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CARACTERIZAÇÃO DE RESERVATÓRIOS TURBIDÍTICOS ATRAVÉS DE MODELAGEM DE PROPRIEDADES ELÁSTICAS: UMA APLICAÇÃO NA FORMAÇÃO CALUMBI, BACIA DE SERGIPE-ALAGOAS, BRASIL

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Coorientador: Dr. Paulo Lopes Brandão Paraizo

DISSERTAÇÃO DE MESTRADO

Programa de Pós-Graduação em Geociências e Análise de Bacias

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Dissertação apresentada ao Programa de Pós-Graduação em Geociências e Análise de Bacias da Universidade Federal de Sergipe, como requisito para obtenção do título de Mestre em Geociências.

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DISSERTAÇÃO DE MESTRADO

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RESUMO

Reservatórios arenosos canalizados em ambientes de águas profundas são de grande importância para a atividade de exploração e produção de petróleo, visto que podem constituir importantes jazidas de petróleo. A natureza bidimensional dos afloramentos descritos na literatura e o caráter pontual das informações adquiridas através de poços compõem fatores limitantes para a adequada caracterização deste tipo de ambiente sedimentar e de suas heterogeneidades. A ausência de informação entre os pontos amostrados por poços em um reservatório petrolífero é usualmente suplantada através da utilização de dados sísmicos 3D. A modelagem geológica mitiga os efeitos da baixa resolução da sísmica e pode ser otimizada na distribuição espacial de propriedades das rochas ao incorporar volumes sísmicos invertidos que dispõem de dados ao longo de todas as camadas litológicas. Este estudo apresenta uma modelagem sintética de propriedades elásticas associadas a propriedades físicas para criticar e otimizar a modelagem geoestatística implementada em dados reais de reservatórios turbidíticos da seção maastrichtiana da Formação Calumbi, Sub-bacia de Sergipe. Aspectos geomorfológicos e litológicos descritos na literatura e em afloramentos análogos na Sub-bacia de Alagoas, associados às suas repostas em função de suas velocidades compressionais, velocidades cisalhantes, densidades e espessuras, foram sucessivamente testados para reduzir a incerteza na distribuição espacial entre os pontos que apresentam uma alta resolução vertical de dados. Os resultados obtidos apontam as variações de velocidades da onda P e da onda S como principais influenciadores no sinal sísmico e no atributo de diferenças entre a impedância P e S. Uma equação permitiu modelar os efeitos destes atributos e, deste modo, implementar correções nos aspectos geométricos e faciológicos das rochas avaliadas.

Palavras-chave: Geociências. Modelagem geológica. Geologia – Métodos estatísticos. Rochas. Bacias (Geologia) – Sergipe (SE) – Alagoas (AL).

ABSTRACT

Sandy channelized reservoirs in deep water environments are of great importance for oil exploration and production as they can constitute important oil reservoirs. The two-dimensional nature of the outcrops described in the literature and the local nature of the information acquired through wells are limiting factors for the adequate characterization of this type of sedimentary environment and its heterogeneities. The absence of information between the points sampled by wells in oil reservoir is usually overcome by using 3D seismic data. Geological modeling mitigates the effects of low seismic resolution and can be optimized regarding the spatial distribution of rock properties by incorporating inverted seismic volumes that have data throughout all the geological layers. This study presents a synthetic modeling of elastic properties associated with physical properties to assess and optimize the geostatistical modeling performed in real data from turbiditic reservoirs in the Maastrichtian section of the Calumbi Formation, Sergipe Sub-basin, Brazil. Geomorphological and geological aspects, described in the literature and in similar outcrops in the Alagoas Sub-basin, associated with their responses due to their compressional velocities, shear velocities, densities, and thicknesses, were successively tested to reduce the uncertainty in the spatial distribution between the points that present high vertical-resolution data. The results obtained show that the variations of the P and S waves are the main influences on the seismic signal and on the differences between impedance P and S attribute. An equation allowed to model the effects of these attributes and, thus, to implement corrections in the geometric and faciological characteristics of the evaluated rocks.

Key-words: Geosciences. Geological modeling. Geology – Statistical methods. Rocks. Basins (Geology) – Sergipe (SE) – Alagoas (AL).

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CAPÍTULO 1

INTRODUÇÃO

A sísmica de reflexão é um método geofísico bastante utilizado na academia e na indústria para investigar a geologia em subsuperfície. A melhoria na qualidade dos dados sísmicos de reflexão tridimensionais permitiu uma melhor compreensão das complexidades geológicas (Stright et al., 2014) inerentes aos processos de transporte e deposição de reservatórios de água profundas. Porém, a escala de investigação do método sísmico não representa em escala de detalhe as heterogeneidades observadas em dados de afloramentos e dados obtidos através da perfuração de poços.

O principal produto do método sísmico é uma imagem do interior da Terra, resultante da interação de um campo de ondas sísmicas e as rochas. Sua natureza pode ser formulada através do modelo convolucional (Yilmaz, 2001), onde o traço sísmico é o resultado da convolução entre uma fonte de energia e as camadas rochosas, mais precisamente das interfaces entre essas camadas. Este fenômeno é possível devido à diferença das impedâncias sísmicas entre os corpos rochosos, que podem ser expressas através de suas propriedades internas, como, por exemplo, suas diferentes litofácies, ou por contrastes produzidos por elementos estruturais, como falhas geológicas.

O formato de aquisição convencional de dados sísmicos é disposto entre uma fonte de energia e receptores distribuídos em uma determinada região (Yilmaz, 2001), onde o conjunto fonte-receptor é deslocado cada vez que a fonte de energia é acionada. Isto garante que cada ponto em subsuperfície seja amostrado diversas vezes melhora a relação sinal-ruído inerentes ao processo. A onda gerada se propaga no interior da Terra e quando encontra uma interface ela sofre uma partição de energia, onde parte desta energia é refletida, parte é transmitida e parte e refratada (Huygens, 1690). A incidência em ângulo deste campo de onda na interface confere uma componente compressional e uma componente de cisalhamento recuperadas nos receptores distribuídos na superfície. Através dos tempos de chegada, as velocidades das ondas compressionais e de cisalhamento podem sem estimadas (Zoeppritz, 1919). Portanto, os dados sísmicos de reflexão fornecem informação apenas entre os limites das camadas geológicas

A propagação das ondas sísmicas no interior da Terra está sujeita aos efeitos de atenuação, absorção e dispersão, o que diminui a sua energia e capacidade de resolução à medida que este campo se propaga em subsuperfície. Outro efeito importante ao qual o dado sísmico está sujeito é o efeito de *tuning* (Widess, 1973), onde o sinal de entrada interfere no sinal de saída de uma camada geológica afetando as amplitudes do traço sísmico e, por consequência, as estimativas de sua espessura. Parte destes efeitos é tratada no processamento sísmico, cujo produto final é a imagem sísmica resultante da geometria de aquisição somados aos efeitos de propagação das ondas sísmicas no interior da Terra. Estas incertezas inerentes ao método vão sendo minimizadas à medida que informações são incorporadas no tratamento destes dados através da perfuração de poços.

Os poços fornecem informações diretas extraídas das rochas e informações indiretas através de perfis geofísicos, delimitando melhor as propriedades sísmicas e geométricas (espessuras das camadas). Estas informações oriundas dos poços podem ser utilizadas no processo de inversão dos dados sísmicos (Veeken & Silva, 2004), que consiste em estimar os parâmetros de entrada que originaram o traço sísmico. Os dados dos perfis sônico e de densidade são utilizados para calcular as impedâncias sísmicas que são extrapoladas segundo alguma técnica, como por exemplo a geostatística. O resultado da inversão sísmica é um modelo de impedância ao longo de um intervalo geológico, e não apenas o contraste de impedâncias em uma interface conforme fornecido pelo dado sísmico convencional.

Informações adicionais podem ser obtidas dos dados sísmicos através de seus atributos sísmicos, que nada mais são que toda informação extraída diretamente ou experimentalmente do dado sísmico. Estes atributos e seu uso combinado fornecem uma melhor interpretação dos modelos geofísicos e geológicos estudados à medida que fornecem informações sobre aspectos geomorfológicos, propriedades físicas e conteúdo de fluídos das rochas. Estes atributos podem ser extraídos ao longo de um único traço sísmico, no caso dos poços, podem ser extraídos sob forma de mapas quando calculados entre um intervalo de dados ou ao longo de uma superfície, e podem ser obtidos sob forma de volume como, por exemplo, através do processo de inversão sísmica. A combinação de atributos sísmicos que convergem para um determinado cenário geológico fornece ao intérprete que o está estudando uma maior segurança para extrapolar a informação obtida através da perfuração dos poços.

A modelagem geofísico-geológica de reservatórios é uma técnica bem estabelecida para mitigar as incertezas na estimativa de informações geológicas no espaço tridimensional. Os principais balizadores são os dados de poços que, através de dados de rochas e perfis geofísicos, apresentam resolução vertical na escala de centímetros. Uma forma de otimizar a confecção destes cenários geológicos é através da modelagem direta, que consiste em compreender as diferentes respostas para a variação dos parâmetros de entrada. Diferentes tipos de variações de cenários geológicos como fácies que possuem gradação suave, conteúdo de fluídos ou até mesmo a própria espessura dos reservatórios, podem produzir o mesmo valor de impedância e consequentemente a mesma resposta sísmica, levando a intepretações errôneas. Isto porque a interpretação de um corpo rochoso é efetuada observando a assinatura sísmica do corpo litológico em sua entrada e sua saída, porém como esta forma do traço sísmico pode variar por diversos efeitos, este corpo pode ser superestimado ou subestimado em suas dimensões. Ao compreender qual parâmetro de entrada possui maior influência no dado observado, uma análise mais focalizada sobre as propriedades físicas que influenciam este parâmetro deve ser realizada, objetivando a otimização do modelo geológico.

Este artigo apresenta um estudo de modelagem de propriedades elásticas em modelos parametrizados com dados reais coletados nas porções *offshore* da Bacia de Sergipe-Alagoas, dados de afloramentos de sistemas análogos e informações de modelos conceituais obtidos na literatura, a fim de otimizar os modelos geológicos usualmente utilizados na indústria petrolífera.

OBJETIVOS

O principal objetivo deste estudo foi melhorar a modelagem de propriedades físicas de reservatórios areníticos turbidíticos canalizados da Sub-bacia de Sergipe, utilizando técnicas de modelagem direta (1D) e sintética (3D) e da compreensão das relações entre essas propriedades e os dados sísmicos e seus atributos. Um conjunto de metas foi definido para a melhor execução desta proposta:

- Avaliar como o dado sísmico e seus atributos associados respondem às variações de parâmetros elásticos, geométricos e de frequência no espaço 1D;
- Construir modelos geológicos sintéticos com parâmetros morfológicos, faciológicos e elásticos descritos na literatura e em dados observados na Bacia de Sergipe-Alagoas para auxiliar a construção e otimização de modelos geológicos em dados reais observados na Sub-bacia de Sergipe, Brasil;
- Compreender as respostas de atributos sísmicos como AVO (*amplitude versus offset*; Shuey, 1985; Fatti *et al*., 1994), impedâncias acústicas e elásticas mediante as variações de elementos arquiteturais de canais, e suas distribuições de fácies litológicas no modelo sintético desenvolvido;
- Otimizar a confecção de modelos geológicos tridimensionais através da análise e distribuição de suas propriedades elásticas em função de parâmetros geométricos e de empilhamento rochoso em contexto deposicional de canais turbidíticos de águas profundas.

JUSTIFICATIVA

A melhor caracterização de reservatórios de petróleo reduz os riscos nas concepções de projetos a serem implementados, otimizando intervenções e posicionando novas perfurações em locais mais favoráveis para a produção de hidrocarbonetos. Este estudo apresenta técnicas de otimização no processo de confecção de modelos geológicos comumente empregados na indústria, que utilizam dados medidos em poços (pontuais) para distribuir propriedades como porosidade e permeabilidade dentro de um *grid* numérico através de geoestatística. Embora estes modelos ajustem o histórico de produção do campo, diversas vezes não são capazes de representar a complexidade inerente aos processos sedimentares. A Formação Calumbi foi escolhida para testar a metodologia por contribuir significativamente para a produção industrial de petróleo na Sub-bacia de Sergipe, dispondo de boa quantidade de dados sísmicos e de poços.

CAPÍTULO 2 - ARTIGO SUBMETIDO À REVISTA MARINE AND PETROLEUM GEOLOGY

CHARACTERIZATION OF CHANNELIZED TURBIDITIC RESERVOIRS THROUGH ELASTIC PROPERTIES MODELING: AN APPLICATION, SERGIPE-ALAGOAS BASIN, BRAZIL.

Leonardo B. Oliveira[*1,2], Wagner Souza-Lima[1], Paulo L. B. Paraizo[2], Adler C. Nascimento[2], Otavio L. Chaves[2].

ABSTRACT

Sandy channelized reservoirs in deep water environments are of great importance for oil exploration and production as they can constitute important oil reservoirs. The two-dimensional nature of the outcrops described in the literature and the local nature of the information acquired through wells are limiting factors for the adequate characterization of this type of sedimentary environment and its heterogeneities. The absence of information between the points sampled by wells in oil reservoir is usually overcome by using 3D seismic data. Geological modeling mitigates the effects of low seismic resolution and can be optimized regarding the spatial distribution of rock properties by incorporating inverted seismic volumes that have data throughout all the geological layers. This study presents a synthetic modeling of elastic properties associated with physical properties to assess and optimize the geostatistical modeling performed in real data from turbiditic reservoirs in the Maastrichtian section of the Calumbi Formation, Sergipe Sub-basin, Brazil. Geomorphological and geological aspects, described in the literature and in similar outcrops in the Alagoas Sub-basin, associated with their responses due to their compressional velocities, shear velocities, densities, and thicknesses, were successively tested to reduce the uncertainty in the spatial distribution between the points that present high vertical-resolution data. The results obtained show that the variations of the P and S waves are the main influences on the seismic signal and on the differences between impedance P and S attribute. An equation allowed to model the effects of these attributes and, thus, to implement corrections in the geometric and faciological characteristics of the evaluated rocks.

Key-words: Geological modeling; 3D model; geostatistics; elastic properties; seismic inversion.

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1 INTRODUCTION

The exploration and production of hydrocarbons over the decades has fostered an understanding of the spatial organization and lithological filling of channelized reservoirs deposited in deep-water environments. The improvement in the quality of three-dimensional seismic data allowed a better understanding of the geological complexities (Stright *et al*., 2014) inherent to this type of reservoir. However, the scale of investigation of the seismic method does not represent the heterogeneities observed in outcrop data and in those obtained through well drilling, presenting information only at the interface between the lithological layers, and not inside.

The geophysical-geological reservoir-modeling is a well-established technique to mitigate the uncertainties in estimating information from data obtained in three-dimensional space. The main source of information are data obtained from well drilling that, using data extracted from rocks and geophysical logs present resolution on the scale of centimeters in the vertical direction. Seismic reflection is the main tool for the three-dimensional understanding of the subsurface, although it has a resolution of around tens of meters. Although the rocky content is well represented in the vertical direction, there is great uncertainty in the spatial representation of the depositional elements and their respective lithofacies. The seismic data inversion (Veeken & Silva, 2004) can optimize the spatial distribution of these heterogeneities by recovering information throughout the entire rock content, in addition to their products having a direct correlation with the physical properties of the rocks and their porous content. The direct modeling of elastic properties analyzes how these parameters vary depending on the architectural elements of the channelized systems and their filling patterns expressed through the seismic data and their attributes.

This article presents a modeling study of 1D and 3D elastic properties in parameterized models with real data collected at the offshore portions of the Sergipe-Alagoas Basin, outcrop data from analog systems and information from conceptual models obtained in the literature in order to optimize the geological models usually used in the oil industry.

The understanding of the seismic responses according to the modeled properties provided an equation that relates elastic parameters and the thickness to the I_p-I_s

attribute. This equation was able to optimize the construction of a geological model of channelized reservoirs of Maastrichtian age from the Calumbi Formation so that they represent, in a more reliable way, the geological reality in subsurface.

