben allowed, in a detail scale, a better understanding of the strike ramp and flexural margin evolution. It was observed that the strike ramp developed higher depths as compared to a flexural margin. At the subsurface, the Sousa half-graben displays an interdigitation between the Antenor Navarro and Sousa formations, in accordance with outcrop observations. The interdigitation of the cretaceous strata corroborates with the concepts discussed by Córdoba et al. (2008). The stratigraphic analysis presented in this work is consistent with previous interpretations of 2D regional data (Córdoba et al., 2008; Pichel, 2014; Souza, 2016).

Given the characteristics presented for the Lower Cretaceous Sequence of the Sousa half-graben and the Santa Helena Step, it is possible to establish a stratigraphic correlation between these two sectors. Based on the similarity of the lithofaciological successions of the wells and the seismic stratigraphic criteria, it is inferred that the Rift Initiation System Tracts and the Rift and Half-graben Development System Tracts of the Santa Helena step and Sousa half-graben are correlated. It is interpreted that these two sectors have shared the same incipient depression during initial crustal stretching and could be initially connected at the beginning of the development of the half-graben and step geometries.

8. Conclusions

The outcrop characterization combined with subsurface analysis (wells integrated with 3D seismic data) allowed new considerations about the tectonic-stratigraphic framework of the Rio do Peixe Basin pre- and syn-rift sequences.

The Lower Devonian pre-rift sequence outlines a remnant basin fill geometry and is significantly affected by the cretaceous faults related to the subsequent rift event. This sequence is interpreted as a deltaic system, associated with transgressive and regressive systems tracts. A chronocorrelative interval to the Lower Devonian Sequence, geographically closer to the Rio do Peixe Basin, is the upper part of the Jaicós Formation and maybe the base of the Itaim Formation of the Parnaíba Basin (NE Brazil). Another chronocorrelation in Northern and Northeast Brazil is the upper part of the Jutaí Formation, in the Solimões Basin; the Manacapuru Formation and the lower part of the Jatapu Formation (Trombetas Group), in the Amazonas Basin; and maybe the Tacaratu Formations, in the Jatobá and North Tucano basins.

The study area comprises the west part of Sousa half-graben (its strike ramp and flexural margin) and the east part of Santa Helena step. Most of the interpreted structures are related to the Early Cretaceous rift event (Neocomian), associated with a sinistral oblique NW extensional kinematics. A second event comprising dextral strike-slip structures was also observed, with subordinate expression in the area, being related to the evolution of the Brazilian Equatorial Margin in the Aptian-Albian.

For the Lower Cretaceous syn-rift sequence, with interdigitated formations, the sequence stratigraphy applied to rift basins allowed to characterize the relationships between tectonics and sedimentation in the context of the strike ramp and flexural margin of the Sousa half-graben and in the stepped-shaped domain of Santa Helena. Along these compartments, systems tracts related to an initial evolutionary phase are recognized at the base, followed by systems tracts associated with moments of high and low tectonic activity. It is interpreted that the Santa Helena Step and the Sousa half-graben were correlated at the beginning of their evolutions, exhibiting similar initial system tracts.

