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Seismic Characterization of Internal Salt Cycles: A Case Study in Santos Basin, Brazil

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Dissertação apresentada ao Programa de Pós-Graduação em Dinâmica dos Oceanos e da Terra do Departamento de Geologia e Geofísica do Instituto de Geociências, da Universidade Federal Fluminense, como parte dos requisitos para obtenção do título de Mestre em Geologia e Geofísica.

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1. INTRODUÇÃO

Com as recentes descobertas de grandes acumulações de hidrocarbonetos no pré-sal das bacias de Santos e Campos no início dos anos 2000, houve uma forte necessidade de se entender o papel da extensa seção evaporítica, comumente denominada de “Sal”, presente nestas bacias. Por serem muito profundos e estarem soterrados por formações extremamente complexas, “imagear” corretamente os reservatórios do pré-sal era (e ainda é) um grande desafio tecnológico. Até então, a composição da seção evaporítica não era bem conhecida, verificava-se fortes variações de espessura e grande variação regional de suas características.

Por estes motivos, por muito tempo, a seção evaporítica foi tratada de forma muito simplificada, tendo sua composição e características reduzidas às da halita. Existe uma razão clara para tal: Maul et al. (2018), ao avaliar as velocidades dos sais de mais de 200 poços da seção evaporítica da Bacia de Santos, verificou que o valor médio das velocidades de todos os sais em conjunto é muito próximo do valor da velocidade da halita, em torno de 4550 m/s que representa cerca de 80% ou mais dos sais presentes na seção evaporítica. Ainda que a dispersão dos valores seja maior, simplificar as velocidades dos sais pela média da halita parece ser uma aproximação bastante razoável e cumpria seu objetivo principal quanto aos principais algoritmos de migração sísmica disponíveis (PSTM – Pre Stack Time Migration) que por sua vez não aceitavam fortes variações laterais de velocidades ou mesmo modelos muito complexos.

A melhoria nos algoritmos, com o padrão para processamento de dados sísmicos da indústria se tornando o PSDM (Pre Stack Depth Migration), e o aumento da capacidade de processamento geram imagens sísmicas cada vez mais detalhadas que revelam o caráter estratificado da seção evaporítica. Estes algoritmos, para garantir os melhores resultados em termos de imagens sísmicas, por sua vez, requerem maior detalhamento dos modelos de velocidades que são inseridos em seu fluxo.

Hoje, após centenas de poços perfurados e trabalhos muito importantes de caracterização da seção evaporítica feitos por Freitas (2006), Gamboa et al. (2008), Fiduk e Rowan (2012), Jackson et al. (2014, 2015) e Rodriguez et al. (2018) entende-se que a estratificação observada é fruto, principalmente, de variações na composição destes sais. Vários destes autores observam forte relação entre proporções maiores de anidrita e sais de K-Mg com fortes reflexões dentro da seção evaporítica.

Alguns propõem uma divisão de unidades baseadas na composição e/ou sismofácies. Gamboa et al. (2008) dividem a seção evaporítica em quatro unidades acima de uma camada de anidrita na base: a primeira seria uma unidade espessa rica em halita, seguida de uma unidade espessa com intercalações de halita, anidrita e sais de K-Mg; uma nova unidade rica em halita mas com espessura menor e, por último, uma unidade com muitas intercalações de halita e anidritae e sais de K-Mg. Fiduk e Rowan (2012) separam seis unidades baseadas em sismofácies e "comportamento reológico". As unidades são divididas entre *"beams"* e *"detachment"*. As três unidades chamadas de "*beams"* são as que apresentam sismofácies mais estratificadas, com reflexões mais intensas e contínuas. O comportamento destas unidades é mais rígido e tende a ter menor movimentação, possivelmente por causa da maior proporção de anidrita; já as unidades "*detachment*" são unidades com sismofácies caóticas com pouca continuidade lateral e apresentam maior mobilidade por terem maior proporção de halita em sua composição. Jackson et al. (2014) separam quatro unidades, de A1 a A4, muito semelhantes às unidades propostas por Gamboa et al. (2008). As unidades A1 e A3 apresentam sismofácies mais caóticas, pouco contínuas e reflexões menos intensas. Já as unidades A2 e A4 apresentam sismofácies muito estratificadas, refletores fortes e com grande continuidade lateral. Rodriguez et al. (2018) utilizam a divisão das unidades feita por Jackson et al. (2014) e vão além, propondo controles climáticos e tectônicos para as variações na composição e no padrão de empilhamento dos diferentes tipos de sal.

Nos últimos anos, alguns autores vêm explorando a aplicação e comparação de modelos de sal estratificados *versus* não-estratificados. Huang et al. (2010) publicaram resultados para a correção de velocidades usando inversão tomográfica na Bacia de Santos utilizando a presença de evaporitos estratificados. Para eles, os tempos de trânsito baseados na tomografia geraram bons resultados, porque a estratificação cria fortes reflexões, o que leva à correta atualização de velocidades. Maul et al. (2018)

verificaram melhoras importantes na formação das imagens de reservatórios do pré-sal ao adicionar estratificações aos modelos de entrada para a tomografia e migração sísmica. Além disso, observaram que o tempo de convergência da atualização de velocidades no processo de tomografia é menor ao ser realizado com modelos que refletem melhor a heterogeneidade da geologia da seção evaporítica, apresentando um importante resultado em termos de eficiência computacional.

Ao que tudo indica, aumentar a complexidade (referindo-se à maior fidelidade geológica possível) dos modelos de entrada para processos sísmicos de migração traz grandes benefícios: aumento da eficiência dos processos com menor tempo de máquina e menos iterações tomográficas necessárias para a atualização do modelo de velocidades inicial; melhoria na qualidade das imagens e, consequentemente, redução de ruídos e maior confiança nas relações de amplitude dos reservatórios do pré-sal. No entanto, ainda há grande espaço para melhoria e muitas questões a serem respondidas. Neste trabalho, esperamos acrescentar dados a esta discussão, apresentando este artigo que aborda um estudo de caso na Bacia de Santos, demonstrando que representar com fidelidade a seção evaporítica pode reduzir erros no posicionamento estrutural em profundidade de reservatórios do pré-sal, assim como diminuir incertezas volumétricas, o que pode ter um impacto direto na concepção de projetos de produção e nas reservas de um campo de petróleo.

O artigo a ser defendido para a obtenção do grau desejado (M.Sc.) tem como base os desenvolvimentos a partir dos primeiros artigos deste projeto, e que são apresentados, nos apêndices A e B, ao final deste texto.

2. ARTIGO

SEISMIC CHARACTERIZATION OF INTERNAL SALT CYCLES: A CASE STUDY IN THE SANTOS BASIN, BRAZIL.

ABSTRACT

With the discovery of the pre-salt reservoirs in the Santos Basin, the necessity to understand and model the large salt bodies in a more realistic way became quite clear. However, a closer look to what is so-called only "salt", which is a general term for evaporites, reveals an enormous depositional complexity, formed by cycles that are directly related to the basin environmental changes and to the geological history. It is known that the balance of the mechanisms that regulate the patterns of precipitation and preservation of evaporites are very delicate and that little climate changes may alter the way these evaporites are formed as well as their depositional geometries. According to outcrop and experimental data, there is a well-defined precipitation order: carbonates, gypsum or anhydrite, halite, and bittern salts such as sylvite, carnallite and tachyhydrite. We found that the major evaporitic cycles described in the literature are trackable in the study area and that the incorporation of their properties and geometry on models produces better results to be used in many applications. The main contribution of this work is to characterize the internal salt cycles using seismic data interpretation, comparing with the well information and evaluating the importance of this incorporation for seismic activities.

Keywords: evaporitic section, seismic imaging, seismic inversion, velocity model

INTRODUCTION

During the Aptian the Santos Basin (SE Brazil) was located in a restricted sea isolated from the open oceanic circulation by the Rio Grande Rise (Kukla et al., 2017). The restricted conditions stayed for nearly 9 My, allowing the formation of brine bodies creating the perfect conditions for evaporite precipitation: high evaporation rates, arid climate, and little freshwater inflow. Gamboa et al. (2009), based on seismic data interpretation, identified four major units that are formed by a sum of several minor evaporitic cycles in the Santos Basin Ariri Formation. Those units have distinct seismic facies and were preserved in the following order: (1) a thick basal layer composed mostly by halite; (2) a layer with anhydrite on the base followed by halite and bittern salts; (3) a thinner layer of halite; and (4) a thinner layer presenting the same sequence described in (2). Fiduk and Rowan (2012) divided the evaporitic section in three beam layers and three detachment zones. The beams are layers that present high amplitude and continuous mappable reflections, they are described as ‘relatively competent’ concentrating most of the anhydrite. The detachment zones are the interval between beams and have low amplitude reflections, poor continuity and are made up mostly of halite. Jackson et al.(2015b) divide the evaporitic section into four units from base to top: A1, A2, A3 and A4. The units were divided based on the percentage of nonhalite evaporites (anhydrite, carnallite, tachyhydrite) and differing densities. A1 is chaotic-to-weakly stratified and rich in halite. A2 is a high amplitude and strong reflective unit with less halite than A1. A3 is poorly reflective, with high halite content; and A4 has very strong reflections, less halite and few layers of low-density evaporites. In this study, as a first approach to interpretation, we started using the four-fold sub-division defined by Gamboa et al. (2008) and Jackson et al. (2015b), before detailing the minor cycles defined by Freitas (2006). Each of these minor cycles, from base to top, is composed of anhydrite, halite, bittern salts, another layer of halite and another anhydrite closing the loop. It is essential to notice that the bittern salts may not always be present in the cycles since its precipitation and preservation conditions rarely occur. They tend to happen on central portions of brines, during an extremely arid climate and with little or inexistent freshwater inflow.