2 GEOLOGICAL SETTING

The Sergipe-Alagoas Basin is located in northeastern Brazil and is configured as a passive margin type (Figure 1). The emerged part is represented by a narrow strip about 20 to 50 km wide (Souza-Lima *et al*., 2002) and 350 km long (Lana, 1990). The submerged portion represents about 2/3 of the total length of the basin. Its limits are found between the Vaza-Barris fault system to the south and the Maragogi High to the north (Lana, 1990; Feijó, 1995). The boundary between the Sergipe and Alagoas sub-basins are the Japoatã, Penedo, and Palmeira Alta highs, around the low course of the São Francisco River (Feijó, 1995). The basin has an elongated shape in the SW-NE direction and its structural framework consists of N-S, E-W and NE-SW faults, subdividing it into several tectonic compartments, usually limited by major faults inherited from the basement structuring (Silva, 2005). The Calumbi Formation is a marine sequence from the Santonian-Recent drift phase evolution of the basin, consisting mainly of shales with sandstones intercalations. The deposition of its sediments was preceded by an important erosive event called sub-Calumbi Formation unconformity. They were deposited in a transgressive cycle that extended until Late Campanian, followed by a regressive cycle, associated to the sediments of the Mosqueiro (mainly carbonates) and Marituba (coastal sandstones) formations, which extend up to the Recent.

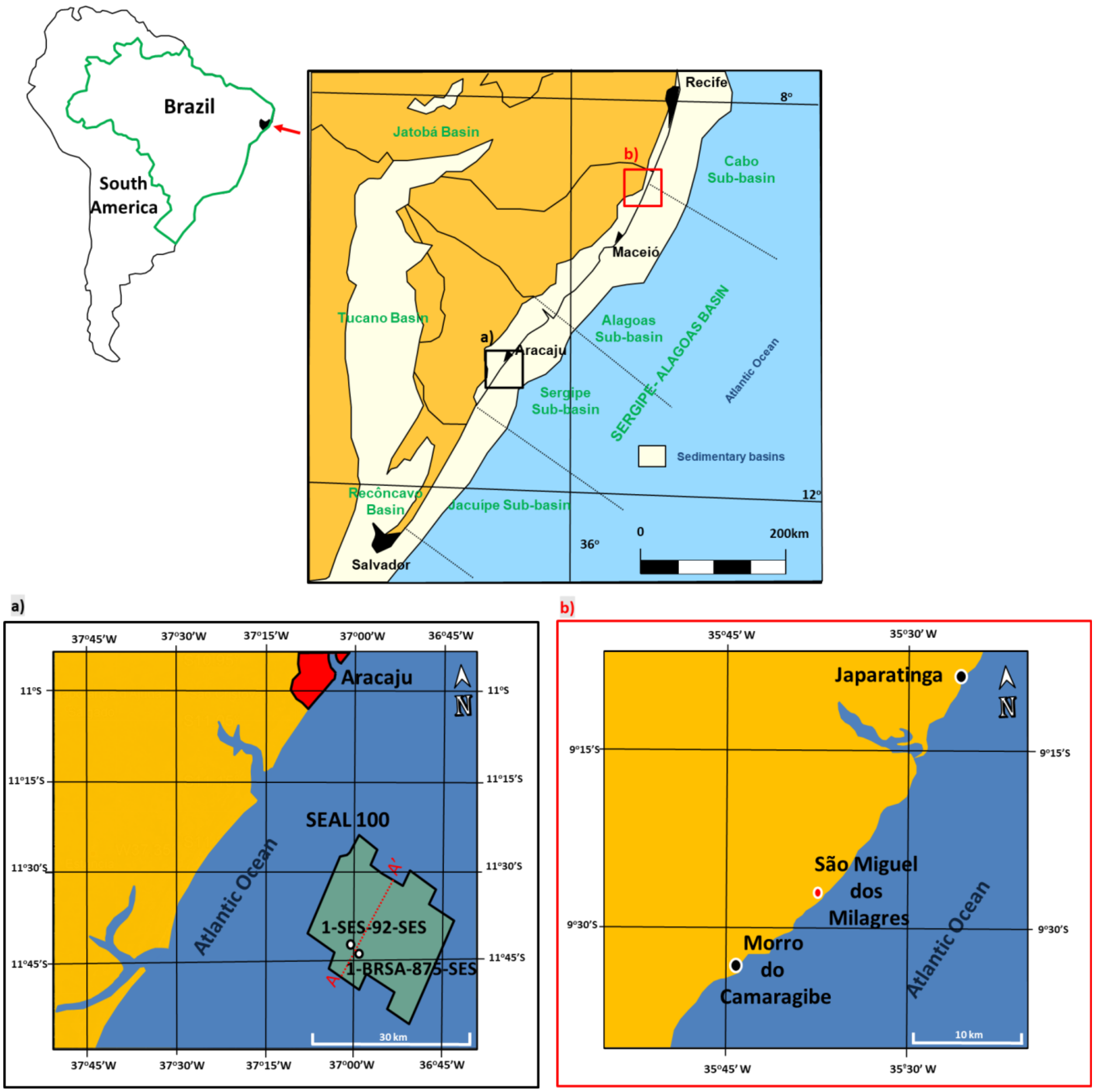

Figure 1 - Location map of the studied area: a) outline of the 3D seismic data volume (SEAL 100), the two wells used for geological and geophysical modeling, and A-A' cross-section; b) outcrops described by Arienti (1996) in the Alagoas Sub-basin here studied as analogous to the subsurface modeled section (modified from Souza-Lima *et al*., 2002).

DATASETS AND METHODS

2.1 DATABASE

Seismic data from a 3D survey (SEAL100) acquired in the offshore Mosqueiro Low were used for the construction of all structural models and as a subsidy in the distribution of physical properties of rocks within the models. The geophysical profiles used were: compression and shear velocities, gamma-ray, density, neutron and resistivity logs~~,~~ obtained from two wells (1-BRSA-875-SES and 1-SES-92-SES) that crossed Maastrichtian reservoirs of the Calumbi Formation in the Sergipe Sub-basin (Figure 1). These logs guided the construction of facies and elastic models. The facies classification used in the synthetic models was supported by the description of outcrops located in Japaratinga and Morro do Camaragibe, north of the Alagoas Sub-basin. These outcrops, although from a lacustrine context and different age (Aptian, Muribeca Formation; Souza-Lima *et al*., 2019), represent turbiditic depositional systems (Arienti, 1996) similar to those interpreted for the Calumbi Formation.

2.2 SEQUENCE STRATIGRAPHY & HIERARCHICAL PATTERN

The sequence stratigraphic framework used in this study was constructed by delimiting the sedimentary packages by sub-aerial unconformities and their correlative conformities (Vail et al., 1977; Posamentier & Vail, 1988). These surfaces were chosen by their clear signature in the seismic sections and validated by well data. The seismic surfaces that separate the different geological ages compose higher orders (3rd order) that were subdivided into smaller scale orders within each interval up to the limit of the vertical resolution of the seismic data (4th order surfaces), delimiting the envelope surfaces for the deposited reservoirs. For the construction of the high-resolution architectural model, the hierarchical classification used was that described by Moraes et al. (2006), similar to those described by Gardner & Borer (2000), Gardner et al. (2003) and Mayall et al. (2006), where a unitary channel element (6th and 7th orders) is part of a composite channel (5th and 6th orders), which are grouped to form a complex of channels, 4th or 5th order surfaces (Figure 2). The conduit element can encompass more than one channel complex (4th or even 3rd order surfaces).

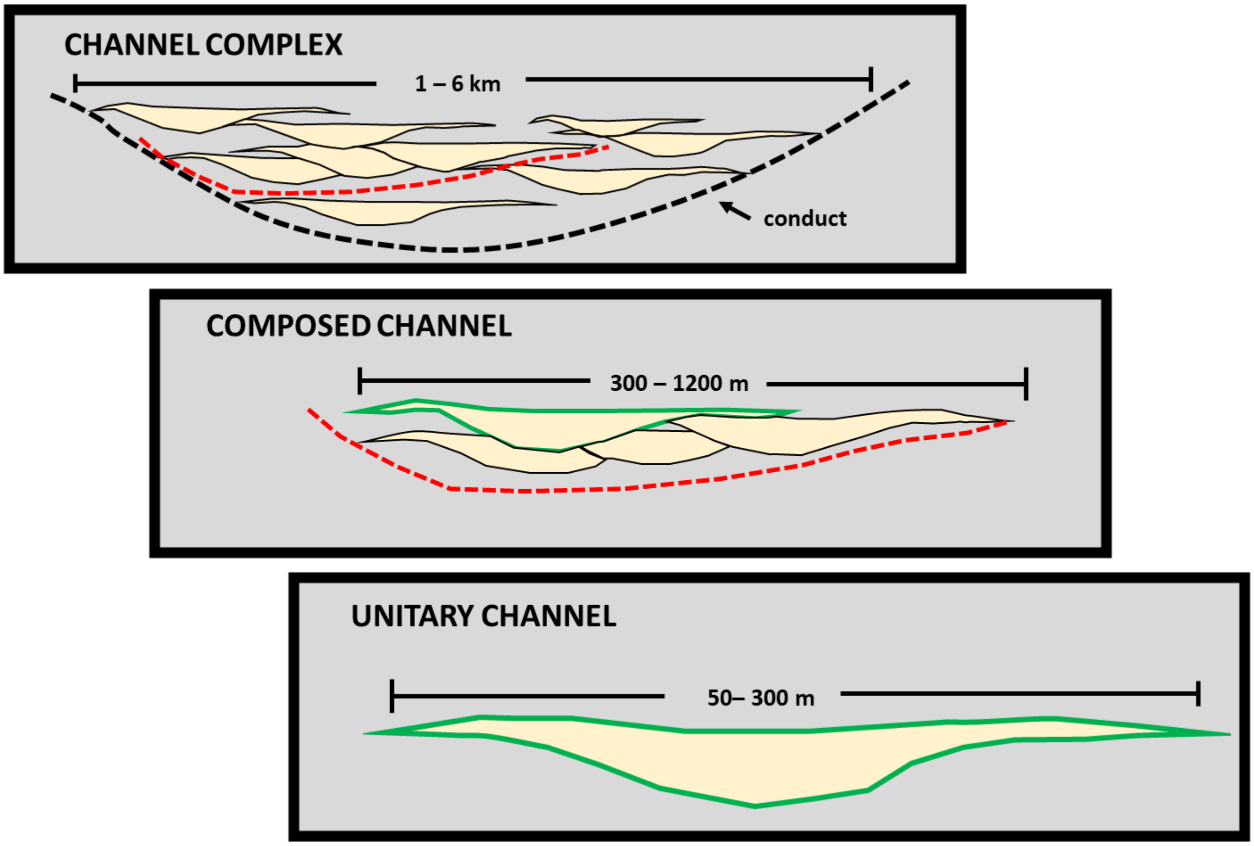

Figure 2 - Hierarchy of architectural elements and the specific dimensions of each individual element (modified from Moraes *et al*., 2006).

2.3 MODELING

2.3.1 PROPERTIES PARAMETERIZATION

The construction and calibration of the structural and facies model used outcrop data collected in the Sergipe-Alagoas Basin corroborated by data investigated at different regions such as the American continent (Gardner & Borer, 2000; Stright *et al*., 2014), Europe (Mutti & Ricci Lucchi, 1972, Kilhams *et al*., 2013) and Africa (Deptuck *et al*., 2007; Joly *et al*., 2017; Zhang *et al*., 2017) to establish its limits of variation. The construction of the architectural elements prioritized geometric aspects such as width, thickness, sinuosity, lateral and vertical channel stacking, and composed channel elements within the channel complex (Gardner & Borer, 2000; Mayall & O'Byrne, 2002; Gardner *et al*. , 2003; Posamentier & Kolla, 2003; Moraes *et al*., 2006 and Deptuck *et al*., 2007). The dimensions of these architectural elements for the model were defined according to the pre-existing descriptions for the Sergipe-Alagoas Basin (Arienti, 1996; Silva, 2005) to give the model better representativeness.

For the internal model filling, a set of described facies of similar outcrops in the basin was used, so that there is a closer correspondence between the synthetic and the observed scenarios. The sets of facies studied were described in detail by Arienti (1996), placing the highest energy events at the base of the systems (Bouma, 1962; Mutti *&* Ricci Lucchi, 1972; Mayall & O'Byrne, 2002), i.e., coarser sediments, high-energy flow at the base, with a tendency to energy and grain size decrease to the top of the system. Each architectural element of a separate canal-levee system was built individually and grouped at the end. The facies were built first by locating their probability of occurrence within the architectural element and then positioned from the bottom to the top, in each system, to be inserted into their respective architectural elements. Figure 3 exemplifies the interpretation of the analogous depositional element through discordant surfaces and the positioning of corresponding lithological facies.

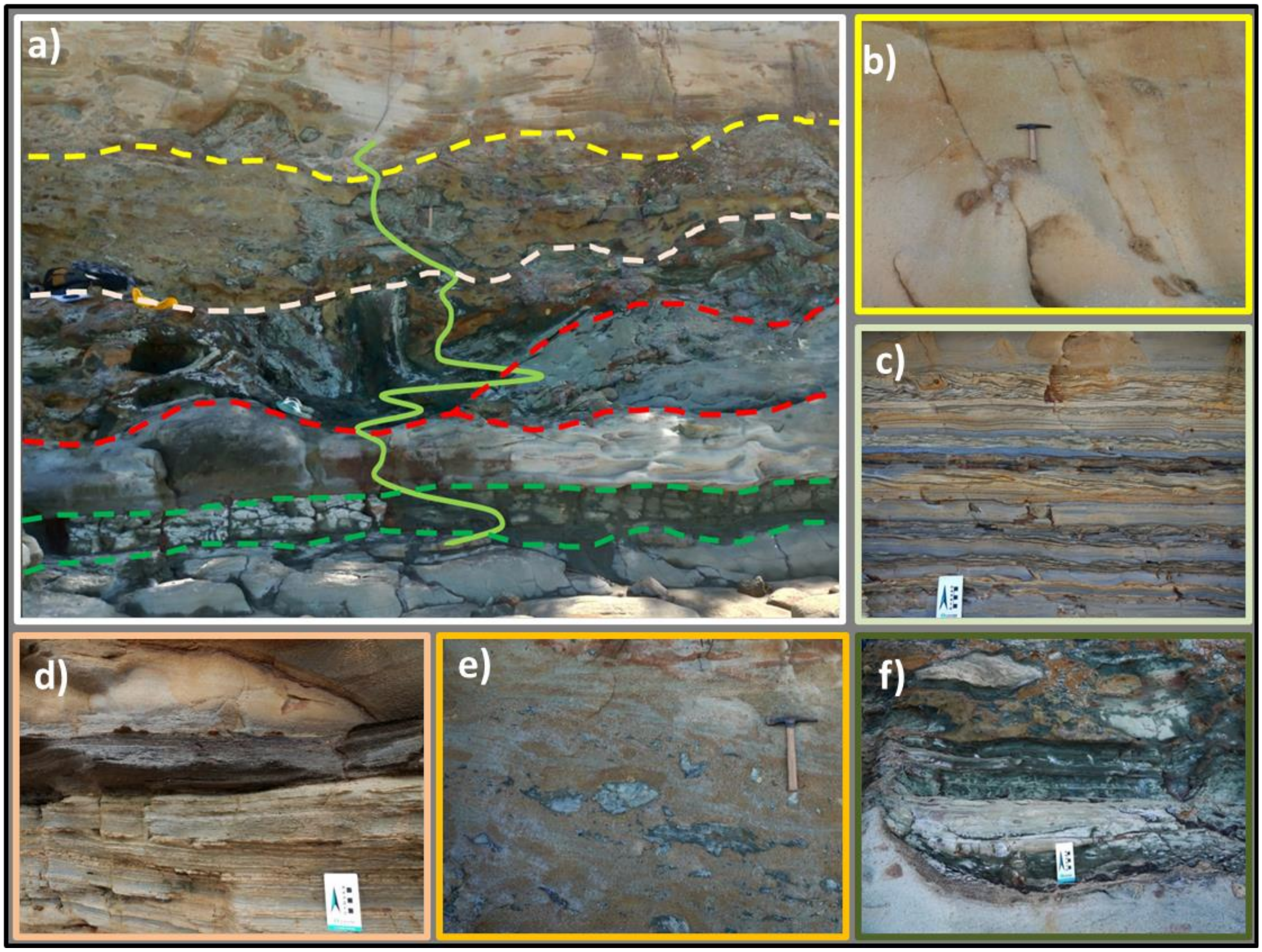

Figure 3 - Facies interpretation based on the outcrops description of Japaratinga and "Morro do Camaragibe" (Arienti, 1996) for positioning the architectural elements and lithological facies within the model, highlighting the main facies observed in the outcrops: a) channelized features and their associated structures. The dashed lines delimit sets of similar energy events, thus composing a characteristic facies. In light green, are plotted data from gamma-spectrometric tool collected in loco; b) massive sandstone facies; c) sandstone-shale interlaminated facies; d) slumping facies; e) high energy facies; f) low energy facies represented (shales).