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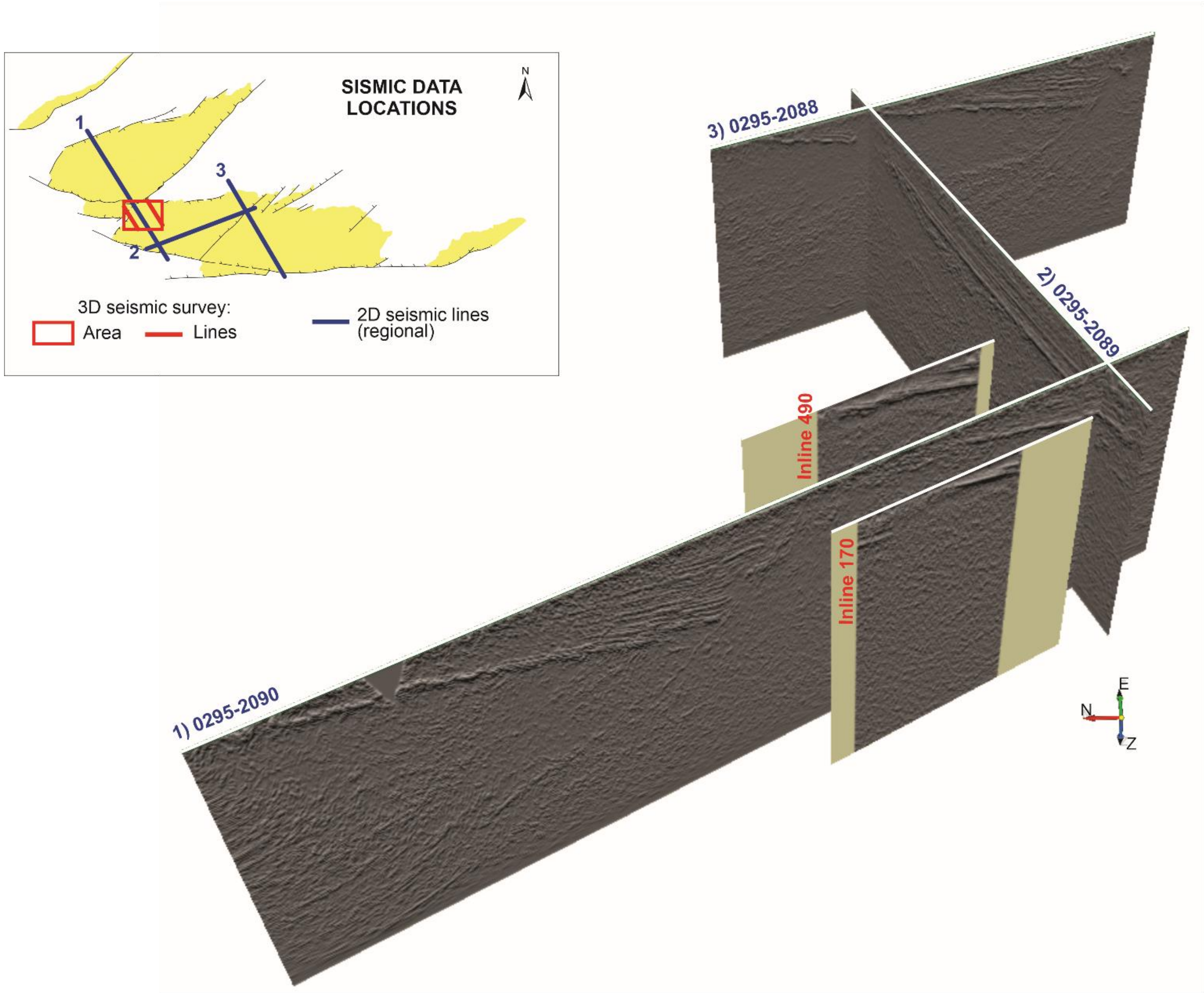