The salt bodies have always been simplified in seismic velocity modeling as an almost homogeneous geological layer, typically represented by using the halite properties solely. These simplifications of the salt properties, mainly considering the halite behavior, affects the seismic migration during the image building, the confidence in reservoir depth forecast, as well as regarding the well drill planning, causing significant budget losses for the companies in the oil and gas business.

Recently several efforts are approaching this matter, detailing the evaporitic section using previous information such as drilled wells and seismic data, aiming to create more accurate and detailed velocity models for any seismic usage (Maul et al., 2015). From our point of view, in order to complement these studies, it is crucial to understand the salt basin cycles depositional dynamics as well as their structural behavior. Once the major salt cycles are mapped for the area (Gamboa et al., 2008; Fiduk and Rowan, 2012; Jackson et al., 2015b) and correlated by Rodriguez et al. (2018), the small salt cycles (Freitas, 2006) can be inferred by using well data information and modeled using any seismic inversion strategy or any geostatistical approach.

In this paper, we performed an interpretation and characterization of the four primary salt cycles in the area of study and used the information we got from the wells to obtain the high frequency others, aiming to characterize the secondary salt cycles. After that we performed seismic inversions considering or not the cycles to build the frequency models. Finally, we used this information to evaluate the relevance of the incorporation of these approaches for seismic activities, especially regarding the uncertainties related to gross rock volume variations.

SANTOS BASIN GEOLOGY BACKGROUND

The Santos Basin formation occurred during the Mesozoic after the Gondwana rifting. The stratigraphy presents three super sequences: Rift, composed mainly by lake and fluvial deposits, Post-Rift, the evaporitic phase which is object of this study, and finally evolved to the passive margin sedimentation, characteristic of the Drift phase (Moreira et al., 2007).

In this context, the Santos Basin tectonic and stratigraphic evolutions are closely connected with the South Atlantic opening, in the Lower Cretaceous. A series of grabens and hemigrabens were filled with non-marine sediments (Piçarras and Itapema Formations) that were covered by posterior shallow marine carbonates (Barra Velha Formation) (Freitas, 2006). Barremian and Aptian reservoirs are also present in the Santos Basin, within the pre-salt section and show lacustrine with marine influence origin; they are composed of carbonate rocks, mostly microbiolites and coquinas. Usually, those reservoirs are covered by a thick salt layer, the Aptian Ariri Formation, in some case over than 2,000 m, and they are found between 5,000 and 6,000 m below the sea level. The precipitation of Ariri Formation evaporites, under investigation in this study, was built between the sag and marine phases during a fast subsidence regime, forming the Aptian South Atlantic Salt Basin.

The Aptian South Atlantic Salt Basin was more than 2,000 km long, 400 km wide in its southern portion and around 100 km wide northward. The estimated average thickness of the whole evaporitic section was around 2,000 m before halokinesis occurred. Nowadays, the evaporitic section varies from few hundred to around 3,000 m (Gamboa et al., 2008). Rodriguez et al. (2018) estimates that the whole evaporitic section was deposited in about 530 ky, with a cyclicity of fourth- to fifth-order, low-amplitude sea-level changes, which are interpreted as having typical greenhouse characteristics. This dimension and volume of evaporite deposition suggest that Santos Basin deposits falls in the basinward evaporites classification as described by Warren (2006).

EVAPORITES AND THE SALT CYCLES

Evaporites are defined as a group of sedimentary deposits formed largely due to evaporation (Warren, 2006). Large bodies of evaporites, also known as saline giants, like the ones found on Santos Basin, are formed in restricted bodies of water under specific climate conditions, especially arid climates and high evaporation rates. The composition and geometry of deposition of the resulting evaporites depends on the chemical composition of the water and adjacent rocks, as well as climatic and tectonic conditions (Rodriguez et al., 2018).

Saline evaporites have high solubility and halokinetic properties, which makes them chemically and physically very mobile, both in the sedimentary environment and particularly during burial and diagenesis. For example, as burial begins and temperature increases, precipitated gypsum dehydrates and becomes anhydrite. These characteristics makes the interpretation of ancient evaporites strongly dependent of climatic and tectonic models.

The evaporites formation has a strong influence in terms of climate variation. In this work we will not discuss deeply about this theme. However, it is important to mention at least the Warren (2016) statement: "*larger examples of modern evaporites are dominantly supra-sea level nonmarine lacustrine deposits, while ancient evaporites are subsea level marine fed systems. Yet, the first-order latitudinal distribution of modern and ancient evaporite basins is similar. That is, the dominant world-scale control on evaporite distribution is climatic and largely the result of the presence of Hadley cells*", to support our main understanding of the whole process of evaporites formation.

As per Warren (2006), there are basically three different models for basin filling with evaporitic precipitation: deep basin/deep water, deep basin/ shallow water and shallow basin/shallow water. According to the mentioned models, we believe that the Aptian South Atlantic Salt Basin is an example of a deep basin/shallow water setting (Figure 1). In this kind of setting, there is predominance of shallow water evaporites deposited as stacked saltern to mudflat cycles in a basin with hydrological level several hundreds of meters below mean sea level. It is important to remember that the world's modern surface does not present the tectonic and eustatic conditions that the formation of widespread marine evaporites require.

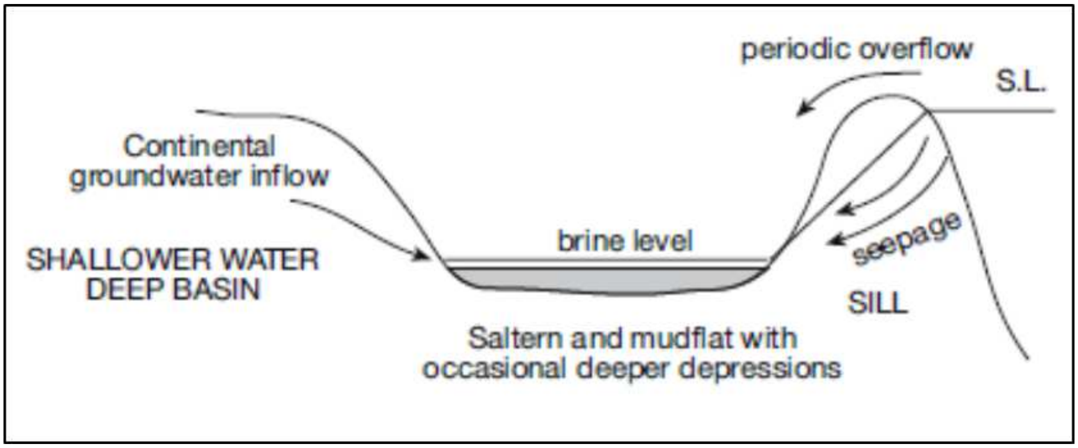


Figure 1. Most likely setting for basinwide evaporites deposition in Santos Basin during the Aptian. (Modified from Warren, 2006).

For the purpose of this research, a salt cycle is defined (after Freitas, 2006 and Rodriguez et al., 2018) as the full length of a brining upward, i.e. basin desiccation, and a deepening upward, i.e. basin filling, movement. Brining upward occurs when the rate of evaporation is higher than the rate of water influx to the system. As water evaporates, the density and ionic concentration of the brine increases, and when this concentration reaches a critical point, the evaporite precipitation begins (Figure 2).

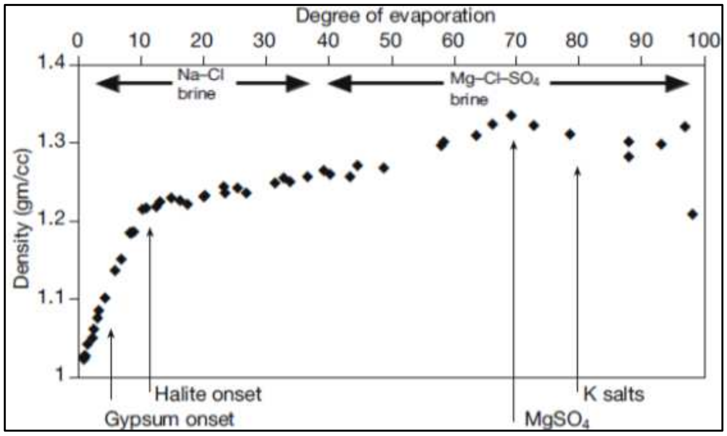


Figure 2. Evaporation pathway of modern seawater showing how density increases and the proportion of various ions in solution change as the brine concentration increases (modified from Warren, 2006).