For parameterization of the elastic model, the geophysical logs of compressional velocity (V_p), shear velocity (V_s), and density (ρ) were used throughout the studied section, covering reservoir and their embedding rocks, for each lithology described in the selected wells. Statistical analysis allowed the categorization of the values of these elastic parameters according to their corresponding lithology, and to establish average values for each property and the variations that may affect their three-dimensional distribution throughout the model.

2.3.2 1D MODELLING

For the 1D modeling, it was used the well 1-BRSA-875-SES, located in the offshore portion of the Sergipe Sub-basin. The studied interval is 26 meters thick and includes reservoirs and facies associated with deposits of Maastrichtian age interpreted as turbiditic channels (Figure 4).

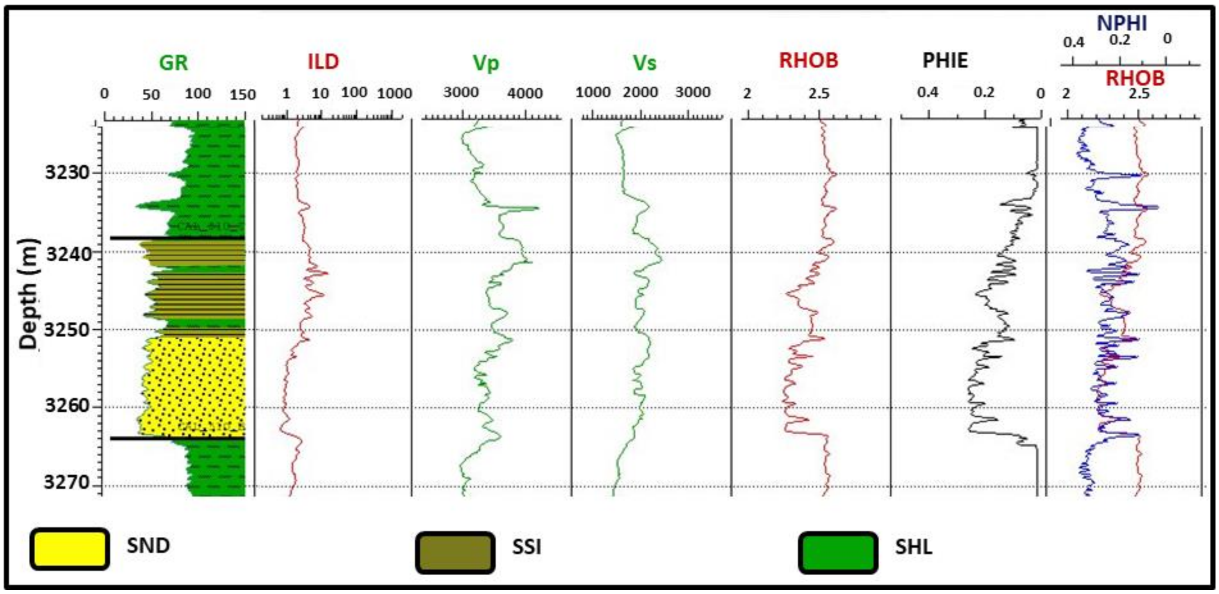

Figure 4 - Geophysical logs from well 1-BRSA-875-SES showing the sandstone facies (SND), sandstone-shale interlaminated (SSI) and shale (SHL). The first track contains a gamma-ray log curve (GR) colored by the facies used for the elastic modeling process. The black lines delimit the top and base of the channelized system. The other tracks contain resistivity (ILD), compressional velocity (V_p), shear velocity (V_s), density (RHOB), porosities (PHIE) and a set of density-neutron (NPHI) curves.

The data used in this modeling were the geophysical profiles acquired in the well, and seismic data and its attributes extracted along the trajectory of the wells (except for the shear sonic log that was not acquired for the well 1-SES-92-SES). The first part of the work consisted of making the impedance profiles P and S from the sonic, shear sonic and density profiles so that they were then converted to the time domain after the seismic-well calibration process and resampled to the frequency of seismic, 4 ms (Figure 5).

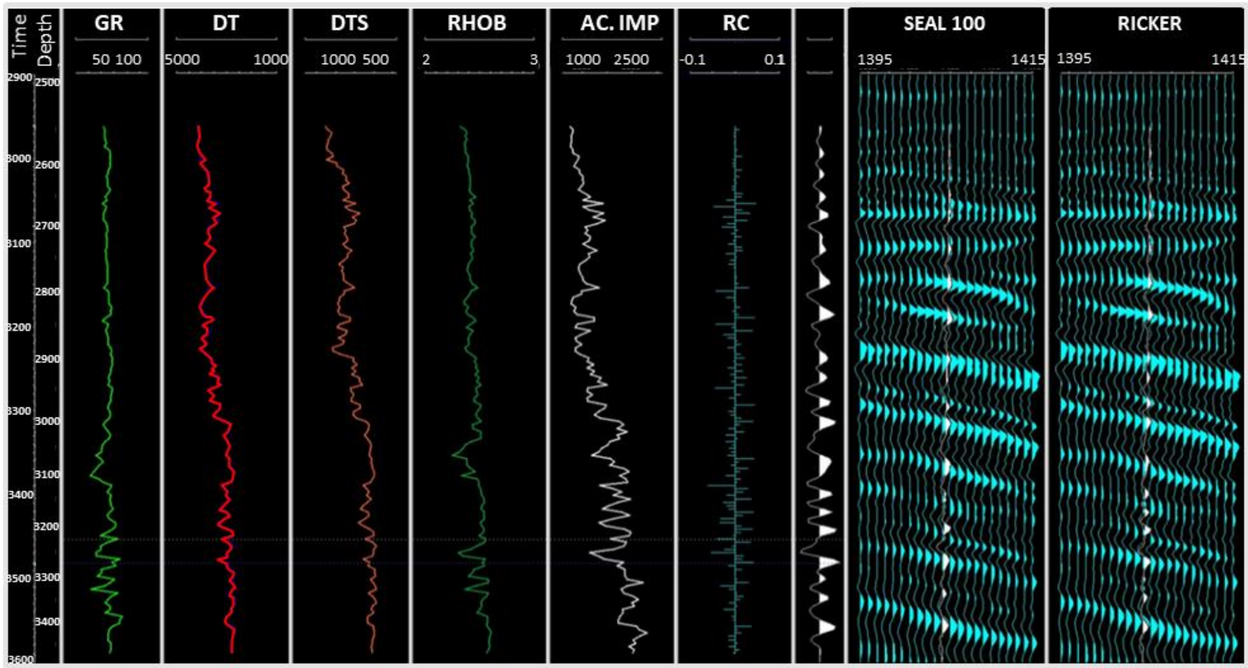

Figure 5 - Well-seismic calibration panel (well 1-BRSA-875-SES) containing: gamma-ray log curve (GR), sonic (DT), shear sonic (DTS), density (RHOB), acoustic impedance (AC. IMP), reflection coefficients (RC), synthetic seismic trace and seismic sections of strike and dip directions crossing the well 1-BRSA-875-SES with synthetic seismograms with wavelet extracted from the data, and with a Ricker of 30hz, respectively.

Reflection coefficients were generated from impedance data and resolved with Ricker wavelets of 25 Hz, 30 Hz, and 35 Hz dominant frequencies (figure 6), similar to the frequency content observed in the 1-BRSA-875 well region (wavelet length of 256 ms, in a 512 ms window, whose limits correspond to an envelope of the Maastrichtian reservoirs containing hydrocarbons in the Sergipe Sub-basin.

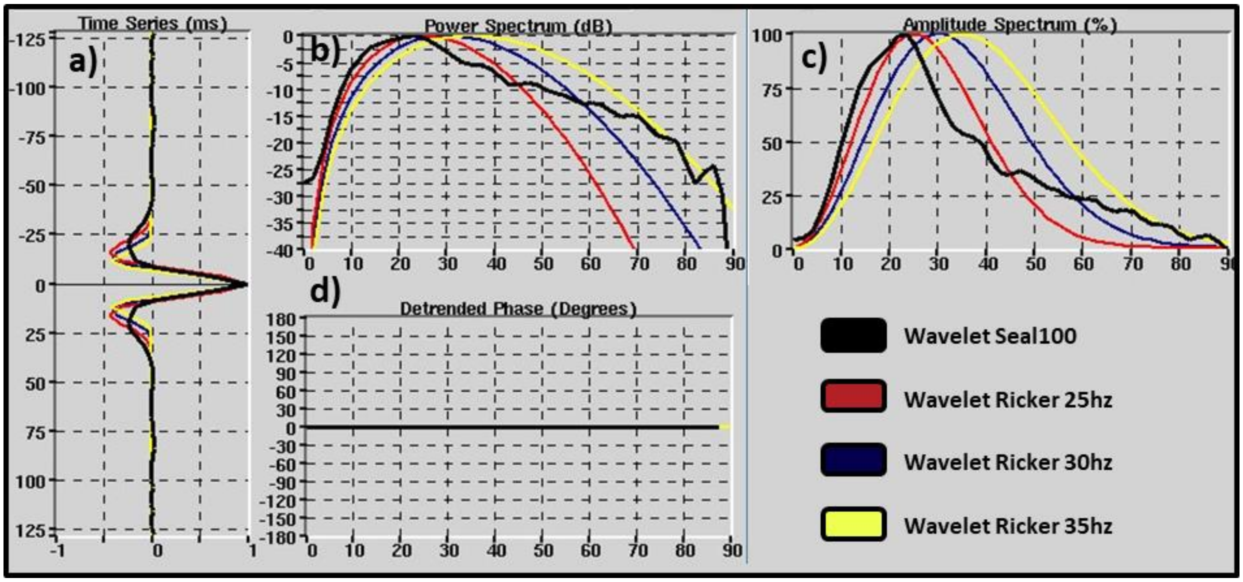

Figure 6 - Analysis panel for the compared wavelets: a) temporal representation of the wavelet; b) power spectrum of the wavelets with frequencies on the horizontal axis and amplitudes intensity on the vertical axis. c) amplitude spectrum with frequencies on the horizontal axis and amplitude values on the vertical axis. d) phase spectrum, with frequency on the horizontal axis and phase values on the vertical axis.

The elastic parameters, reservoirs thickness and seismic frequency in the 1D space were analyzed together (Figure 7). The process consisted of varying one property while the others remained fixed, and evaluating its influence on the synthetic seismic data and its attributes. This criterion was adopted because it is the conventional *modus operandi* for the seismic interpretation process when there is no information on the available wells. The range variation of the properties was estimated through statistical analysis over the studied interval while the other properties were fixed at their average values. The samples were collected at the white peak for the entrance and the black peak for the exit for sandstones, for this study considered as negative and positive values of amplitude, respectively. Similar analyzes were also performed for the V_p/V_s ratio attributes and the difference between P and S impedances (I_p-I_s).

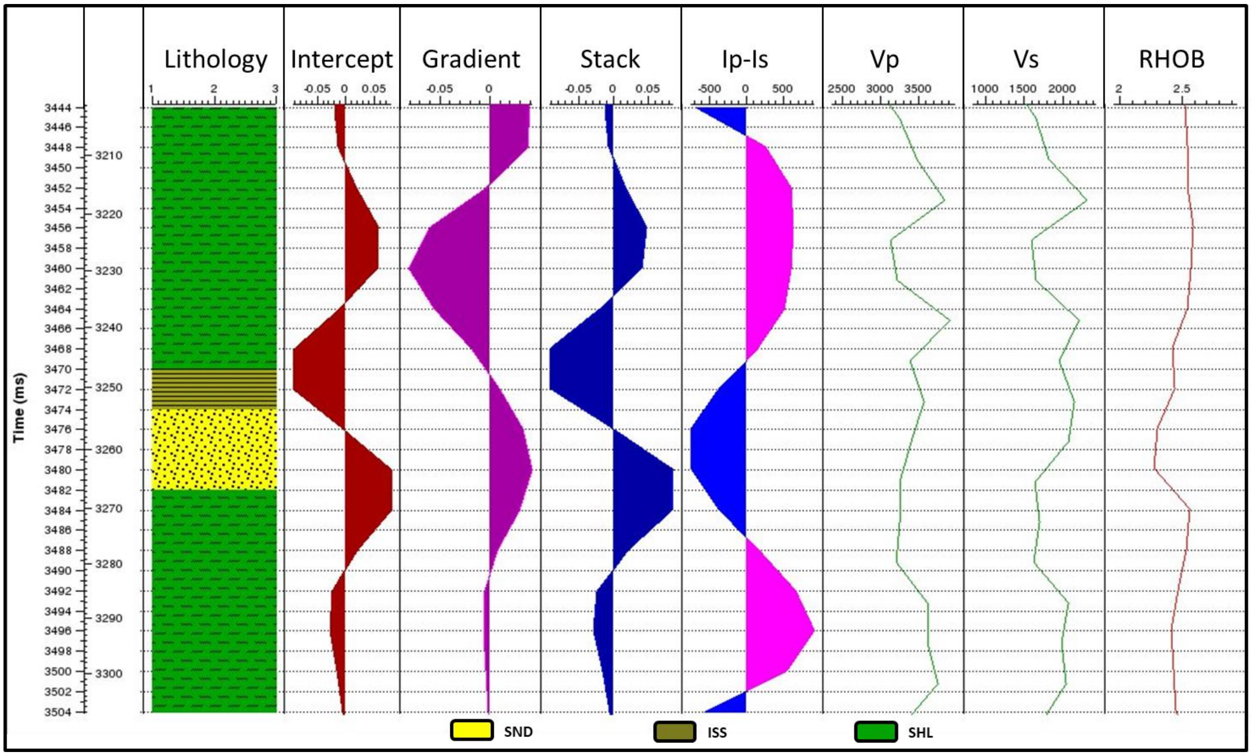

Figure 7 - Physical properties for ~~of~~ well 1-BRSA-875-SES. The vertical axis in the time domain, exhibiting the lithological representation in the first track, followed by the intercept trace, gradient, total stacking, I_p-I_s (the difference between the impedance of the P and S waves), P wave velocity (V_p), S wave velocity (V_s) and density (RHOB).

2.3.4 GRID CONSTRUCTION

2.3.4.1 SYNTHETIC MODELING

The software used to create the numerical grid was Petrel (Schlumberger, version 2015). The geology was represented in a numerical grid whose cell size measures 1 m vertically to 20 m horizontally. A large conduct was dimensioned with 4960 m of extension, 3130 m of width and an average depth of 130 m, oriented in the NW-SE direction. The unitary channels were dimensioned with the architectural channel element varying between 100 to 140 m in width to 15 to 10 m in depth, the base to the top of the channel, dimensions compatible for these types of features in a deepwater sedimentation environment (Moraes *et al*., 2006). These channels also varied in thickness along the depositional axis. The channels levees were built twice the width of their respective channel, being measured from the center of the channel. The non-reservoir architectural element represents the rocks not associated with the confined flow, i. e., they are the embedding rocks. The architectural elements are in agreement with what has been described for the Sergipe-Alagoas Basin (Arienti, 1996; Silva, 2005), and also with what has been described in the literature (Mayall & O'Byrne, 2002; Moraes *et al*., 2006; Deptuck & Sylvester, 2007) and what was observed in the basin in the study of analogous outcrops.