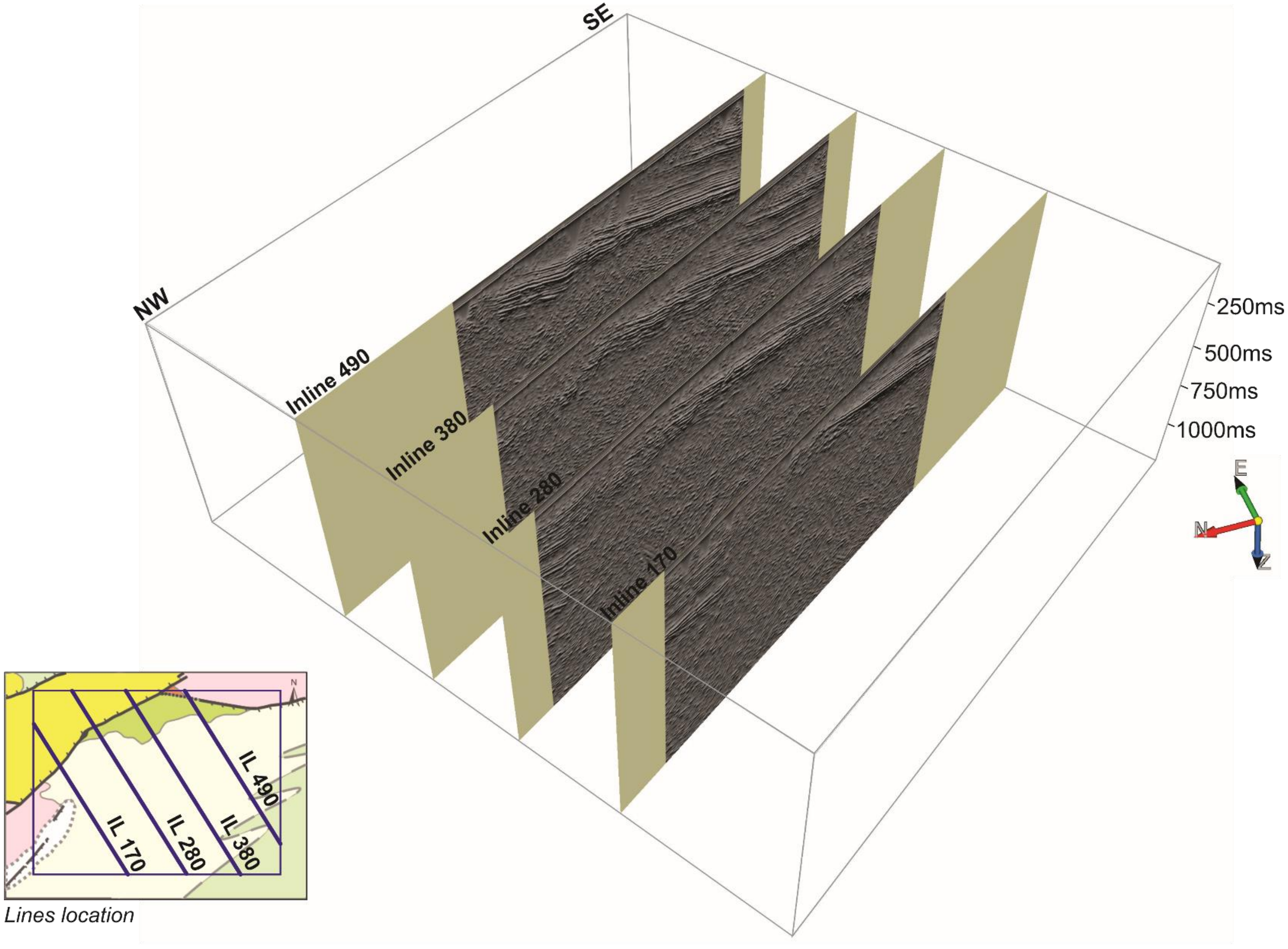
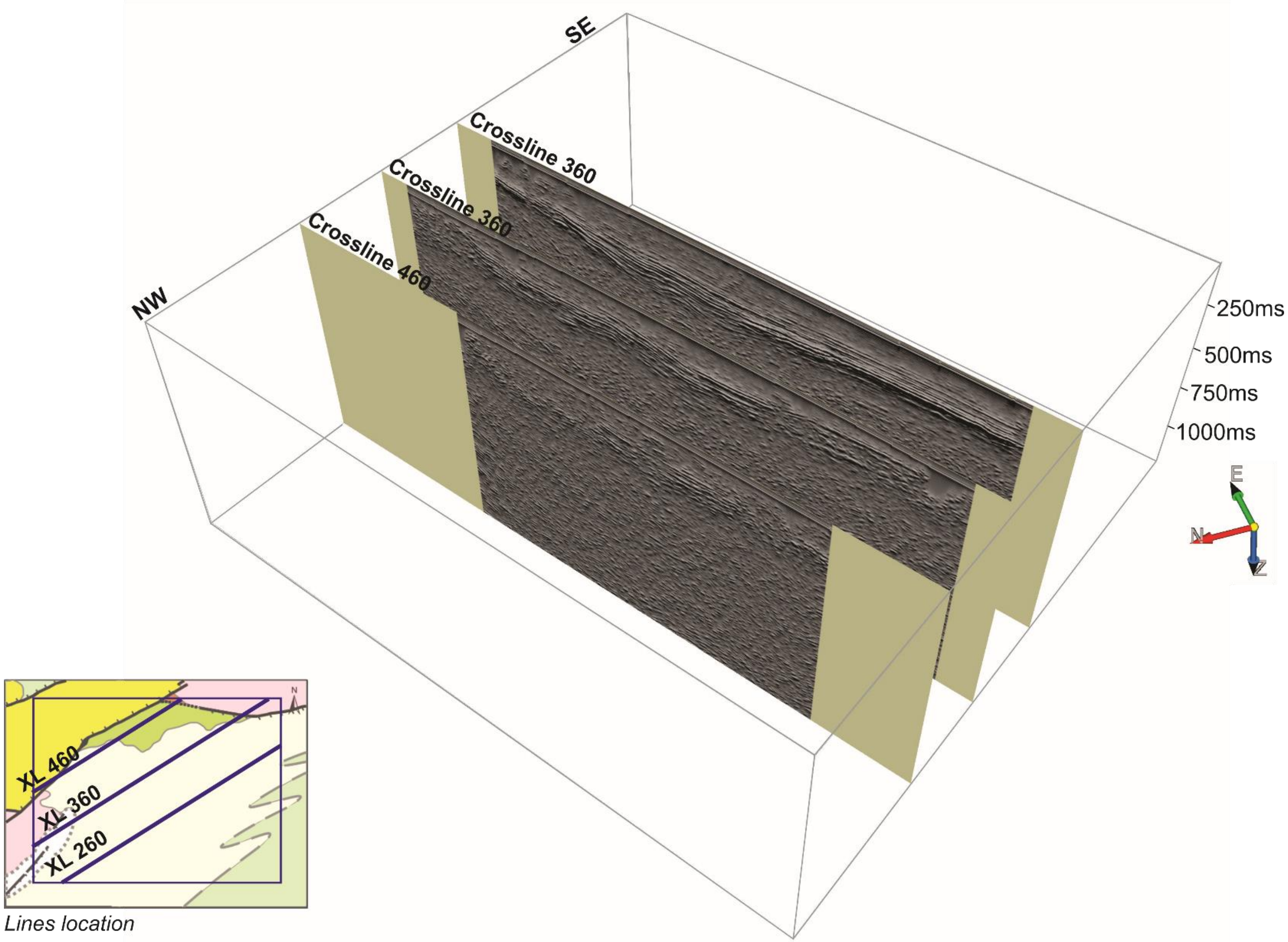
Appendix A, B, C, D - Supplementary data