This mentioned approach is also demonstrated in Usiglio (1849), who conducted the first known experiment of complete seawater evaporation in order to understand the behavior of evaporites precipitation. He observed that as the degree of evaporation increased, evaporites precipitate from the least to the most soluble: carbonates, gypsum or anhydrite, halite and, finally, bittern salts (K-Mg rich salts). This evaporation pattern would later be known as the “Usiglio Sequence” and this concept is largely used.

It is logical to assume that the deepening upward (brining downward), i.e., when the water inflow into the basin is higher than the evaporation rate, presents the inverse relationship: bittern salts, halite, gypsum and carbonates.

THE IMPORTANCE OF CHARACTERIZATION OF THE EVAPORITIC SECTION

According to Maul et al. (2019), based on the data acquired from about 200 drilled wells, the most common mineral found in the Santos Basin evaporitic section is halite, which is the reason why frequently the whole evaporitic section characteristics, such as velocity and density, are approximated to be the same as halite. However, a closer look to tomographic inversions reveals inconsistencies and velocity anomalies that do not conform to the stratigraphic configuration found in the seismic data.

Until the early 2,000´s, the evaporitic section was modeled as having fairly homogeneous compressional velocity – 4,500 m/s (similar to the halite compressional velocity value). This is a valid assumption for PSTM (Pre-Stack Time Migration) algorithms, which cannot handle strong lateral compressional velocity variations.

With the increase in processing power and the development of new migration algorithms, PSDM (Pre-Stack Depth Migration) became the industry standard, and the representation of existing lateral variations for velocity inputs is necessary for the creation of more reliable seismic images (Ji et al., 2011).

Huang et al. (2010) considered the presence of layered evaporites in Santos Basin and published results for velocity correction using tomographic inversion. Tomography based intrasalt travel times yield good results because layered evaporites create strong reflections, ensuring the correct update. Without a proper initial model, even tomographic inversions are not able to represent correctly and update the velocities, due to the complex nature of the environment that may have steep dips and sharp contrasts. Some authors have explored the use of inhomogeneous/heterogeneous evaporitic sections for enhancing migration output (Maul et al., 2015; Gobatto et al., 2016; Fonseca et al., 2017; Fonseca et al., 2018; Maul et al., 2018a, 2018b).

Tarantola (1984) and Zhang and Wang (2009), among other authors, strongly indicate FWI and intrasalt tomography to update salt velocity models. Still, both methods need a good starting velocity model that, to some degree, represents the local geology

AREA OF STUDY AND AVAILABLE DATA

The area of study is inserted in the pre-salt province of Santos and Campos Basins (Figure 3). A PSDM volume covering an area of approximately 100 km² and 8 wells with a basic suite of logs are available (Table 1). In order to simplify the official names of the wells, we are using capital letters (A to H) and table 1 brings the correspondence between the official names (ANP) and our nomenclature. Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) provided all the data.

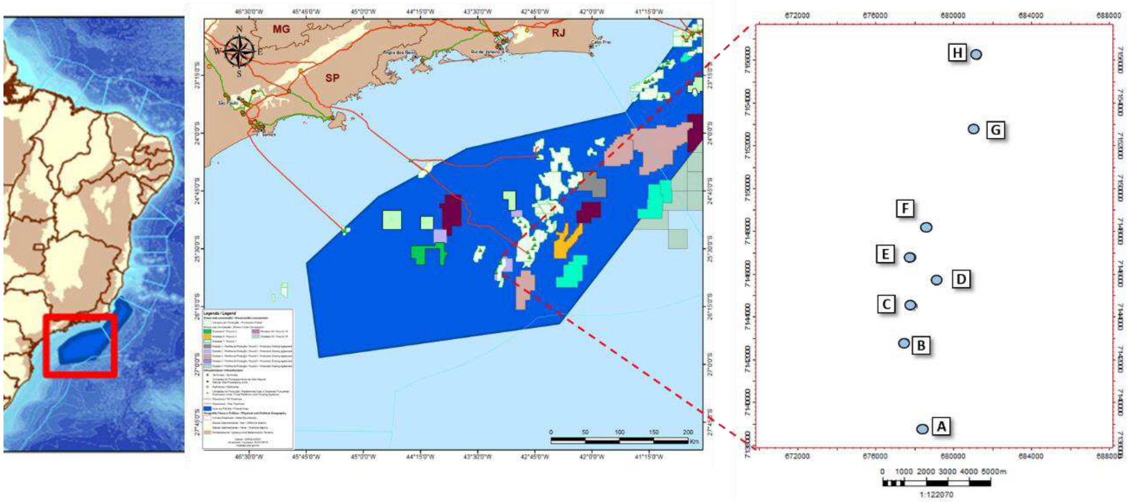


Figure 3: Location of study area (regional) and details of available data. Blue polygon delineates the area of the pre-salt province for both Santos and Campos Basins, totaling an area of approximately 350,000 km², and water column varying from 2,000 to 3,000 m. Rightmost panel shows in detail the well locations (A to H) inside the 3D seismic volume zone (rectangle).
Adapted from http://www.anp.gov.br/dados-tecnicos/117-envio-de-dados-tecnicos-a-anp/5154-poligono-do-pre-sal.

This Study	ANP
A	3-BRSA-923A-SPS
B	7-SPH-1-SPS
C	1-BRSA-594-SPS
D	9-BRSA-1043-SPS
E	7-SPH-5-SPS
F	9-BRSA-928-SPS
G	7-SPH-8-SPS
H	8-SPH-23-SPS

Table 1: The official names used in this study, after the ANP (National Agency of Petroleum - Brazil) authorization.

METHODOLOGY

The proposed methodology in this work consists of:

a) Analysis of the available logs inside the salt section. In this case we observe the presence/absence of data, as well as the property values registered;
b) Interpretation of brining upward/deepening upward salt cycles on the well logs;
c) 1D seismic signal modeling for each well in order to understand any seismic signature of the salt cycles (major and minor), evaluating the possibility to track these cycles through the seismic data;
d) Map the interpreted salt cycles on the seismic data;
e) Use mapped cycles surfaces as guides to create low-frequency models for seismic inversion;
f) Performing a seismic inversion that reproduces the stratification observed in the well data using a low-frequency model driven by the interpreted cycles;
g) Convert impedance values to velocity using an empirical relationship;

h) Compare the mismatch between a reference surface and its correspondent well marker and GRV (Gross Rock Volume) among the different models: 1 – Constant Velocity Model; 2 – Tomographic Model; 3 – Inversion Model; 4 - Cycles Model.

RESULTS

Based on descriptions of Jackson et al. (2015b), we have identified units, defined below, in the wells that share the same seismic facies and compositional characteristics as A1, A2, A3 and A4 previously described. It is also possible to map units throughout the whole seismic data despite the complex halokinetic structures (Figures 4 and 5).

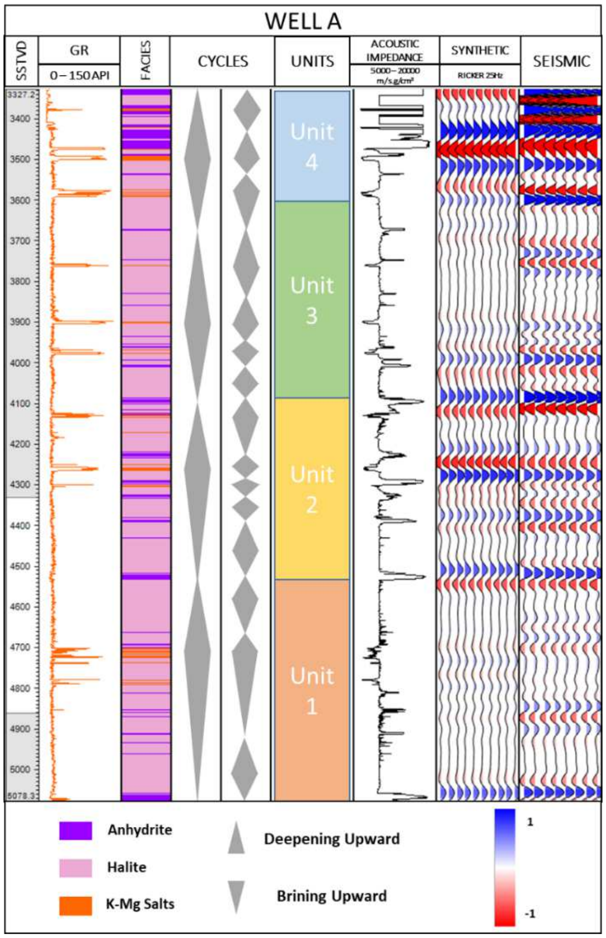


Figure 4: Well section showing the extracted seismic along the wells and the correlation with synthetic calculated from reflectivity coefficients log, derived from acoustic impedance, convolved with a Ricker wavelet of 25 Hz. From this section, it is possible to observe that there is a change in reflection characteristics of the units as described in literature.