Once the geometric scenario was elaborated, the facies were positioned within their architectural elements in which different stacking patterns (horizontal and vertical) were contemplated, as well as a sinuosity variation of these bodies as the energy of the system varies. In the model, the construction of the architectural elements considered the cut and fill hierarchy, where the newer channel overlaps the older one, i.e., the incision was considered.

These architectural elements were filled with the facies described according to Arienti (1996), and were organized to fill the architectural elements from the bottom up. The base of the channels was essentially filled by slumping or diamictite facies, followed by conglomerates or conglomeratic lags of very coarse granulation, with some permo-porosity, but not interesting as reservoir facies. These facies are deposited during the periods of highest energy of the turbiditic flows. The fine to coarse-grained sandstones represent the main reservoir facies and overlaps diamictites and conglomerates. The interlaminates of sandstone and shale are deposited due to the decrease in the energy of the system and can be found at the more superior portions to the channels (abandonment facies) or at the adjacent portions to the channel, the levee architectural element. Shales are facies deposited at a time when the energy of the system is very low, and are essentially characterized as non-reservoir facies, although they can occur internally in all architectural elements (Figure 8).

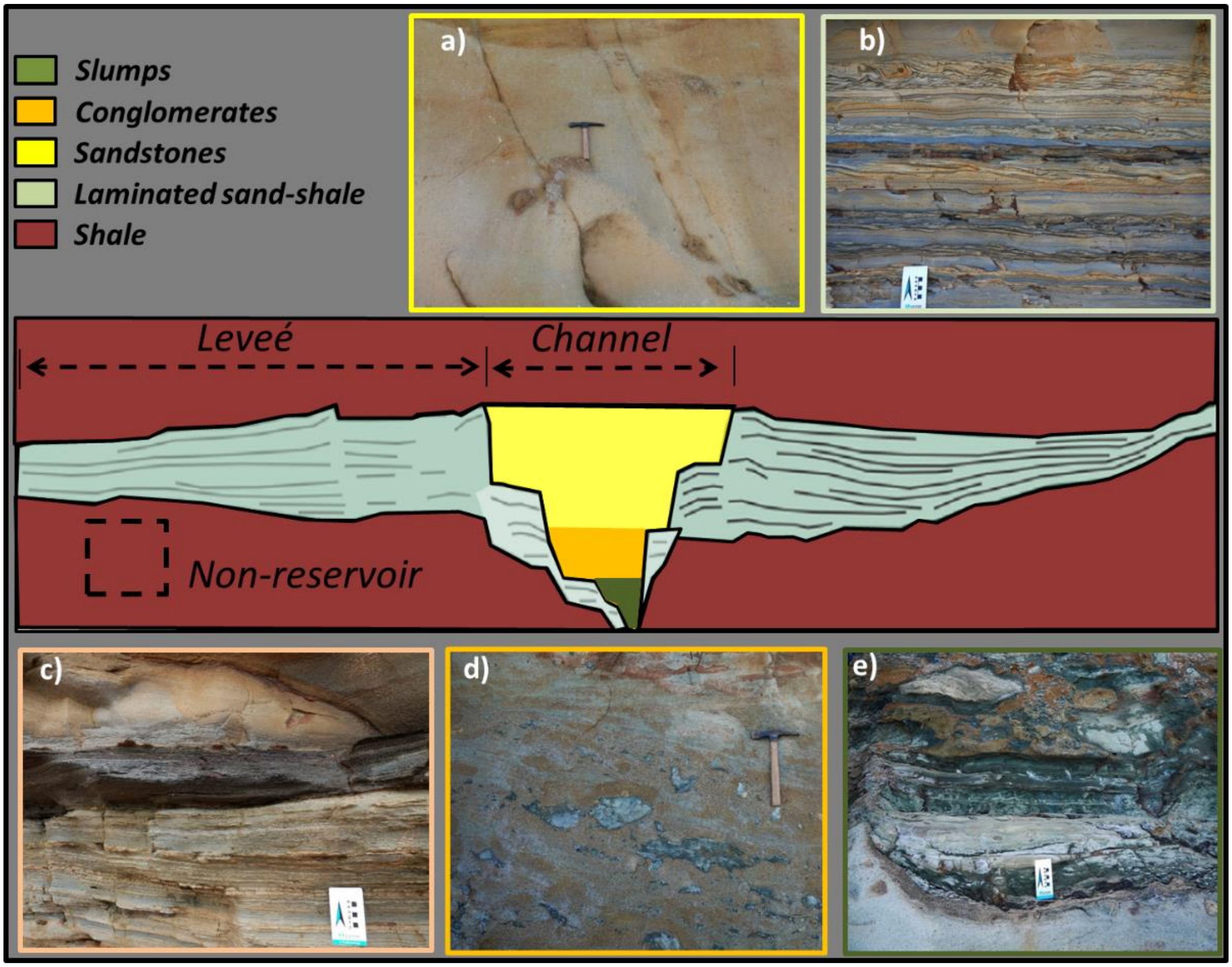

Figure 8 - Architectural elements used for the modeling, subdivided into channel, levee, and non-reservoirs. a) sandstone facies, that represent the main reservoirs; b) sandstone-shale interlaminated facies, which can represent secondary reservoirs; c) non-reservoir facies, expressed by shales; d) facies of coarser sediments and conglomerates; “e) slumping facies. These facies are inserted into the architectural elements where each architectural element can contain one or more of these facies.

Thus, the channel architectural element can contain all the facies described, the levee architectural element contains the heteroliths and the non-reservoir architectural element contains only shales (Figure 9).

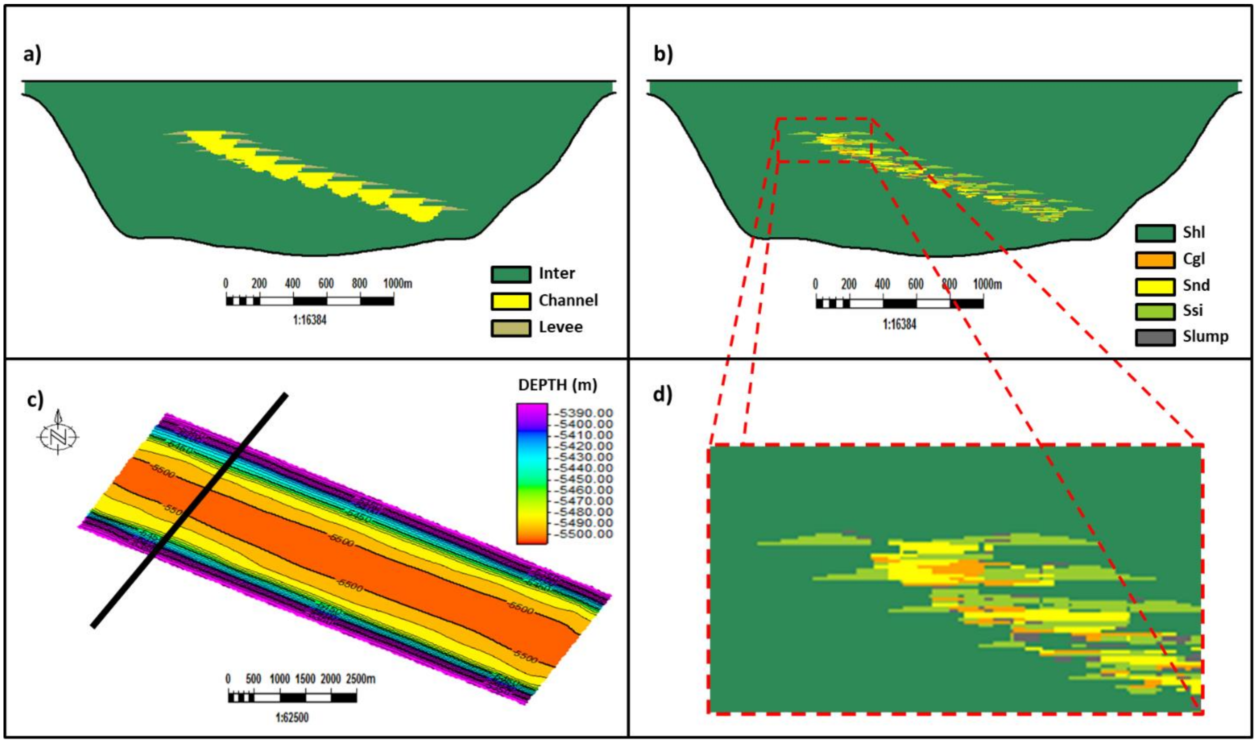

Figure 9- Cross-sections for the synthetic model: a) depositional trough showing the architectural elements generated through modeling, where in dark green is the non-reservoir “inter-channel architectural element (shales) in yellow the “channel” element (sandstones) and in ocher the “levee” architectural element (interlaminated); b) depositional trough showing the facies distributed in the architectural elements “slump” facies slumped sediments, “shl” = shales, “snd” = sandstones, “cgl” = conglomerates, and “ssi” = sandstone-shale interlaminates. c) plan view of the depositional trough with the cross-section location - warm colors represent the greatest depths; d) zoom into the facies variation from “b”.

The construction of the elastic model was guided by analyzing the values of V_p, V_s and density (ρ_B) in the wells containing hydrocarbon reservoirs in the studied section. A statistical analysis was performed in the reservoirs interval, and the average values for each elastic property were used for the variogram model to support the properties distribution along the grid (Figure 10).

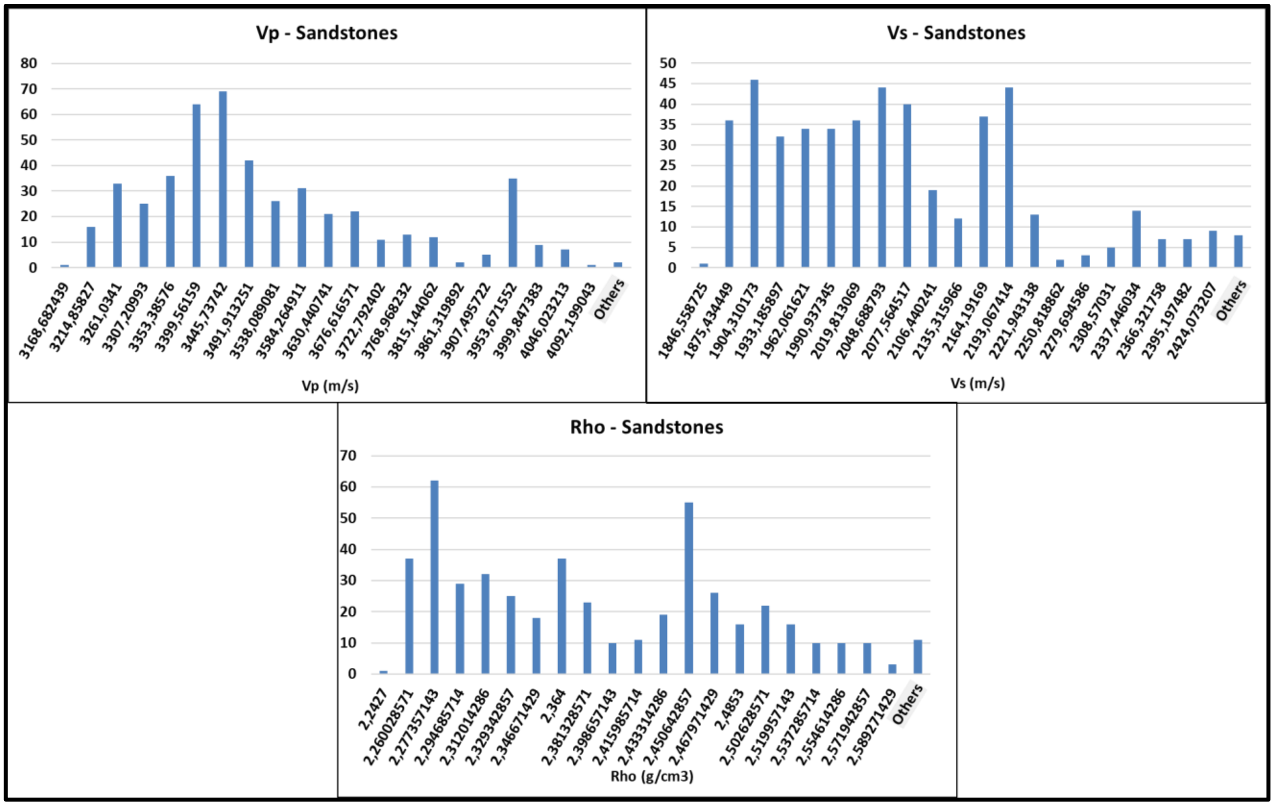

Figure 10 - Histograms illustrating elastic properties frequency values (compressional velocities, shear velocities and density, respectively) for the Maastrichtian sandstones of the Sergipe Sub-basin deepwater reservoirs (well 1-BRSA-875-SES).

The elastic properties were populated on the grid through normal distribution histograms and anisotropic variograms, respecting the main orientation of the turbiditic flow as well as the geometric factors of the trough where all facies were deposited. Each elastic property was parameterized according to its distribution range defined in the analysis of the data available for the Maastrichtian section (Figure 11).

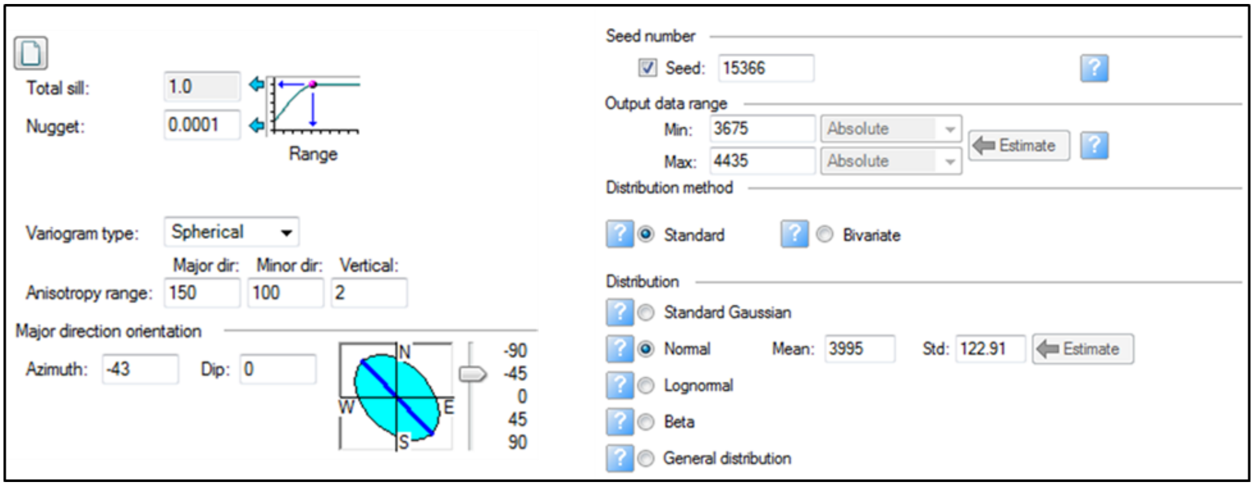

Figure 11 - Parameterization example of variogram for the V_p property of the sandstone facies for a three-dimensional distribution in the numerical grid. On the left, the geometric attributes of the variogram, such as its transversal and longitudinal investigation dimensions, and its vertical extension. On the right, the variation ranges of the V_p values of the same facies obtained from statistical analysis.

With the elastic parameters properly positioned within the grid, equation 1.1 (Fatti *et al*., 1994) was applied for zero ($\theta = 0$), near θ = 5, mid ($\theta = 20$) and far ($\theta = 35$) at each point of these models:

$$R_{pp}(\theta) = (1 + \tan\theta^2)\frac{\Delta I_p}{2\Delta I_s} - 8\left(\frac{V_p}{V_s}\right)^2 sin^2\theta\,\frac{\Delta I_s}{2I_s} - \left[\frac{1}{2}tan^2\theta - 2\left(\frac{V_s}{V_p}\right)^2 sin^2\theta\right]\frac{\Delta_\rho}{\rho} \qquad (1.0)$$

where: Rpp is the reflection coefficient, θ is the angle of incidence, I_p *is the P wave impedance,* I_s *is the S wave impedance,* V_p *is the compressional velocity,* V_s *is the shear velocity and* ρ *is the density.*

From the reflection coefficients obtained, wavelets were used (Figure 6) to generate their respective seismic volumes through the convolutional model, within the Open Works platform (Landmark, version r5000). Useful frequency content for the seismic data was arbitrated between 10 to 35 Hz. After the convolution of the wavelets with the reflection coefficients, all the offsets were added together to generate the full-stack data, and finally, evaluated whether it actually represents the geology expressed in the built model.