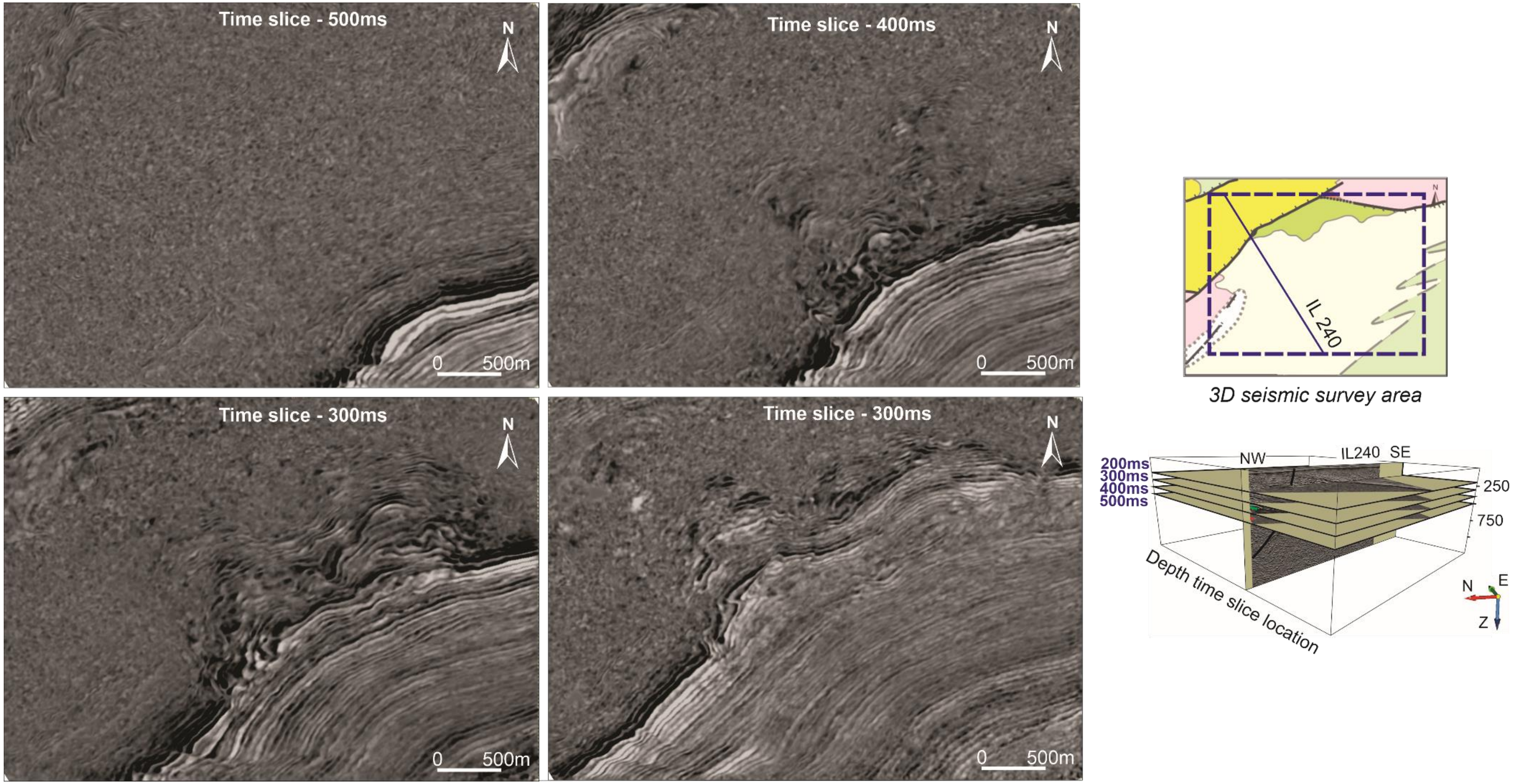
Appendix A. Supplementary data 1 - Uninterpreted lines from 2D regional seismic data (0295_RIO_DO_PEIXE_2D) integrated with lines from 3D seismic data (0027_3D_RIO_DO_PEIXE). Ps.: This figure corresponds to Figure 9B.