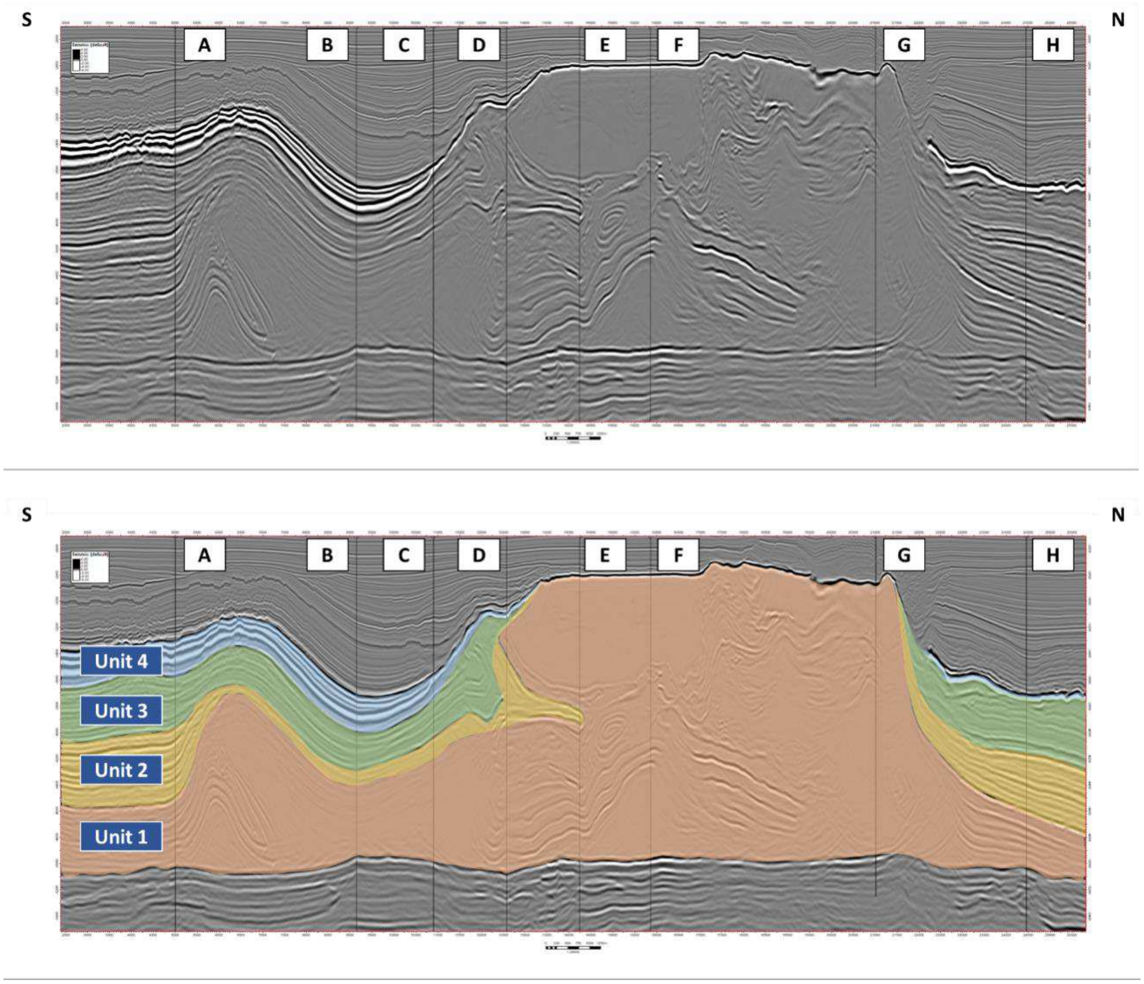


Figure 5: Composite seismic section along the wells. Upper: seismic section in depth. Lower: Interpreted units used for this study. For location see figure 3.

Unit 1: Unit 1 presents a mostly transparent, chaotic seismic facies with locally stronger reflections and large thickness variations. Unit 1 has a high halite proportion (~92%). The lower boundary is a strong positive reflection (increasing impedance) related to the basal anhydrite/carbonate lithological contact; the upper boundary is a positive reflection related to a relatively thick anhydrite layer.

Unit 2: Unit 2 is a highly stratified unit, with strong reflections, less halite (~83%) and more anhydrite/halite/bittern salts intercalation. The upper boundary, as Unit 1, is a positive reflection related to a relatively thick anhydrite layer.

Unit 3: Unit 3 shares the same characteristics as Unit 1, although less chaotic, presenting more transparent seismic facies, with a few continuous reflections. As Unit 1, the halite proportion is around 92%. Unit 3 is thinner than Unit 1 and does not present dramatic thickness variations; the upper boundary is a positive reflection.

Unit 4: Unit 4 has less halite than the other units (~43%) and a high proportion of anhydrite (47%) and bittern salts (10%). Because of that intercalation, Unit 4 has the strongest reflections observed on the evaporitic section, is highly stratified and is the thinner unit. The upper boundary is a strong positive reflection associated with the top of the evaporitic section, which is an anhydrite layer.

In table 2 we correlate our mapped four units with those used by Gamboa et al. (2008), Fiduk and Rowan (2012) and Jackson et al. (2015). Despite different classifications, the units have roughly the same seismic facies and boundaries among studies.

This Study	Gamboa et al. (2008)	Fiduk and Rowan (2012)	Jackson et al. (2015)
Unit4	Thinner Interbedded unit	B1	A4
Unit3	Thinner Halite-rich unit	D1	A3
Unit2	Interbedded unit	B2	A2
Unit1	Halite-rich unit	D2	A1
		B3	
		D3	

Table 2: Interpreted units and their counterparts in literature.

After performing the inversion studies and having the acoustic impedance deliveries we must convert this property (IP – P impedance) to P-velocity (compressional velocity) that can be used for several seismic processes. In this case we decided to use the same empirical equation used in Maul et al. (2019) and illustrated in figure 6. They grouped the salt mineral established by Maul et al. (2018c): LSV (Low Velocity Salts) which is a family of salts that have the compressional velocities lower than halite, and is mainly composed by carnallite, tachyhydrite and sylvite. The HSV (High Velocity Salts) which are salts presenting compressional velocities higher than halite, such as anhydrite and gypsum. The halite is also called as the background mineral once it represents about 80% of occurrence in the majority of the analyzed consulted studies.

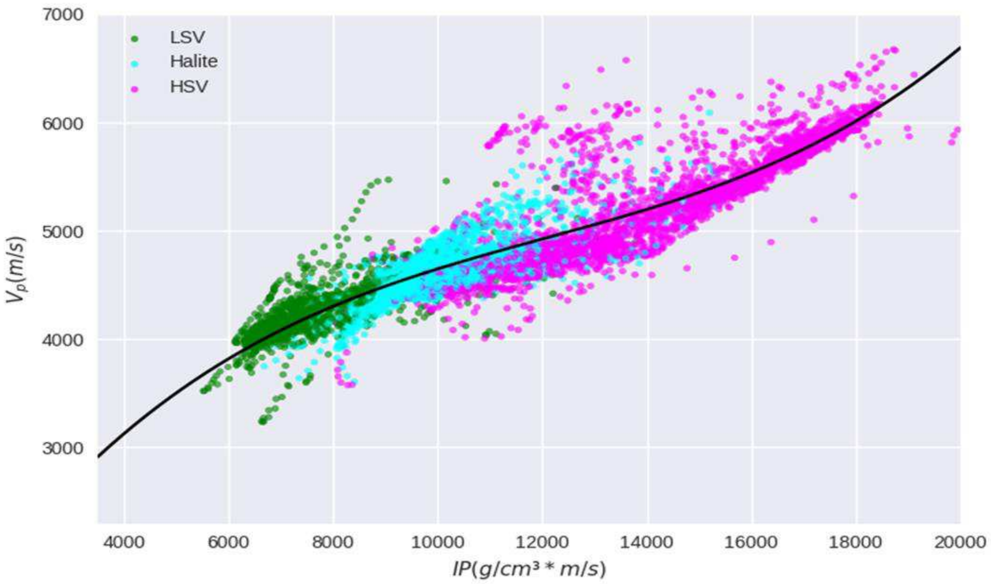


Figure 6: Vp x IP for different salt groupings based on their P-wave velocities. The black line is the polynomial regression that is used to convert impedance values to velocity values, and the referred equation is presented in the referred work (Maul et al., 2019)

One of the most straightforward ways to assess the impact of a velocity model in a hydrocarbon reservoir is through time x depth conversion analysis. Four different scenarios were modeled in order to convert the seismic surface relative to the base of salt (top of reservoir). Figures 7 to 10 present the velocity models using the same composite section used in figure 5.

a) Constant Velocity Model: Model that represents the evaporitic section as a homogeneous salt body, with constant properties and salt velocity of 4,550 m/s;