Cross-sections were extracted along the channel complex in its proximal, intermediate, and distal portions, so that variations in architectural and facies models could be observed through their expressions in the obtained synthetic seismic data. For the same stratigraphic interval, images expressing wavelet variations of different frequencies were obtained for different source-receiver distances, expressing the sensitivity in relation to the geological properties and the acquisition parameters of the seismic data. These analyses were also carried out in map view, in order to observe the seismic behavior in the basal, intermediate, and abandonment portions of the depositional system.

2.3.4.1 REAL CASE MODELING

For the geological modeling of the data observed in the basin, the structural model was generated through the seismic interpretation in three-dimensional volumes, positioning the envelope of the model into the embedding rocks, i.e., the shales. The seismic interpretation strategy adopted was such that the shape and position of the architectural elements could be guided through seismic cubes of attributes, so that the uncertainty of position of the reservoir limits could be reduced. The difference between the acoustic and elastic impedances (I_p-I_s) was used in the studied area. This attribute was chosen through qualitative analysis of what best represents the geometry of channelized bodies observed in analogues from the basin and also from the literature

The same procedure was adopted for facies. They were separated according to their responses in geophysical logs and rock samples from analogous reservoirs. After the distribution of facies, the elastic parameters were distributed on the grid to assess how close it could be possible to obtain the input parameter that gave rise to the architectural elements of this model, in this case, the I_p-I_s attribute.

The values of the elastic parameters were obtained through the velocity and density profiles available for the wells that crossed the reservoirs and were distributed through kriging on the grid. For comparative purposes, these parameters were distributed through the minimum and maximum values and their means through kriging along the grid interval, with the impedance cube P as trend. These parameters were then distributed with the average values set for the sandstone facies, using the same cube as a trend. Finally, the values for the sandstone facies were distributed through the facies statistics, and the values of V_p and V_s were distributed using maps of V_p and V_s derived from the equations obtained in the modeling. The proposed methodology is outlined in Figure 12.

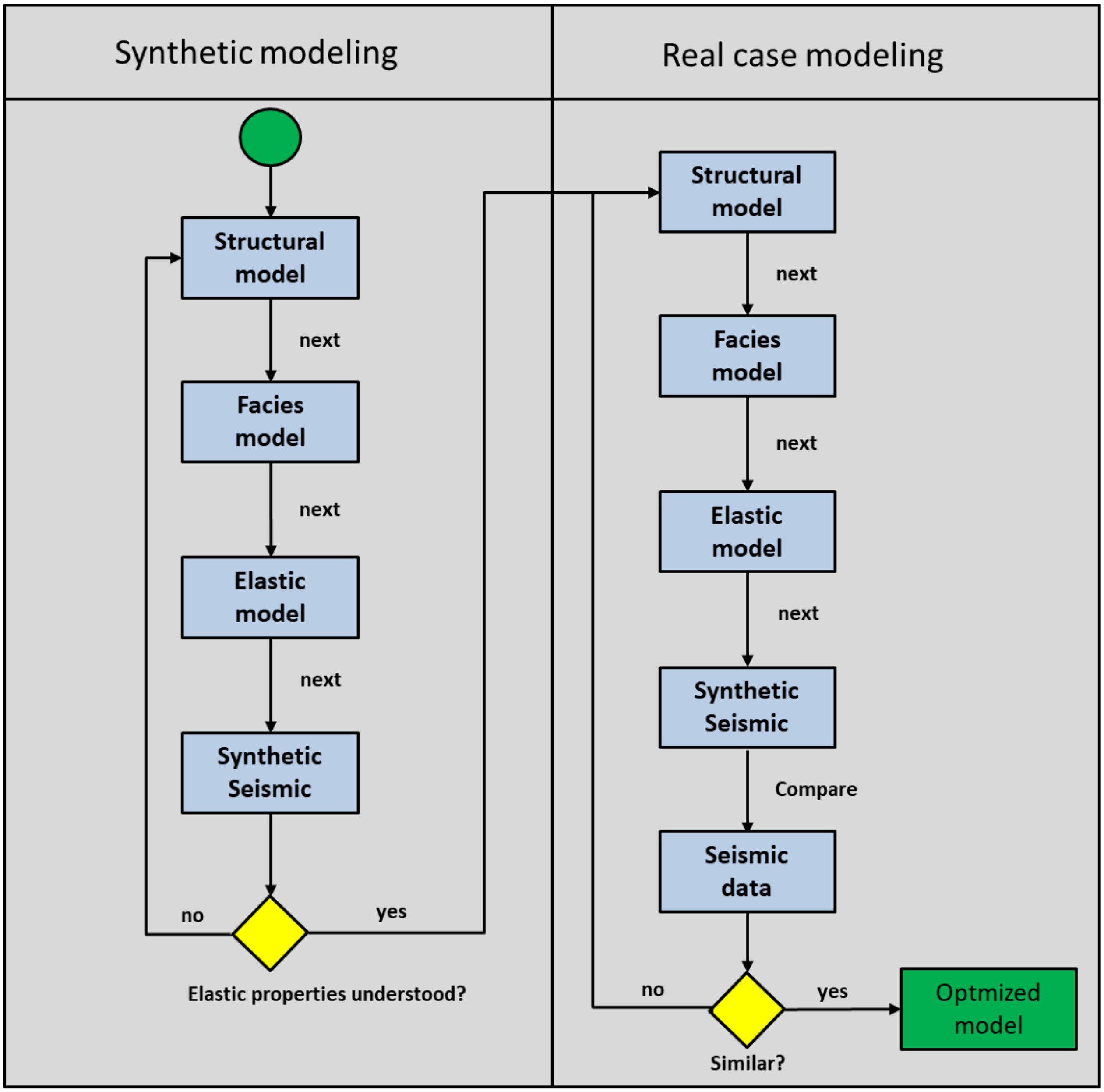

Figure 12 - Flowchart representing the conceptual modeling (left), where the architectural elements and facies are created according to the data described in the literature and data described in the basin, and the geological modeling (right), where the data were collected and described in the basin.

3 RESULTS AND DISCUSSIONS

Understanding the subsurface geology is essential for the characterization of an oil reservoir. The delimitation of the depositional system to which this reservoir is related, is the initial stage of this process and is strongly influenced by the seismic model available in the region to be studied. The interpretation of the seismic volume provided the external geometries of the geological bodies (Figure 13). The seismic interpretation revealed regional horizons linked to the 2nd and 3rd order surfaces, of a more regional character, and 4th order surfaces, which envelop the Maastrichtian channelized reservoirs of the Calumbi Formation, modeled in this study. A greater detailing was not possible due to the limited vertical resolution of the seismic data available in the area, estimated between 25 to 30 meters, with seismic speeds around 3000 m/s, and useful frequency content from 20 to 35 hz (Figure 6; Widess, 1973).

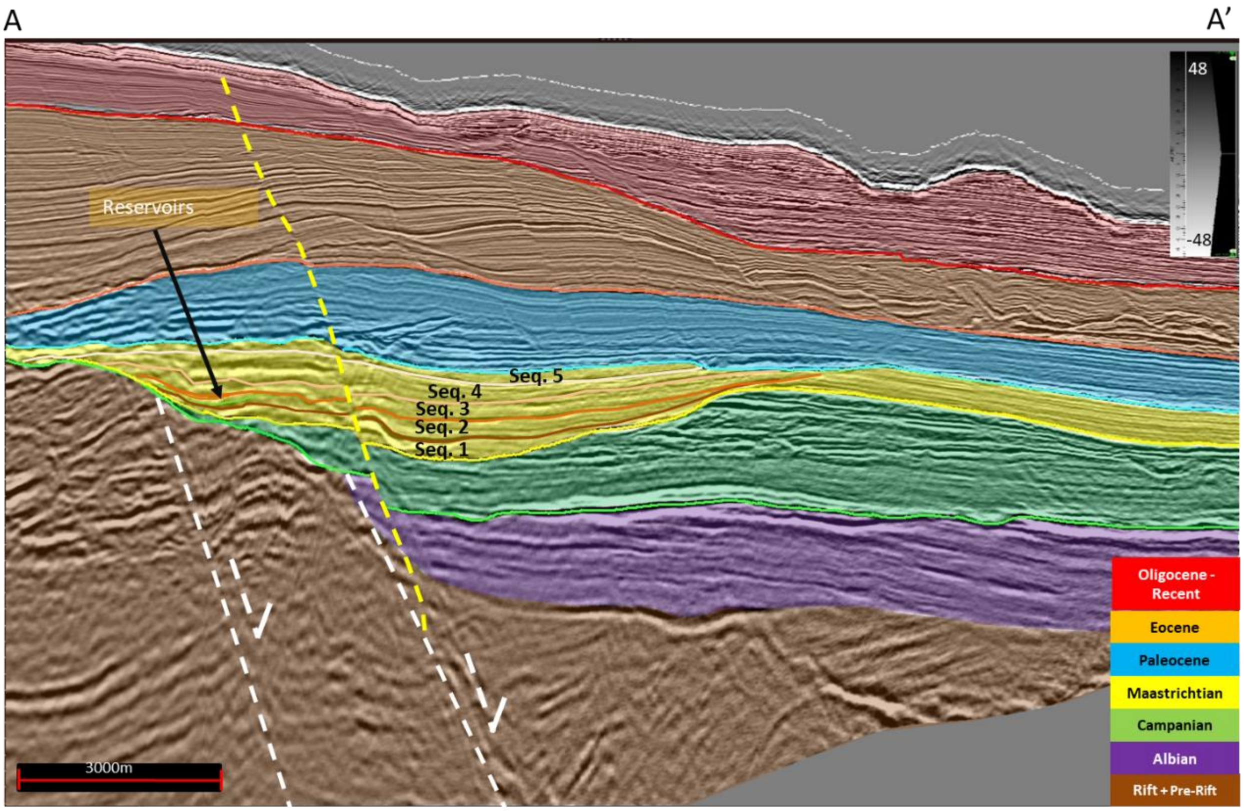

Figure 13 - Interpreted seismic section exhibiting the external geometries of the geological bodies necessary for modeling (A-A' in figure 1). The colored sections represent different geological ages with an emphasis on the Maastrichtian section, in yellow. Within this sequence are the internal subdivisions corresponding to the limits of 4th order sequences. The characterized reservoirs are positioned in sequence 2 (4th order). The dashed lines represent fault plans.

Seismic attributes corroborate the interpretation of the reservoirs as a set of channels inserted into a complex of 4th order channels. The attribute of the minimum values of the difference between P and S impedances, obtained through seismic inversion, provided the best product for this characterization (Figure 14c).

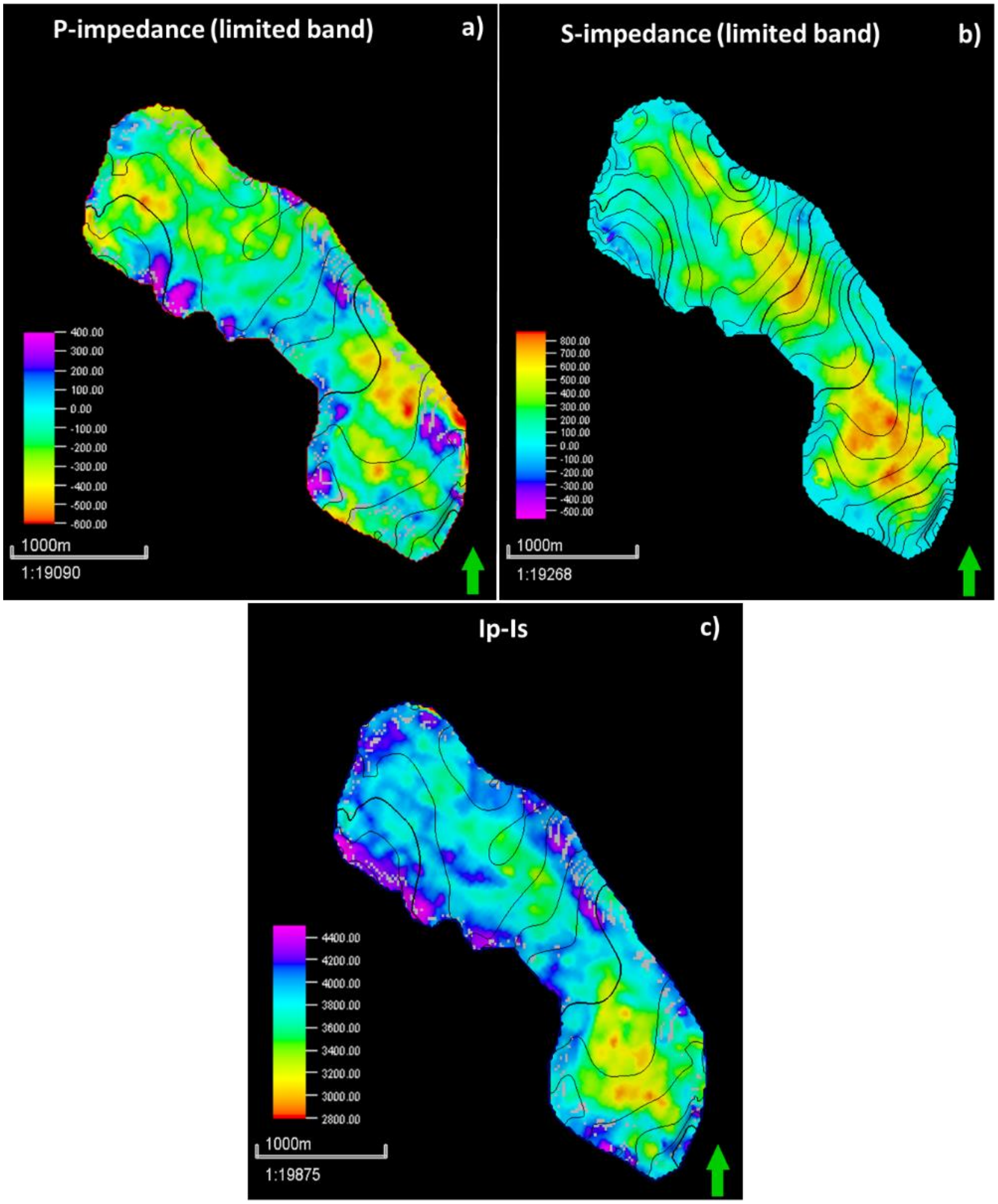

Figure 14 - Maps of seismic attributes extracted between the upper e lower surfaces that envelop the studied reservoirs: a) map of minimum I_p values; b) map of maximum I_s values; c) map of minimum I_p-I_s values.

The addition of well information into the seismic interpretation process enabled its calibration with data obtained directly from the rocks and, indirectly, through geophysical logs, as they provide more accurate information, although punctual. The data integration allowed to interpret the reservoirs as a system of Maastrichtian turbiditic channels, delimited by 4th order stratigraphic surfaces with an average thickness of 30 m. Well-logs interpretation supported a facies set beginning with conglomeratic sandstones at the base of the channels, with normal gradation towards the top of the sands, overlaid by sandstone and shales heteroliths and finalized by shales (Figure 15).