Appendix B. Supplementary data 2 - Uninterpreted lines from 3D seismic data (0027_3D_RIO_DO_PEIXE) from a dip view (inlines). Ps.: This figure corresponds to Figure 10.



Appendix C. Supplementary data 3 - Uninterpreted lines from 3D seismic data (0027_3D_RIO_DO_PEIXE) from a strike view (crosslines). Ps.: This figure corresponds to Figure 16A.



Appendix D. Supplementary data 4 - Uninterpreted time slices from 3D seismic data (0027_3D_RIO_DO_PEIXE). Ps.: This figure corresponds to Figure 16B. The images at the right shows the coverage area of the seismic data and the location of the time slices in depth; inline 240 used as a reference.

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Capítulo 4

DISCUSSÕES E CONSIDERAÇÕES FINAIS

4. DISCUSSÕES E CONSIDERAÇÕES FINAIS

A área de estudo compreende a poção aflorante e de subsuperfície da sequência pré-rifte (Eodevoniana) da bacia do Rio do Peixe, estando situada na porção oeste do Semi-gráben de Sousa (rampa direcional e margem flexural) e porção leste do Degrau de Santa Helena. Nesta área, a caracterização de afloramentos combinada à análise de subsuperfície (poços integrados com dado sísmico 3D), permitiu novas considerações para a tectono-estratigrafia das sequências pré e sin-rifte da bacia.