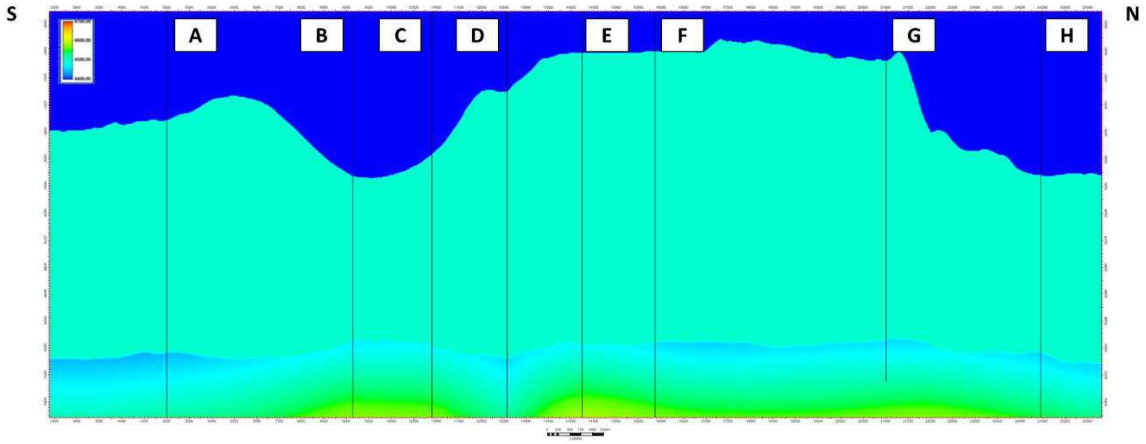


Figure 7: Constant Velocity Model – 4,550 m/s. Capital letters A to H refer to the wells used in this study.

b) Tomographic Model: This model is a product of the standard seismic processing workflow used for this seismic data;

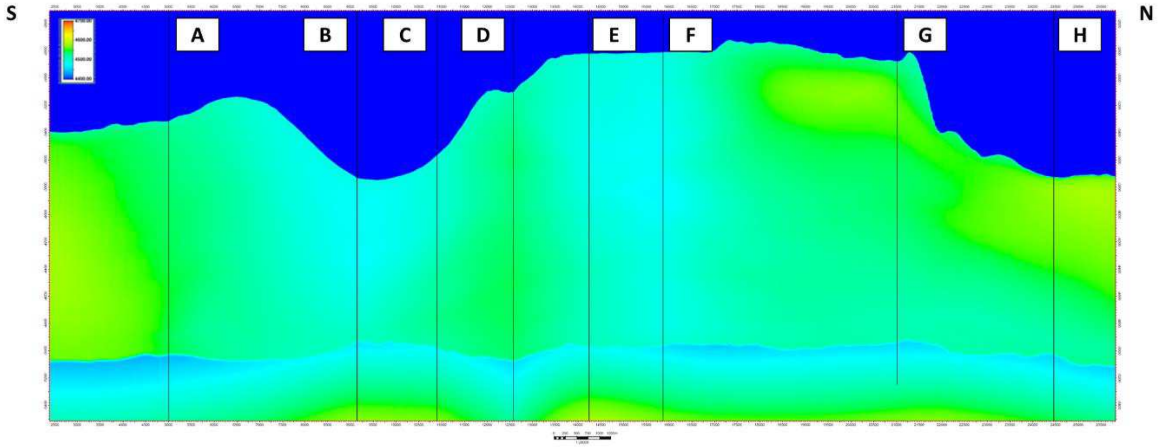


Figure 8: Tomographic Model. Capital letters A to H refer to the wells used in this study.

c) Standard Seismic Inversion Model: This velocity is calculated using the methodology described in Maul et al. (2009). The inversion considered a standard model-based seismic inversion approach.

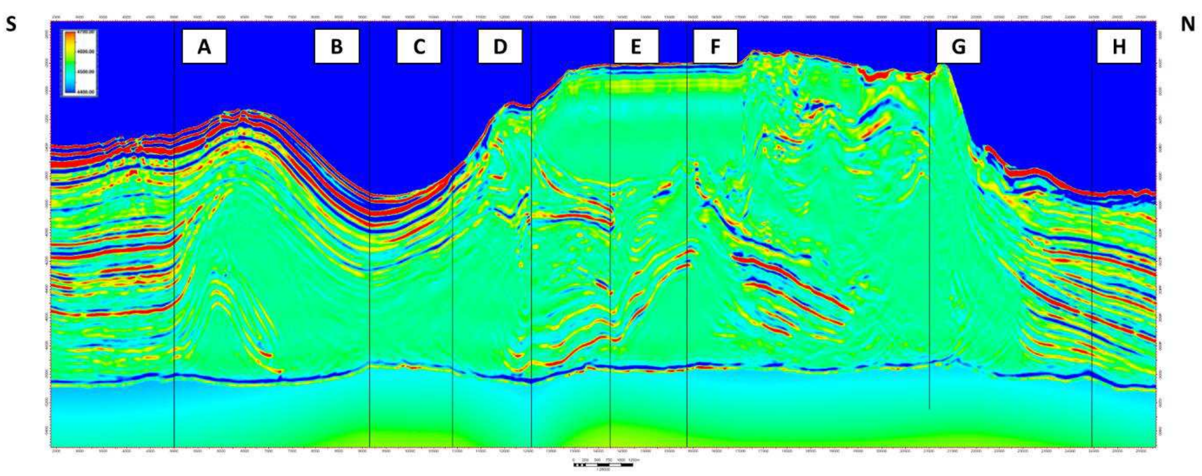


Figure 9: Standard Seismic Inversion Model. Capital letters A to H refer to the wells used in this study.

d) Salt Cycles Seismic Inversion Model, considering the salt cycles in the process. The velocity is also calculated using the methodology described in Maul et al. (2009).

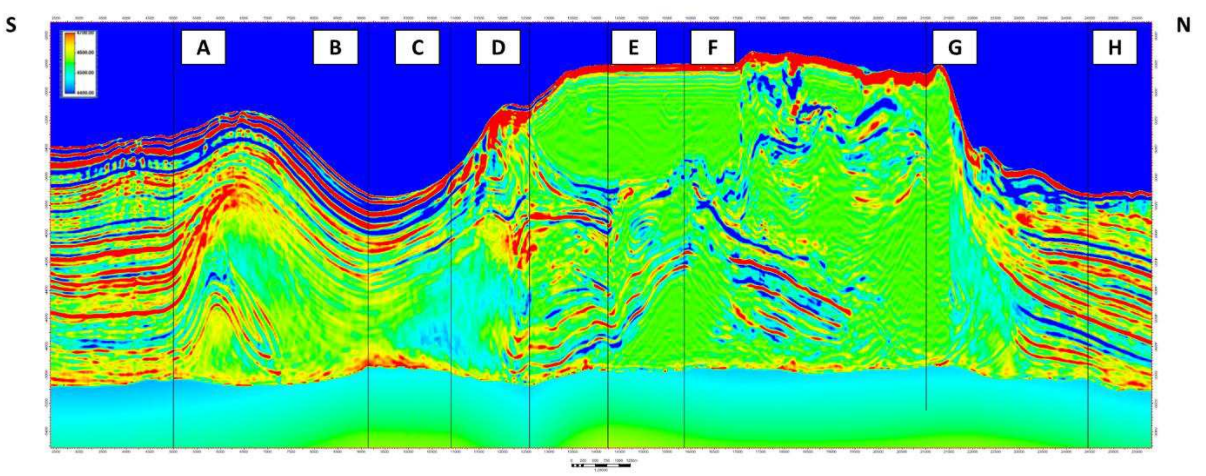


Figure 10: Salt Cycles Seismic Inversion Model. Capital letters A to H refer to the wells used in this study

Using the velocities from the four different models we calculated the depth to the reference level, in this case the base of salt that corresponds to the top of the pre-salt reservoir (Figure 11).