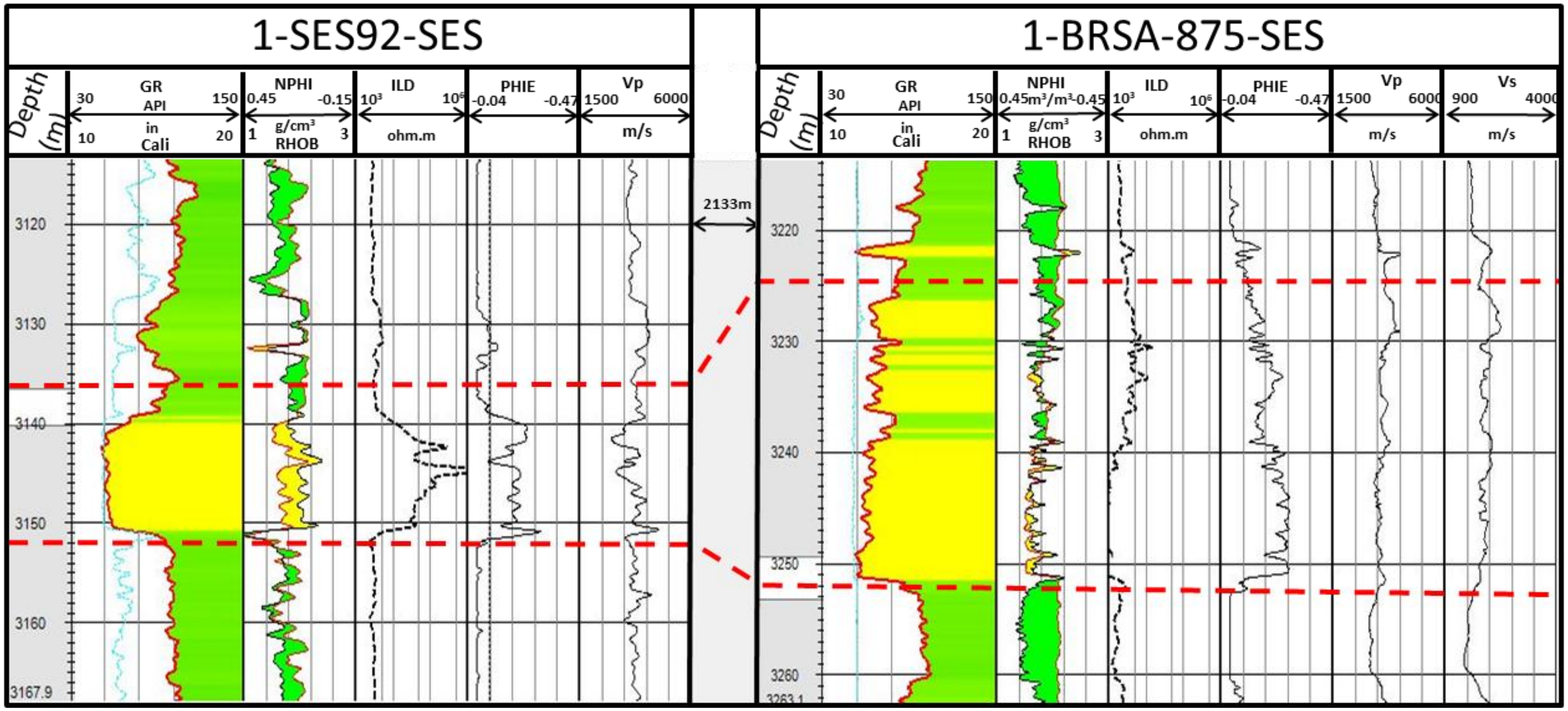

Figure 15 - Geophysical logs for the wells 1-SES-92-SES and 1-BRSA-875-SES showing the correlation between the reservoirs. First track contains the gamma-ray (GR) log colored by facies of fine-grained sediments (shales and siltstones) in green and of coarse-grained sediments (sandstones and conglomerates) in yellow. The second track contains the density (RHOB) and neutron (NPHI) curves, colored in yellow by potential reservoirs and in green by non-reservoirs. The following tracks represent the resistivity (ILD), porosity (PHIE), and P wave (V_p) and S wave (V_s) velocities, respectively.

Synthetic seismograms generated from the sonic, density and wavelet logs obtained directly from the seismic data, enabled the identification of the seismic signature of the entire 4th order interval, and some of its filling facies (Figure 5). The upper interlaminates show positive amplitude values (black peak in this study), while the underlying sandstones, identified as the best reservoir facies, exhibit negative amplitude values (white peak in this study; Figure 16).

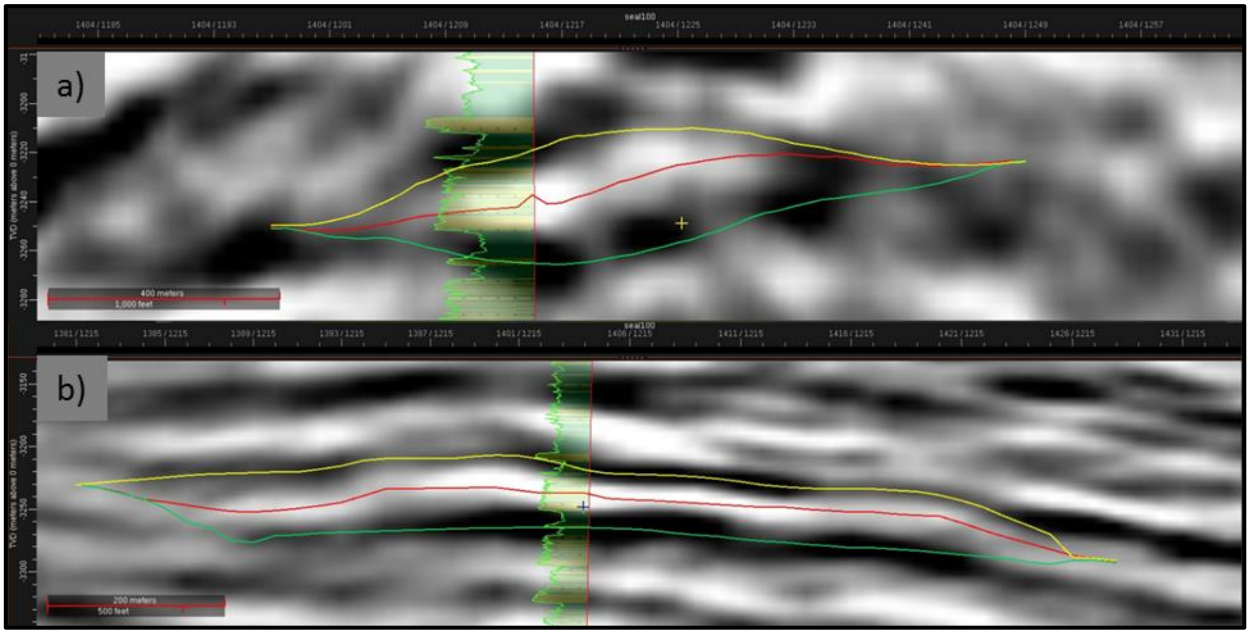

Figure 16 - Seismic sections across well 1-BRSA-875-SES, representing strike (a) and dip (b) orientation. The red vertical line represents the well trajectory projection containing on its left the gamma-ray curve colored according to the interpreted lithology. The yellow horizon represents the entry of the modeled interval, the red horizon represents the entry of the best portion of the reservoir and the green line the exit of the channel complex.

As the information from wells is punctual, it can be extrapolated to the adjacencies by means of the seismic data. However, different combinations of impedance contrasts, originated by differences in lithologies, fluid content and even the layer thickness can provide the same seismic signature.

A better understanding of the factors affecting seismic amplitudes can be obtained through direct modeling, optimizing this extrapolation. The graphs in Figure 17 show the influence of compression and shear velocities, densities, and thicknesses in the sandstones sampled by the wells. It is evident that the parameters that most impact the amplitudes of these bodies are the seismic velocities to the detriment of the thickness.

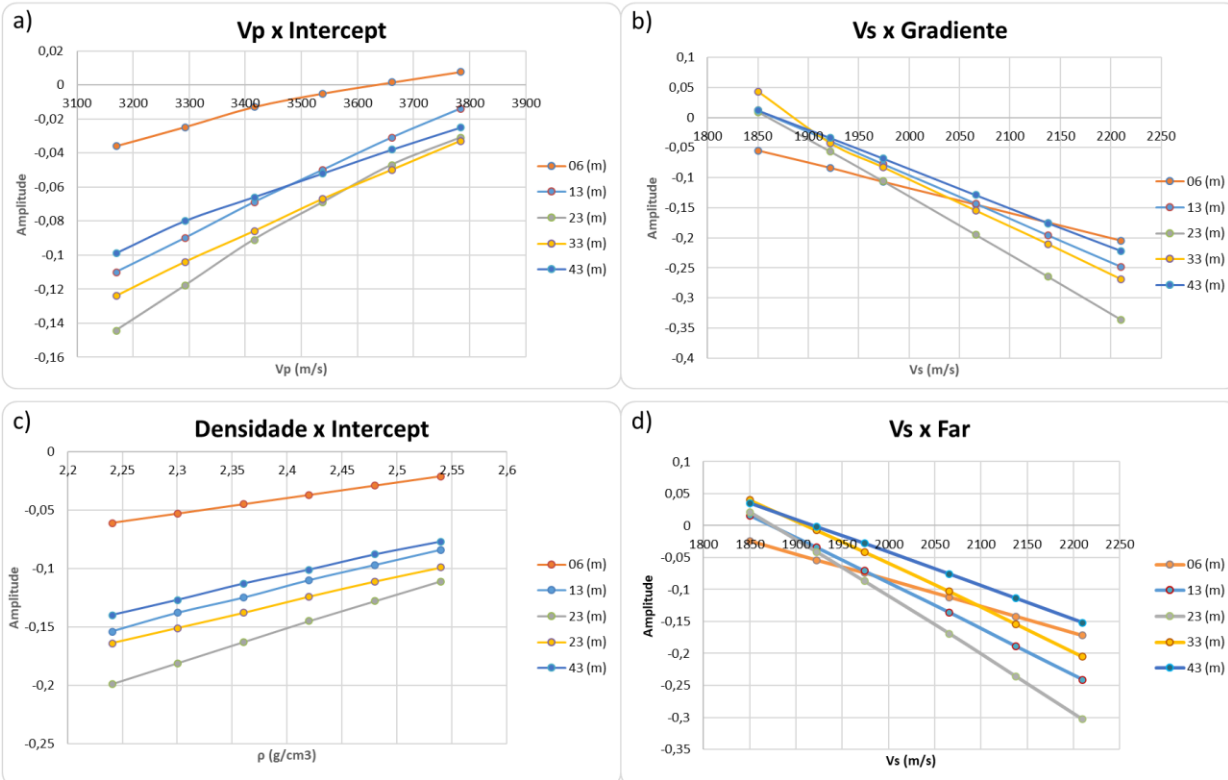

Figure 17 - Correlation graphs displaying the behavior between elastic parameters (horizontal axis), seismic amplitude of the reservoir top (vertical axis) and thickness variation (different line colors) generated from the geophysical logs for well 1-BRSA-875-SES. Graphs "a" and "c" represent the acoustic cases by the relations between V_p and density, while graphs "b" and "d" represent the elastic case through the relations between V_s, gradient and far.

Although these sedimentary bodies are subjected to tuning effects (Figure 18), this influence prevails even for very small thicknesses modeled for the seismic sampling limit (4 ms). It can be assumed that sandstones with petrophysical properties different from those sampled by the wells can be neglected in the construction of the geological model either because they have smaller thicknesses, or because they have smaller porosities related to an increase in compressional velocity.

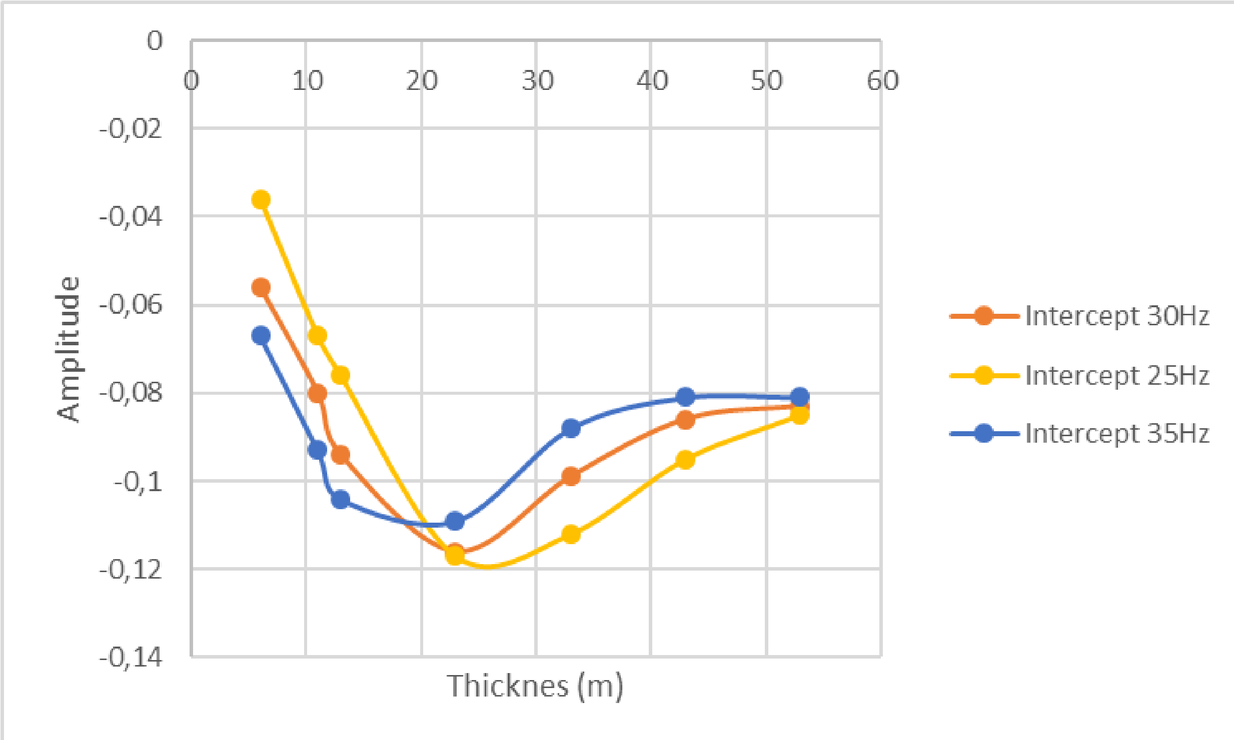

Figure 18 - Amplitude x thickness graph illustrating the tuning effect measured in the seismic data, where the thicknesses are distorted by the interaction of the input and output amplitude peaks for the modeled reservoirs.

The refinement of the structural model was possible with the use of the I_p-I_s attribute in such a way that the geometry of the channels showed a better result than the use of the amplitudes only (Figure 14). The modeling of parameters that influence this attribute was restricted only to compression velocities, shear velocities, and thicknesses, as they are the main sources of variation in relation to the seismic data and its derivatives. The results obtained show that the main variations of V_p and V_s are below the tuning zone (Figure 19), and that after 30 m (average limit of seismic resolution) these variations are smoother or even non-existent.