A falha de Melancia é a principal da área, separando o Degrau de Santa Helena do Semi-gráben de Sousa. Esta falha configura um *splay* NE da falha de Brejo das Freiras, sendo uma falha normal lístrica, de mergulho para NW. No piso desta falha ocorrem falhas secundárias sintéticas gerando uma estruturação em degraus na borda NW do semi-gráben de Sousa. Neste semi-gráben é observado que o contato do embasamento com o pacote sedimentar na margem flexural e na rampa direcional se dá com a presença de falhas.

De maneira geral, predominam na área falhas com componentes de rejeito normais, que podem exibir dobras associadas. As características geométricas e cinemáticas dessas estruturas são compatíveis com a distensão NW-SE do evento rifte neocomiano, corroborando com estudos anteriores (Matos 1992; Córdoba *et al.* 2008 e Nunes da Silva, 2009). De forma menos expressiva, um segundo conjunto de estruturas também foi caracterizado, podendo estar relacionado a fase de abertura da Margem Equatorial brasileira (fase Sin-Rifte III; Matos, 1992).

Em relação aos aspectos estratigráficos da Sequência Devoniana, verifica-se em sua base uma geometria externa de preenchimento, sendo consideravelmente afetada por falhas do evento rifte. Este comportamento é identificado a partir da interpretação do dado sísmico 3D integrado a interpretações prévias de linhas sísmicas 2D regionais (Souza, 2016; Rapozo, 2020).

Para a Sequência Eodevoniana, foram constatadas três unidades deposicionais, cujo a descrição aqui apresentada é coerente com a Formação Pilões proposta por Silva *et al*. 2014. Com base em dados litofaciológicos e sismoestratigráficos, a Formação Triunfo proposta por estes autores não foi reconhecida neste trabalho, sendo seus litotipos pertencentes à base da Sequência Eocretácea (Formação Antenor Navarro).

As unidades estratigráficas devonianas foram agrupadas em tratos de sistemas transgressivo e regressivo, relacionados a um sistema deltaico, exibindo depósitos de frente deltaica, de transição para prodelta e de planície deltaica. Fácies deltaicas e a ocorrência de um episódio de transgressão e regressão também foram reconhecidos por Silva *et al*. 2014. Vale mencionar que, nesta sequência, Roesner *et al.* (2011) caracterizam um ambiente de influência marinha com forte influxo de águas continentais, em um ambiente marinho costeiro a transicional.

No Nordeste brasileiro, o registro estratigráfico devoniano de maior expressão e geograficamente mais próximo da Bacia do Rio do Peixe consiste na bacia do Parnaíba (Vaz *et al.,* 2007). Nela, o intervalo eodevoniano cronocorrelato corresponde à parte superior da Formação Jaicós e possivelmente a base da Formação Itaim (Roesner *et al*., 2011). Outras cronocorrelações no Norte e Nordeste do Brasil consistem: na porção superior da Formação Jutaí, na Bacia do Solimões; a Formação Manacapuru e a porção inferior da Formação Jatapu (Grupo Trombetas), na bacia do Amazonas; e possivelmente a Formação Tacaratu, na Bacia do Tucano Norte e Jatobá.

Em relação à sequência rifte, na porção do degrau de Santa Helena, foram identificadas 6 unidades deposicionais eocretáceas, em parte influenciadas pela tectônica da falha de Melancia. Adaptando o conceito de tratos de sistemas tectônicos de Kuchle & Scherer (2010) e Alvarenga (2016) para região do degrau, foi possível interpretar os seguintes tratos de sistemas: Trato de Sistemas de Início de Rifte - sistema fluvial (Formação Antenor Navarro) de uma ampla bacia, desenvolvido no momento de estiramento inicial, que ficou preservado na porção basal do Degrau de Santa Helena; Trato de Sistemas de Desenvolvimento de Rifte - sistema lacustre raso (Formação Sousa) no desenvolvimento da forma embrionária do degrau; Trato de Sistemas de Alta Atividade Tectônica - aumento da atividade tectônica no degrau, gerando, a partir da Falha de Melancia, um sistema de leque fluvial distal com canais fluviais entrelaçados (Formação Rio Piranhas) e planícies aluviais e/ou lagos rasos (Formação Sousa); Trato de Sistemas de baixa atividade Tectônica - menor criação de espaço de acomodação e maior aporte sedimentar, onde o sistema de leque fluvial passa para porções proximais, com canais fluviais entrelaçados (Formação Rio Piranhas).