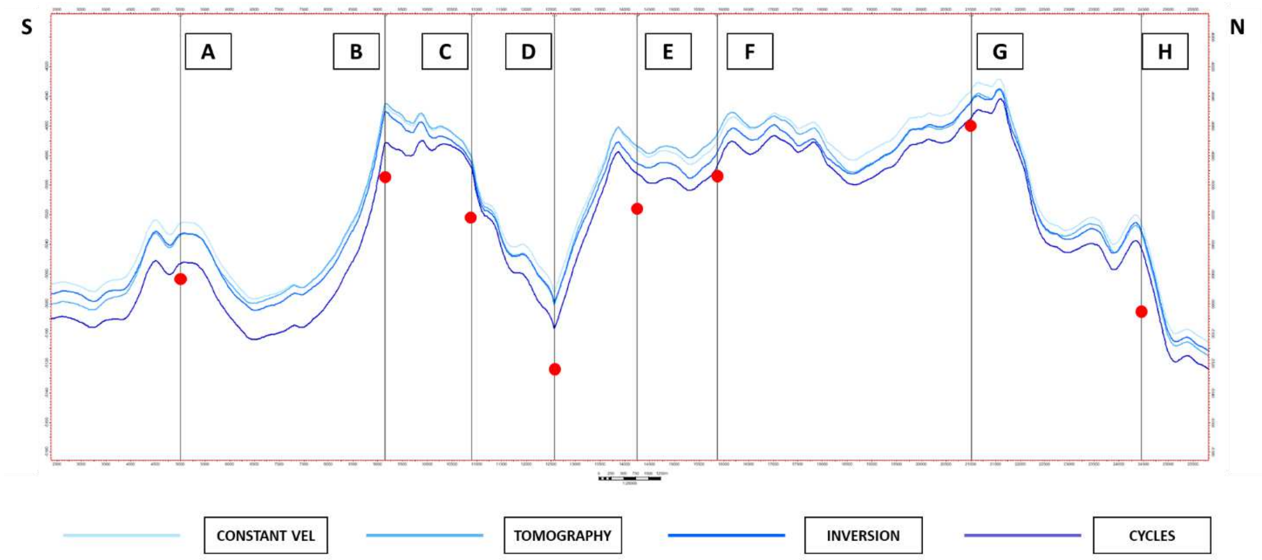
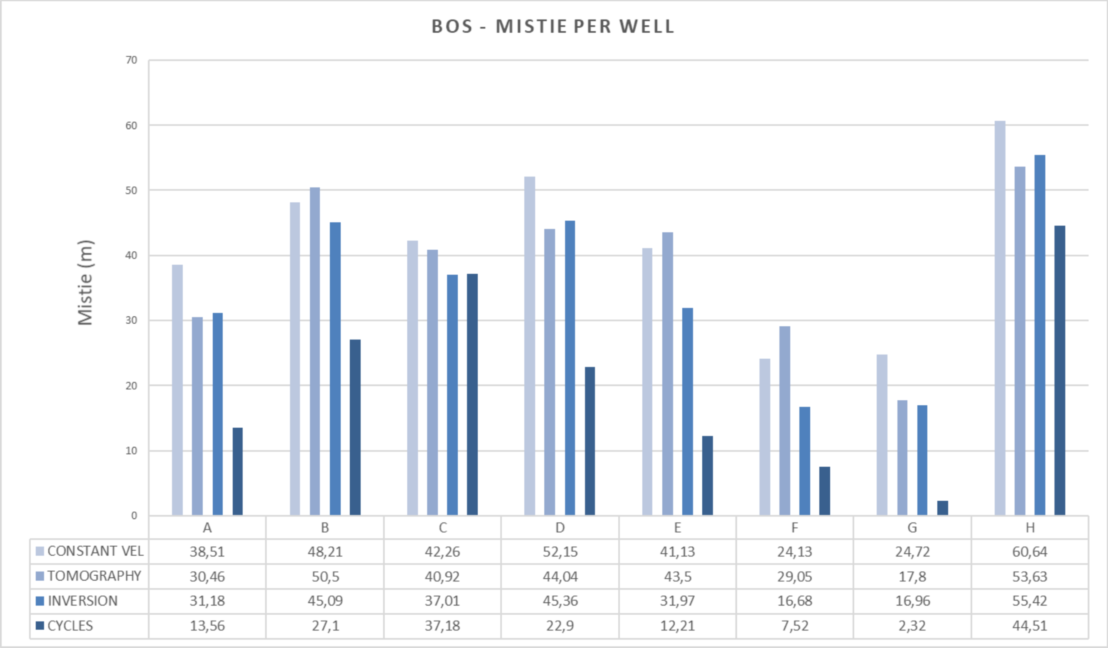


Figure 11: Base of salt surfaces considering the different velocity models. The base of salt well markers are indicated by the red circles. **VE:30x.**

The mismatch between the well marker and the depth surface is a good measure of how good a velocity model is for depth forecasting (Figure 11). Figure 12 presents the calculated differences for the generated depth surfaces using the four salt velocity models compared to each well marker depth.



	A	B	C	D	E	F	G	H
▪ CONSTANT VEL	38,51	48,21	42,26	52,15	41,13	24,13	24,72	60,64
▪ TOMOGRAPHY	30,46	50,5	40,92	44,04	43,5	29,05	17,8	53,63
▪ INVERSION	31,18	45,09	37,01	45,36	31,97	16,68	16,96	55,42
▪ CYCLES	13,56	27,1	37,18	22,9	12,21	7,52	2,32	44,51

Figure 12: Mismatch (module) between well marker and base of salt surface per well comparing different velocity models.

DISCUSSION

In this small portion of the Santos Basin where we conducted this study, there are many locations with evaporitic stratifications. They appear as undisturbed to highly folded, when looking at the seismic data. Even though the stratifications are showing clear signs of movement, the seismic facies are easily distinguishable among each other, allowing its interpretation.

Rodriguez et al. (2018) suggest that the compositional differences among units (A1-A4) occurred due to changes in salinity, possibly driven by variations in the frequency of marine incursions (deepening upward) and near-desiccation (brining upward) episodes. The authors established the unit boundaries observing high seismic amplitude contrasts in association with well information. These units were equally recognized in the present study (Units 1 to 4) in well and seismic data corresponding to anhydrite layers thick enough to be solved by the seismic method, appearing as a strong positive seismic reflector (Figures 4 and 5).

However, the units not always correspond to the same stage of the interpreted low-frequency cycles. Unit 1/Unit 2 and Unit 2/Unit 3 boundaries are interpreted as the end of a deepening upward and the beginning of a brining upward cycle, registered as thick anhydrite layers (Figure 4). Unit 3/Unit 4 boundary corresponds to a thick carnallite layer, which is interpreted as part of a brining upward cycle, corresponding to a strong negative seismic reflector (Figure 4).

The velocity models created have increasing complexity. The high-frequency cycles presented in figure 4, especially those inside Units 2 and 3 were considered when building the Salt Cycles Seismic Inversion Model, delivering more feasible geological velocity model (Figure 10) when looking at figure 5 in comparison to the models presented in figures 7 to 9. The average error reduces progressively towards more complex models, as shown on table 3.

MODEL	AVG. MISMATCH (m)
CONSTANT VELOCITY MODEL	37.51
TOMOGRAPHIC MODEL	35.90
STANDARD SEISMIC INVERSION MODEL	31.47
SALT CYCLES SEISMIC INVERSION MODEL	22.91

Table 3: Average mismatch for different velocity models. The error progressively reduces towards more complex models.

Since the Salt Cycles Seismic Inversion Model deliver the minimum average mismatch, we assume this as the appropriate model to be considered as the reference one for comparison. An important information obtained from the depth variability analysis is the calculation of GRV – Gross Rock Volume. In this study GRV means the volume of rocks that are above a reference level such as a hypothetical hydrocarbon/water contact. The table 4 shows a GRV calculation with a hypothetical hydrocarbon/water contact at -5,357 m TVDSS.

MODEL	GRV $(\times \mathbf{10^{10} m^3})$
CONSTANT VELOCITY MODEL	6.72
TOMOGRAPHIC MODEL	6.53
STANDARD SEISMIC INVERSION MODEL	6.49
SALT CYCLES SEISMIC INVERSION MODEL	6.15

Table 4: Gross Rock Volumes calculated using a hypothetical hydrocarbon/water contact of -5,357m.

The GRV reduction from Constant Velocity Model to Cycles Model is approximately 8%. Comparing the industry standard Tomography Model with the Cycles Model we have a reduction of about 6%. Finally, when we compare the Inversion Model, we observe a reduction of 5%. Meneguim et al. (2015) observed a displacement in GRV when considered two models: tomographic and model-based seismic inversion. Maul et al.

(2018c) using the same approach of comparison found a 3% displacement of GRV variation.

Besides presenting single numbers reflecting the GRV, we can also evaluate its spatial distribution variation between our reference model and the others. The difference maps (Figure 13) show that the major observed differences are located mainly in the SW portion of the study area. Pontes et al. (2019) concluded that this greater difference in the SW is mainly related to a thicker halite over a stratified salt layer not captured by the tomography update during the seismic processing phase.