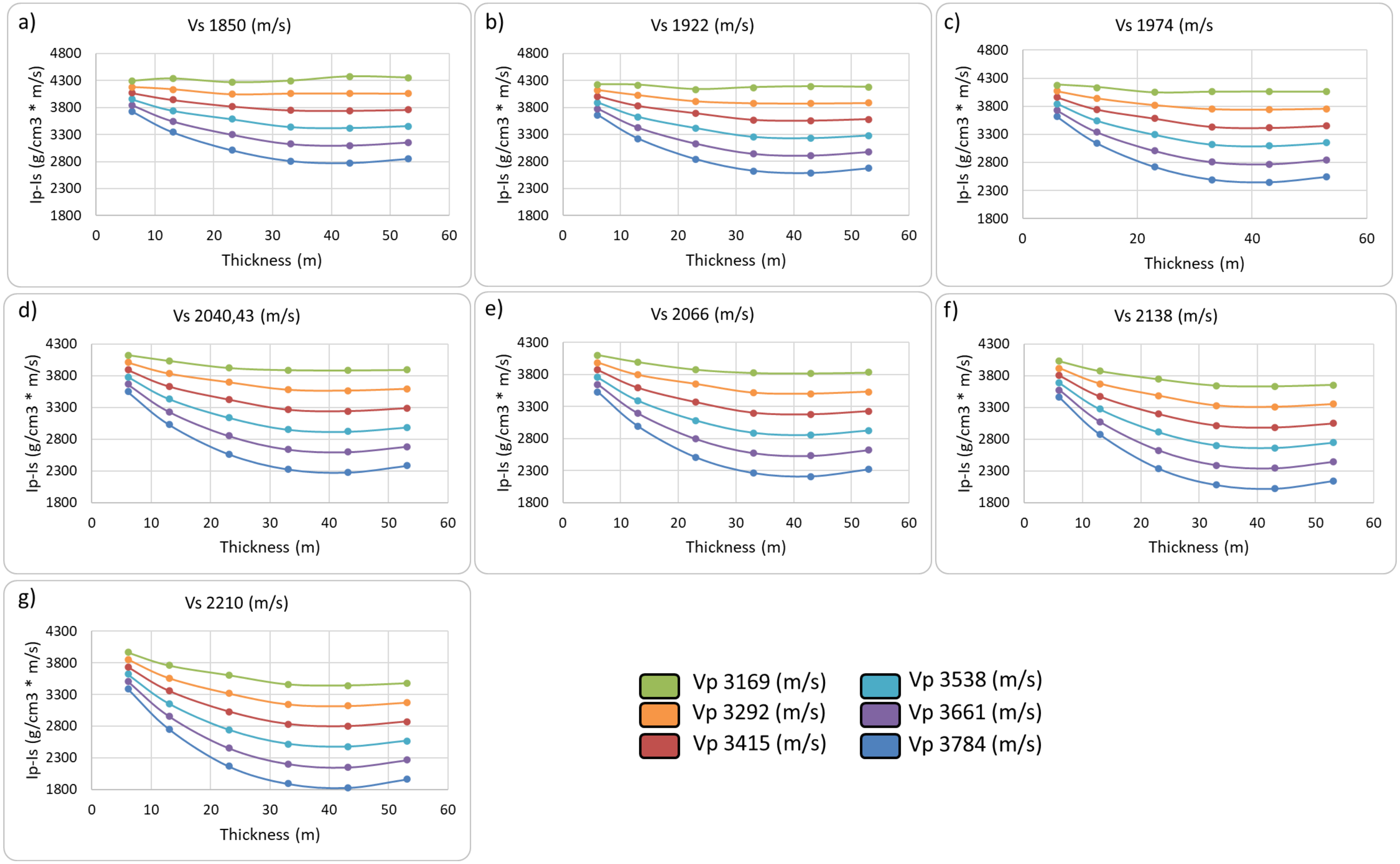

Figure 19 - I_p-I_s response analysis graphs for V_p, V_s, and thickness variations. Greater variations are observed for V_p and V_s values than the thickness.

The analysis of these relations allowed the creation of an equation that relates I_p-I_s, V_p, V_s and thickness, from the curves that best adjusted the points collected in the analysis. This final equation was obtained from 5th order polynomial equations that adjusted the curves shown in Figure 19, whose coefficients for each term were correlated for each value of the elastic properties and the thickness of the sands.

$$I_p - I_s = A * h^2 + B * h + C \tag{2.0}$$

$$\begin{aligned} A = \Big(&(1{,}65627E-09) * V_s^2 + \big(-(7{,}53887E-06)\big) * V_s + (7{,}06985E-03)\Big) * V_p \\ &+ \big(-(6{,}71070E-06) * V_s^2 + (3{,}13561E-02)\big) * V_s \\ &+ (-3{,}05415E+01) \end{aligned} \tag{2.1}$$

$$\begin{aligned} B = \big(&(-1{,}19909E-07) * V_s^2 + (5{,}31421E-04) * V_s + (-4{,}70777E-01)\big) * V_p + \\ &\big((3{,}93777E-04) * V_s^2 + (-1{,}86378E+00) * V_s + (1{,}71574E+03)\big) \end{aligned} \tag{2.2}$$

$$\begin{aligned} C = \big(&(8{,}08450E-07) * V_s^2 + (-3{,}52563E-03) * V_s + (4{,}16185E+00)\big) * V_p + \\ &\big((-2{,}91002E-03) * V_s^2 + (1{,}23309E+01) * V_s + (-1{,}01000E+04)\big) \end{aligned} \tag{2.3}$$

Where I_p is the P wave impedance, I_s is the S wave impedance, V_p is the P wave velocity, V_s is the S wave velocity, A, B and C are coefficients that depend on V_p and V_s, and h is the thickness of the sand interval.

The equation can estimate with a good degree of reliability which values of V_p and V_s generate the values of the attribute I_p-I_s given the reservoirs thickness values of the. The comparison of the modeled I_p-I_s data with the measured data allowed to adjust the input parameters on the geological modeling if there is a discrepancy between them, for example, low values of V_p in areas where it is known that the porosity is low, implying an erroneous classification of facies as reservoirs.

The thickness and frequency variation were tested in a synthetic three-dimensional model with calibrated parameterization in the basin and with the data provided in the literature. At this model, the depositional trough was oriented from NW-SE with the flow direction equally oriented in this same way (Figure 20). The structural framework can be seen in Figure 21 where the frequency remained fixed at 30 hz and only the thickness varied along the depositional axis, decreasing its values in the same direction as the turbiditic flow decreases its energy of the. It is possible to affirm through the seismic data generated from the grid (Figure 21) that the tuning effect significantly impacts the seismic model, especially in the distal section, where this effect tends to significantly overestimate deposit thicknesses, in addition to connecting a system originally disconnected, depending on the frequency of the data in this region.

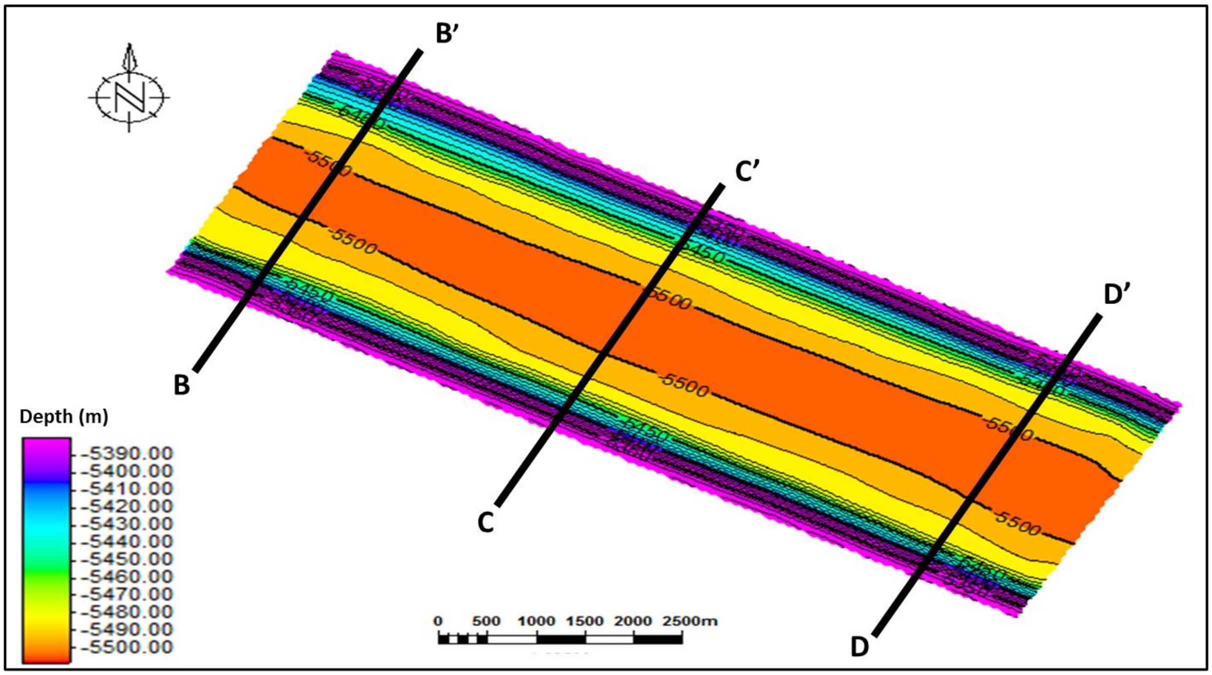

Figure 20 - Plan view of the depositional trough oriented in NW-SE direction. These sections will be analyzed in figure 21.

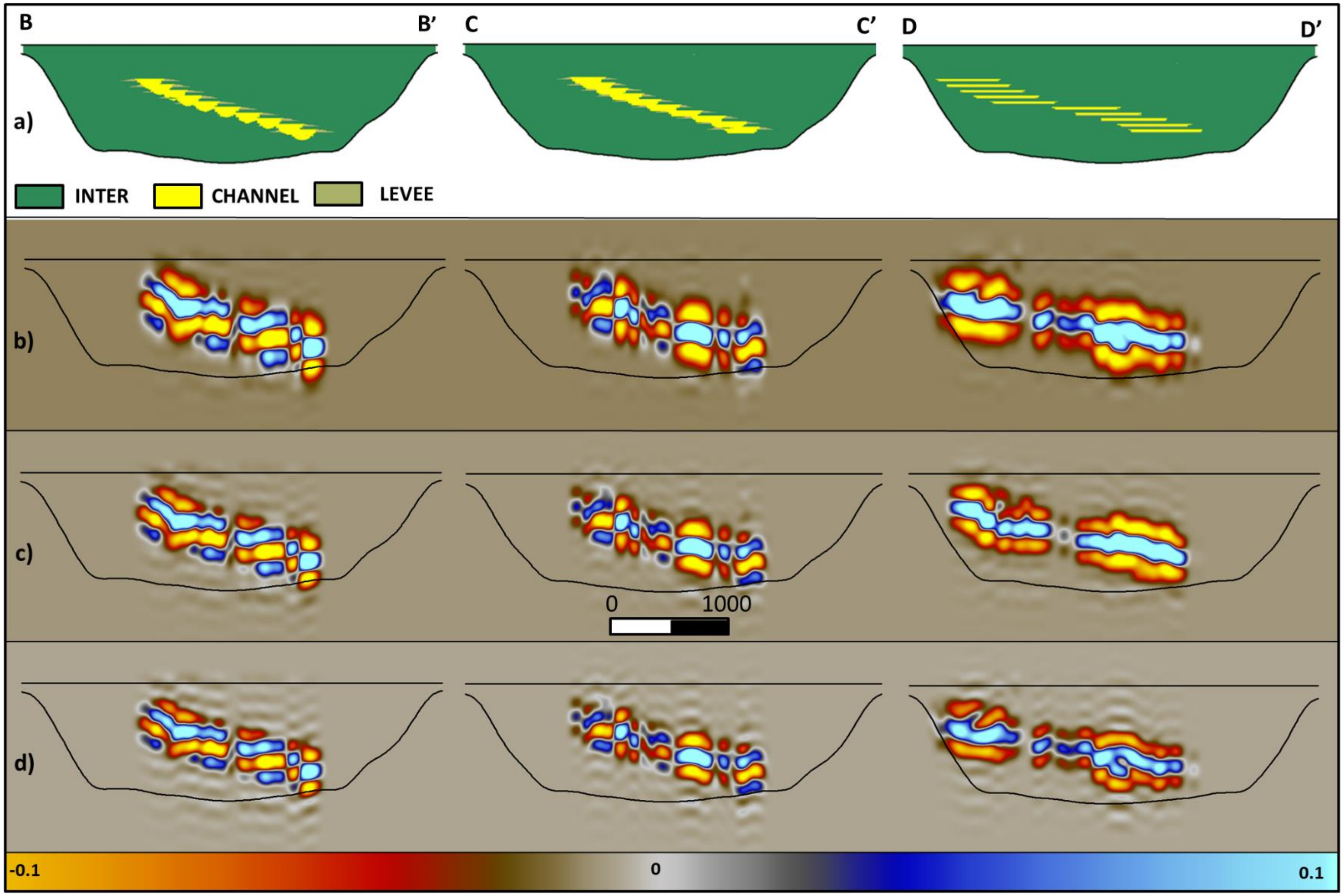

Figure 21 - Cross sections orthogonal to the trough depositional axis (Figure 20). a) represent the proximal, intermediate and distal sections, respectively, with the architectural elements in evidence. b) show the synthetic seismic data generated from a 25 Hz Ricker dominant frequency wavelet applied to the model. c) represent the same cross sections, but the seismic data was generated from a 30 Hz dominant frequency Ricker wavelet. d) represent the same, but with seismic data obtained from a 35 Hz dominant frequency Ricker wavelet.

A three-dimensional geological model was constructed ~~made~~ for the Maastrichtian turbiditic channels to evaluate the influence of the modeled parameters in one dimension for a real case. Models were built with the property's distribution based on statistical analysis and another model with the application of equation 2. In both cases, the I_p-I_s attribute was used in the construction of architectural elements; values of impedance up to 3700 g/cm^3*m/s were considered as a channel architectural element. After the distribution of the facies, the model acquired a satisfactory configuration for the type of reservoir to be studied (Figure 22).

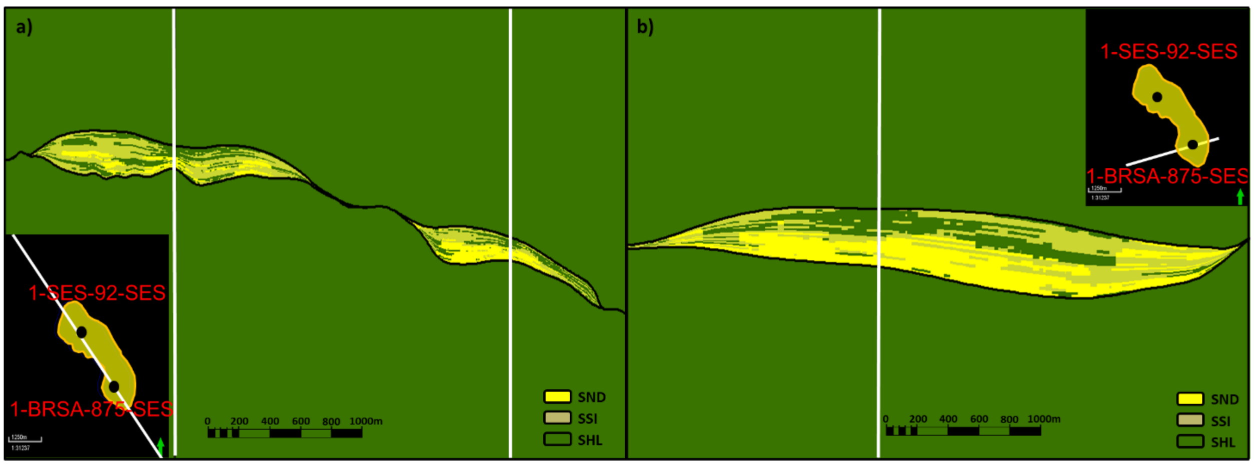

Figure 22 - Geological sections of dip (a) and strike direction through well 1-BRSA-875-SES (b) showing the modeled facies. SND = sandstones; SSI = sandstone-shale interlaminates and SHL = shales.

The distribution of elastic properties enables rectifying the facies distribution, as relatively high values (greater than 3815 m/s) of V_p for this area were associated with non-reservoir facies (sandstone-shale and shale interlaminates) for the upper sands in the studied interval at well 1-BRSA-875-SES (Figure 10; Figure 15). The results outline a channel complex with at least two composite channels presenting a certain degree of hydraulic communication (Figure 23a), similar to the geometries obtained for the attribute extracted from the seismic data (Figure 21).