Verifica-se que o contraste de relevo provocado pela Falha de Melancia não foi muito expressivo quando comparado à falha de borda de semi-gábens, não exibindo indícios significativos de cunhas clásticas de fluxos de gravidade nas adjacências da falha. Vale salientar que a baixa recarga hídrica do paleoclima árido a semi-árido durante a deposição (Lima & Coelho, 1987; Lima Filho, 1991), no caso da região do degrau, também contribui para menor ocorrência de fluxos de gravidade. De maneira geral, em toda a bacia, este paleoclima influencia para a não geração de lagos muito profundos.

No Semi-gráben de Sousa, 5 unidades deposicionais da sequência rifte foram reconhecidas, agrupadas nos seguintes tratos de sistemas: Trato de Sistemas de Início do Rifte - sistema fluvial (Formação Antenor Navarro), que se intercala, em profundidade, para um sistema lacustre raso (Formação Sousa), desenvolvidos numa depressão incipiente, no início do estiramento crustal; Trato de Sistemas de Desenvolvimento de Meio-gráben - sistemas deposicionais semelhantes ao trato anterior, contudo em condições relativamente mais profundas, relacionados ao estabelecimento de uma forma embrionária de meio-gráben; Trato de Sistemas de Alta Atividade Tectônica - em condições de aumento da atividade tectônica, tem-se neste trato um aumento do aporte sedimentar a partir da margem flexural, com sistema de leque aluvial e/ou deltaico (Formação Antenor Navarro) relacionado à deposição tardia nesta margem, considerando também a possibilidade uma planície aluvial distal e/ou lago raso (Formação Sousa). Após este último trato de sistemas, já no limite superior do dado sísmico, é inferido um início de Trato de Sistemas de Baixa Atividade Tectônica.

A interpretação estratigráfica apresentada para o Sequência Eocretácea do Semi-gráben de Sousa permitiu, em escala de detalhe, a melhor compreensão da região sua de rampa direcional e margem flexural. A análise aqui apresentada está coerente com a interpretação deste semi-gráben em dados 2D regionais da bacia (Córdoba *et al*., 2008; Pichel, 2014; Souza, 2016). A relação de interdigitação entre as formações eocretáceas apresentada por Córdoba *et al.* (2008) e Nunes da Silva (2009) também foi constatada.

A partir das características apresentadas para a Sequência Eocretácea do Degrau de Santa Helena e do Semi-gráben de Sousa, verifica-se uma semelhança entre seus Tratos de Sistemas de Início de Rifte e do Trato de sistemas de Desenvolvimento de Meio-gráben e de Desenvolvimento de Rifte. Interpreta-se que durante os momentos iniciais de estiramento crustal tenha ocorrido uma ampla depressão, no qual os setores compartilharam de mesmos sistemas deposicionais, sugerindo que estes compartimentos estivessem inicialmente conectados antes do desenvolvimento da geometria em semi-gráben e em degrau.

Diante dos resultados e conclusões obtidos neste trabalho, são recomendados para estudos futuros: (i) uma melhor caracterização do evento tectônico relacionado à abertura da margem equatorial, contendo análises estruturais a partir de afloramentos; (ii) a procura por novos exemplos da Sequência Eodevoniana na Bacia do Rio do Peixe, visando novos dados sedimentológicos, estratigráficos e paleontológicos; (iii) uma revisão do entendimento evolutivo para o Degrau de Santa Helena, ainda pouco explorado, tomando em consideração a evolução tectono-sedimentar aqui apresentada para a falha de Melancia.

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