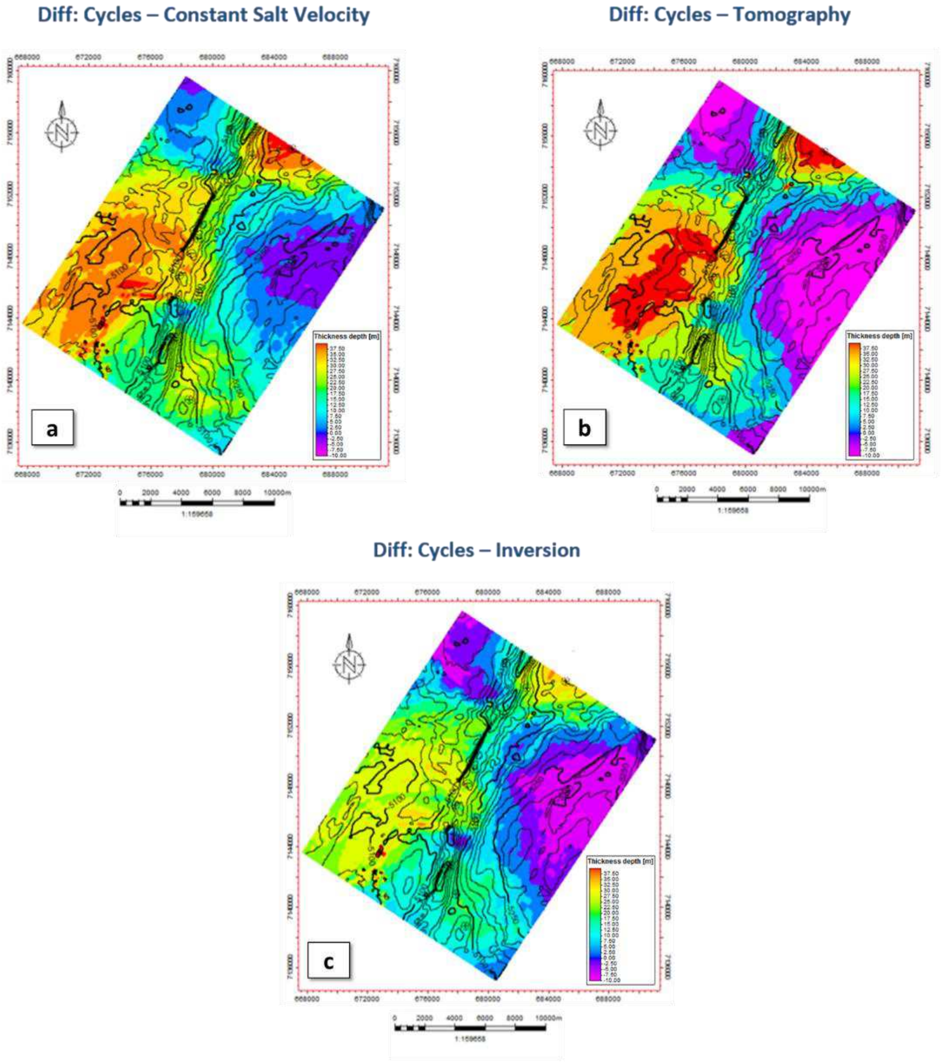


Figure 13: Difference maps of the Salt Cycles Seismic Inversion Model and the other approaches. a) Salt Cycles Seismic Inversion Model - Constant Velocity Model b) Salt Cycles Seismic Inversion Model - Tomographic Model and c) Salt Cycles Seismic Inversion Model – Standard Seismic Inversion Model. Note that the SW area presents largest thickness variation. This is due to the difficulty of the simpler models to correctly represent the geological complexity of the area.

CONCLUSION

Our results confirm that the salt section in the Santos Basin is not a homogeneous section presenting heterogeneities that result from the salt cycles evaporation. These heterogeneities form stratification which usually are not solved due to the intrinsic absence of seismic resolution.

The incorporation of geological features on the process of velocity model building using seismic inversion, especially when including the mappable units, brings strong improvements to depth positioning, by reducing the mismatch errors according to the well marker information.

The use of different salt velocity models delivers different Gross Rock Volumes (GRV) for the pre-salt reservoir. In our case the Salt Cycles Seismic Inversion Model resulted in the smallest average mismatch when compared to the well information. The industry standard, Tomographic Model, is 6% higher than the Salt Cycles Seismic Inversion Model in terms of GRV in this case, which is a relevant volumetric difference that can impact the whole production concept of a field.

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IMPORTANTES ASPECTOS PARA A FORMAÇÃO DE SEÇÕES EVAPORÍTICAS, SUA COMPOSIÇÃO E SUAS EVIDÊNCIAS

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RESUMO: De forma geral, em termos de indústria do petróleo, principalmente em áreas *offshore*, a seção eveporítica é normalmente considerada como sendo composta por um único mineral, a halita, com propriedades aproximadamente constantes. Esta seção é denominada, em muitos estudos, apenas como sal. Entretanto, diversas imperfeições de modelos geológicos vêm sendo observadas quando da perfuração de novos poços, visando atingir os reservatórios da chamada seção Pré-Sal da Bacia de Santos, ficando claro que a seção evaporítica não pode, nem deve ser considerada como sendo homogênea. Ao contrário, embora sempre predomine a halita, são encontrados diversos outros minerais tais como anidrita, gipsita, carnalita, taquidrita, silvinita dentre outros, todos provenientes de processos naturais de evaporação de salmouras. A partir de qualquer novo aporte de água nestas salmouras se dá origem a um novo ciclo evaporítico, já tendo sido descrito em alguns trabalhos mais de uma dezena dos mesmos. Ao se observar imagens sísmicas fica clara a presença de diversos refletores internos na seção evaporítica, caracterizando obviamente a reposta de distintas litologias, ou seja, a seção não é composta, unicamente, por um só mineral, a halita. O presente trabalho visa ilustrar os resultados obtidos através dos diversos estudos contemplando a presença de estratificações existentes na seção evaporítica da Bacia de Santos, ao longo dos últimos anos, através da combinação de atributos sísmicos. Serão apresentados, de forma simplificada, as formas de modelagem destas estratificações, sua importância e seus principais benefícios quando utilizados. Os resultados indicam, por exemplo, a necessidade de desenhos de novas aquisições sísmicas e reprocessamentos sísmicos, visando melhorar a preditividade de litologias para subsidiar o posicionamento de novos poços para a extração de petróleo, propiciando maior segurança operacional e otimização de recursos financeiros. A incorporação das estratificações nos modelos de velocidade, permitem diminuir as incertezas das imagens sísmicas geradas, melhorando a qualidade dos atributos sísmicos calculados melhorando o imageamento dos reservatórios situados logo abaixo do sal e, consequentemente, propiciando melhores condicionantes para extrapolação de propriedades de reservatórios amostradas em poços, através de correlação com atributos sísmicos, de forma mais confiável. Permitem, também, o desenvolvimento de estudos geomecânicos mais robustos, propiciando maior acertividade em termos de taxas de produção e de injeção.

PALAVRAS-CHAVE: ESTRATIFICAÇÕES, EVAPORÍTICA, HALITA

Interpretation, Characterization and Importance of the Internal Salt Cycles for Seismic Processes: a Santos Basin Example

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This paper was prepared for presentation during the 16th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil,19-22August 2019.

Abstract

Along with the discovery of the Pre-Salt reservoirs in Santos Basin, the necessity to understand and model the large salt bodies in a more realistic way became quite clear, especially for seismic purposes. However, a closer look to what is so-called only by "Salt" reveals an enormous depositional complexity, formed by cycles that are directly related to the basin environmental and geological history. One of the industry major challenges is to model these salt bodies using the available data since the climate mechanisms that regulate salt deposition and preservation are yet to be fully understood. Nowadays, it is known that the balance of the mechanisms that regulate the salt precipitation is very delicate and that little climate changes may alter the way salt minerals precipitate and their preservation. According to analog and experimental data, there is a defined precipitation order, which, in general, behaves like this: carbonates, gypsium or anhydrite, halite, and complex salts (tachyhydrite, carnalite, sylvite). It is possible to say that geological and environmental factors control salt precipitation and preservation together and that the major cycles described in literature are trackable in the studied area and that the incorporation of their properties and geometry on models produces better results. The main contribution of this work is to interpret and characterize the internal salt cycles using seismic data, comparing with the well information and evaluate the incorporation importance of this task for seismic processes.

Introduction

During the Aptian period, the area that is currently is named as the Santos Basin (SE Brazil) has been characterized as a restricted sea for a period of about 9 m.y., cut off from oceanic circulation by the Rio Grande Rise (Figure 2). This restricted sea had the perfect conditions for the salt precipitation: high evaporation rates, arid climate, and little fresh water intake. As per Gamboa et al. (2009), based on seismic interpretation, the Ariri Formation has four major salt cycles. Those cycles were preserved in the following order: (1) A thick basal layer of halite (2) A layer with anhydrite on the base followed by halite and other salts (3) a thinner layer of halite (4) a thinner layer presenting the same sequence described in (2). The same authors cite Freitas (2006) recognition of other minor cycles within these four major cycles. Each minor cycle, from base to top, is composed of anhydrite, halite, complex salts, another layer of halite and anhydrite. It is important to notice that the complex salts may not be always present in the cycles since its precipitation and preservation are only met at very specific climatic and environmental conditions. They tend to occur on central portions of brine bodies, during an extremely arid climate and with little or inexistent freshwater input.

The Ariri Formation has always been simplified in seismic velocity modelling as a homogeneous geological feature, typically using the halite properties. These velocity models are used for seismic processing, time-depth conversion and as low-frequency models for inversion and geomechanic studies. The simplification of the evaporites properties affects seismic migration, reservoir depth prediction and well planning, causing important budget losses for the companies in the oil and gas business.

Recently several efforts are approaching the problem and detailing the evaporite section, aiming to create more accurate velocity models for any seismic usage (Maul et al., 2015 and other papers). In order to complement these studies, it is crucial to understand the salt basin cycles depositional dynamics as well as their structural behavior. Therefore, enabling one to go beyond seismic data when interpreting higher frequency cycles. Since the major cycles have been mapped for the area, the small cycles can be inferred by using well data information and modeling, such as seismic inversion or any geostatistical approach.

In this research, we performed an interpretation and characterization of the main salt cycles in the area of study, compared them with the information we got from the wells and tried to characterize the minor salt cycles. After that, we evaluate the importance of the incorporation of these results for seismic processes.

Method

This work is part of a master's research and focus on the identification of the major and minor cycle's boundaries using a basic well log suite (DT, RHOB, GR) of 10 wells. A1D synthetic modelling to predict the seismic response of the boundaries and, whenever possible, these boundaries were mapped (Figure 3). The attribute and thickness maps calculations enables better understanding of the geometrical relations and textural variations of the salt cycles. Many of the minor cycles do not have a seismic reflection response, but it is sometimes possible to infer their existence based on the depositional context and the relation to the major cycles. By mapping as many cycles as possible, we have a better understanding of their geometrical relation and spatial distribution of each cycle.

Available Data

The data used in this research is a piece of seismic data (around 100 km2) from the Sapinhoá Field in Santos Basin, offshore Brazil and 10 drilled well. All the information were provided by the Brazilian National Petroleum Agency (ANP).