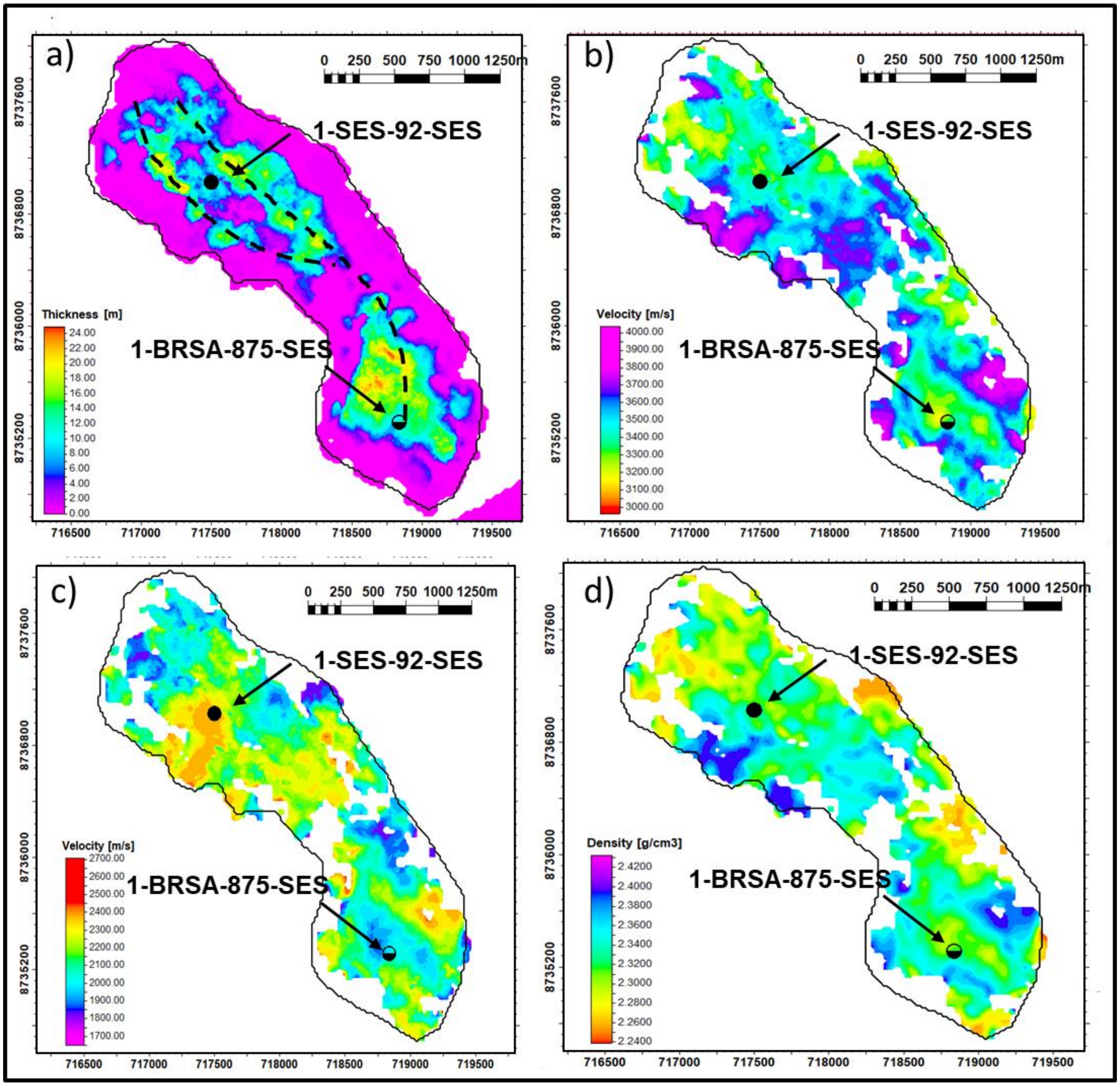

Figure 23 - Maps of the geological-geophysical modeling results obtained from statistical analysis: a) isopach map of the sandstone (“snd”) facies and through axis denoted by dashed lines ; b) map of the average compressional velocities of the “snd” facies; c) map of average shear velocities of the “snd” facies; d) map of the average densities of the “snd” facies.

After the elastic parameters were modeled through statistical analysis, I_p-I_s values were obtained through 3 different ways: kriging using the modeling technique, through the application of equation 2.0 in the modeled data and extracting I_p-I_s attribute in the seismic impedance volumes (Figure 24). The direct application of the resulting variations generated a very optimistic result, especially in the regions around the wells (Figure 24a) when compared to the observed seismic data (Figure 24c).

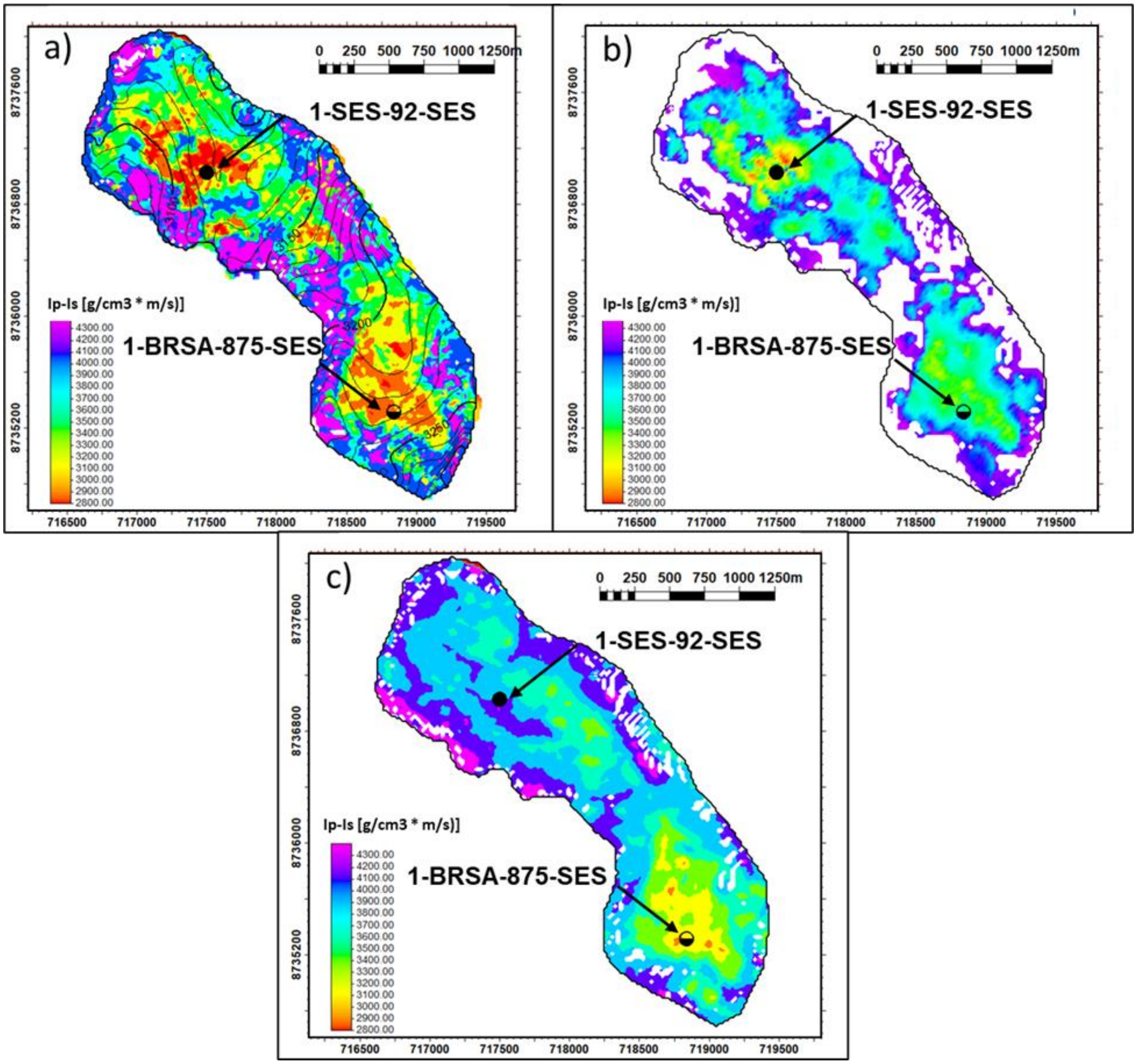

Figure 24 - I_p-I_s attribute maps obtained by kriging the elastic properties (a), through the application of elastic parameters and thickness through equation 2 (b) and extracted from the seismic data (c).

The result obtained from the direct application of equation 2.0 (Figure 24b) demonstrated a behavior closer to the three-dimensional model constructed using the acquired data in the basin. It was slightly more optimistic for the region of the well 1-SES-92-SES and more conservative for the well 1-BRSA-875-SES area concerning the attribute extracted from the seismic data. This behavior can be explained by lower values of V_p, which are correlated with higher values of porosity, implying better quality reservoirs. The results previously shown in Figure 19 can serve as a reference for the optimizations to be implemented when building the geometric model and its filling facies, such as which V_s value is expected for a given V_p and thickness for a sandstone. Another possible optimization is that regions with porosities lower than expected (relatively high V_p values) can be changed from sandstone facies to non-reservoir facies. These adjustments must be carried out in an iterative way between one-dimensional and three-dimensional modeling as many times as necessary until the I_p-I_s-values of the resulting model approach the results expressed in Figure 24c.

4 CONCLUSIONS

Seismic is a robust tool to assist the information distribution from wells through geological modeling techniques. Despite the limitation of its resolution and the data information being present only at the layers interface, these effects can be mitigated with the use of attributes and seismic inversion which can provide information contained within these layers. For the case study of Maastrichtian turbiditic reservoirs from the Sergipe-Alagoas Basin, the use of the I_p-I_s attribute to define the depositional geometry is very consistent with the sedimentary environment in which these channels were generated.

The 1D modeling provided important relationships between elastic parameters and thicknesses in relation to the seismic data and its derived attributes. This technique demonstrated that the effects of V_p and V_s on the I_p-I_s attribute can be stronger than the thickness variations of the modeled turbiditic reservoirs, and used as a guide in the construction of the geological model. Understanding the influence of these parameters on the seismic data and its attributes allowed to implement improvements in the construction of the geological model, such as the reclassification of some reservoir intervals as non-reservoir and vice versa. The analysis of the influence of V_p, V_s and sandstone thickness in relation to the I_p-I_p attribute allowed to create in 1D an equation capable of making a quality control of the modeled geology comparing the resulting value of I_p-I_s obtained through the application of the equation with the values of I_p-I_s extracted from the seismic.

The tuning effect in the “synthetic 3D model” data showed a much more intense signal, suggesting a better facies quality, or greater thickness in reservoirs that were just getting thinner. This implies in misinterpretations, implying the wells positioning at intervals unfavorable for hydrocarbon production, culminating in economic losses for a project.

The construction of three-dimensional models using seismic data and their attributes, especially in the architectural elements, presented results compatible with the conceptual models expected for turbiditic channels. The optimization by using elastic parameters proved to be effective on the facies, mainly by the analysis of compression velocities.

5 DATA AVAILABILITY

All data used in this study is available at http://www.anp.gov.br/exploracao-e-producao-de-oleo-e-gas/dados-tecnicos/acesso-aos-dados-tecnicos

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CAPÍTULO 3

CONCLUSÕES

A sísmica é uma ferramenta robusta para auxiliar a distribuição das informações oriundas dos poços na técnica de modelagem geológica. Apesar da limitação da sua resolução e da informação dos dados estar presente apenas na interface das camadas, estes efeitos podem ser mitigados com uso de atributos e inversão sísmica que podem fornecer informações contidas no seu interior. Para o caso dos reservatórios turbidíticos do intervalo Maastrichtiano da Sub-bacia de Sergipe, o uso do atributo de I_p-I_s para delimitar a geometria deposicional foi bastante condizente com o ambiente em que estes canais foram depositados.

A modelagem 1D fornece relações importantes entre os parâmetros elásticos e as espessuras em relação ao dado sísmico e seus atributos derivados. Esta técnica demonstrou que os efeitos de V_p e V_s sobre o atributo de I_p-I_s podem se sobrepor às variações de espessuras dos reservatórios turbidíticos modelados, utilizado como guia na construção do modelo geológico. Compreender a influência destes parâmetros sobre o dado sísmico e seus atributos permitiu implementar melhorias na construção do modelo geológico da área estudada, como por exemplo a reclassificação de um intervalo do topo do reservatório do poço 1-BRSA-875-SES como não-reservatório, devido aos seus valores altos de velocidades compressionais atribuídos a regiões de baixa porosidade. A análise da influência de V_p, V_s e da espessura das areias em relação ao atributo de I_p-I_s permitiu confeccionar em 1D uma equação capaz de fazer um controle de qualidade da geologia modelada comparando o valor resultante de I_p-I_s obtido através da aplicação da equação com os valores de I_p-I_s extraídos da sísmica adquirida.

O efeito *tuning* nos dados do “modelo sintético 3D” mostrou um sinal muito mais intenso, sugerindo uma melhor qualidade de fácies, ou maior espessura em reservatórios que estavam apenas ficando mais delgados. Isto implica em interpretações sísmicas equivocadas, sugerindo possíveis locações de poços em áreas desfavoráveis para a produção de hidrocarbonetos, culminando em prejuízos econômicos para um projeto.

A confecção de modelos tridimensionais usando dados sísmicos e seus atributos sobretudo nos elementos arquiteturais apresentou resultado compatíveis com os modelos conceituais esperados para os canais turbidíticos. O uso de parâmetros elásticos como otimizadores da modelagem geológica tridimensional se mostrou eficaz na otimização das fácies, em função da análise principalmente das velocidades compressionais.

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ANEXOS

ANEXO 1

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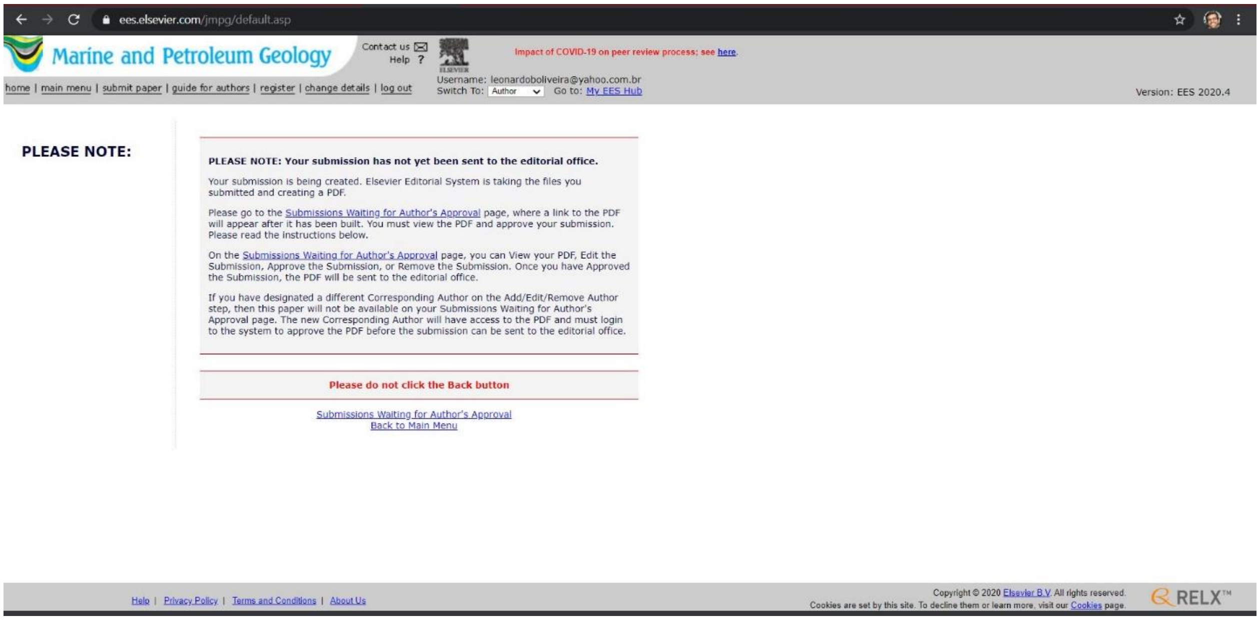

ANEXO 3

Os coautores Adler da Cruz Nascimento e Otávio Leite Chaves contribuíram significativamente para a elaboração do artigo submetido e, portanto, desta dissertação de mestrado. Adler da Cruz Nascimento foi responsável pela otimização do escopo do projeto, de contribuições inestimáveis na análise dos atributos elásticos e na confecção do modelo 3-D sintético. Otávio Leite Chaves contribuiu diretamente na elaboração das correlações geológicas entre poços além de contribuir na parametrização do modelo geológico utilizado no caso observado na bacia.