Results, Conclusions and Future Works

The seismic data and 1D modeling analysis show that it is possible to identify and to map the four major cycles described in Freitas (2006) as well as some minor cycle boundaries. Experimental and analog data suggests that little changes in the variables that balance the precipitation/deposition system can have dramatic impact on the composition of the evaporite layers. For instance, a global change that makes the climate water can prevent the preservation of complex salts. On top of that, diagenetic and geomechanical changes are obviously important but are still not contemplated in this study, allowing further researches and discussions.

The preliminary results of this study, as we are still in the first year of the current research, indicate that the cycles can be defined as a predictable succession of salts that are deposited within specific climate conditions. A regular salt deposition for seawater, without any climate change, is: anhydrite or gypsium, halite, and the complex salts. The main cycles described in literature are trackable, at least in the study area (Figure 4).

In the development of this investigation we will focus on the impact of the salt velocity modelling, including the cited cycles, over the seismic illumination study, seismic migration and seismic inversion. We expect considerably better results in these processes, as well as for the time-depth conversion, including the uncertainties analysis for both: signal quality and positioning.

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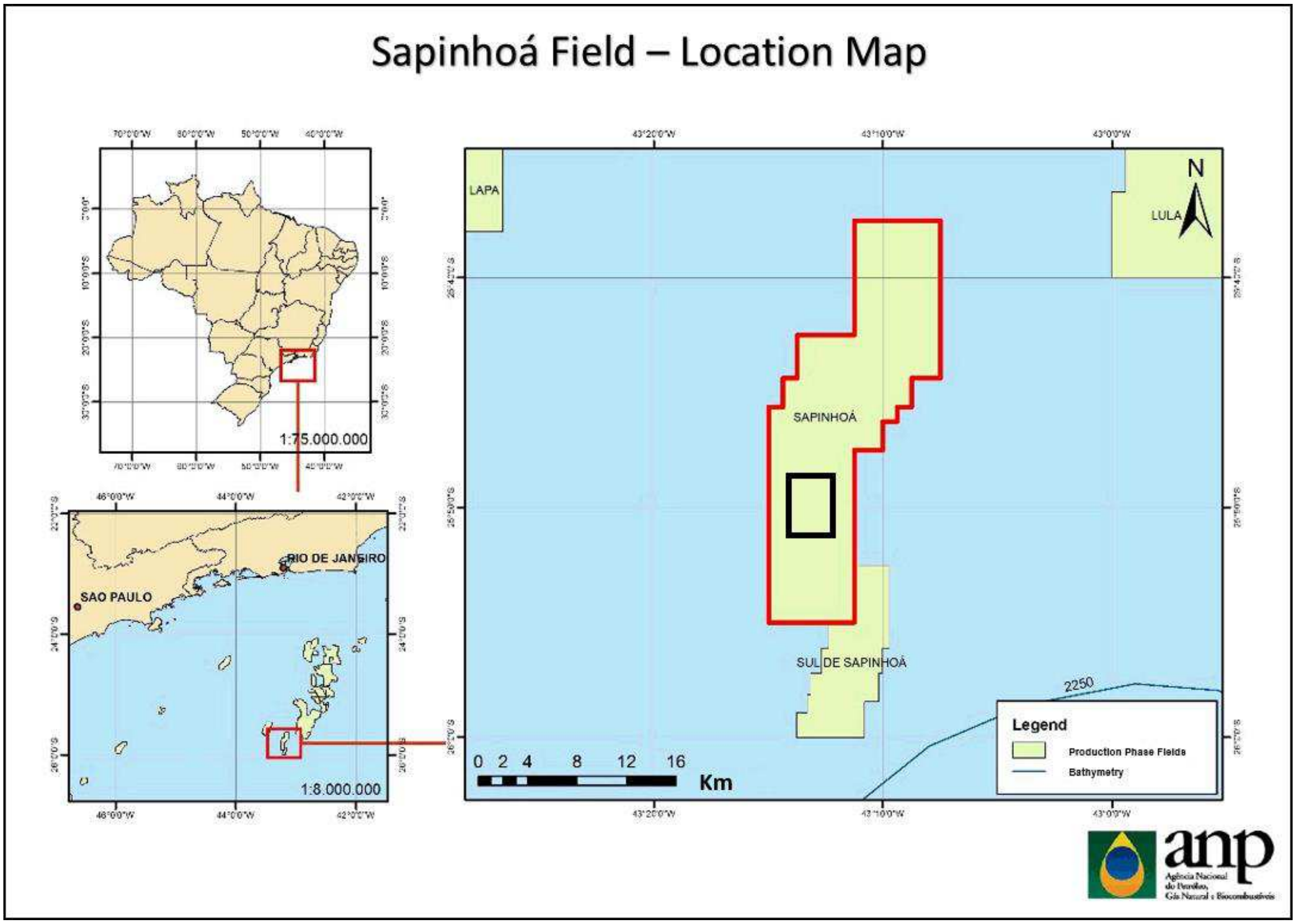

Figure 1: Sapinhoá Field is located in the central portion of Santos Basin, approximately 290 km from Rio de Janeiro city. The average water depth is 2,140 m. The black polygon represents the 3D seismic interpreted area used for this work.

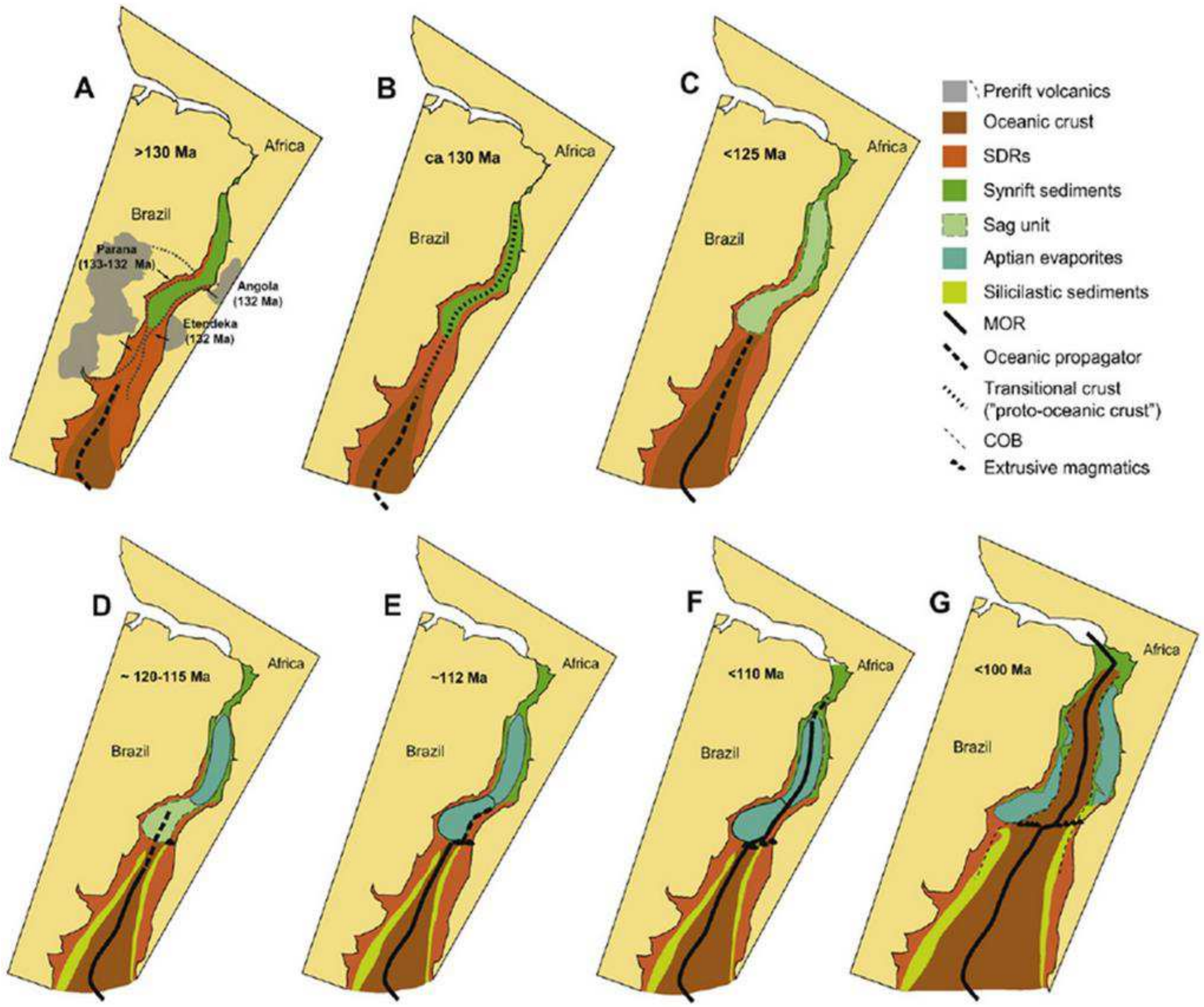

Figure 2: Schematic geodynamic evolution of South Atlantic showing the separation of South American and African continents during the Aptian, creating the necessary condition for deposition of evaporites (Kukla *et al.* 2017).

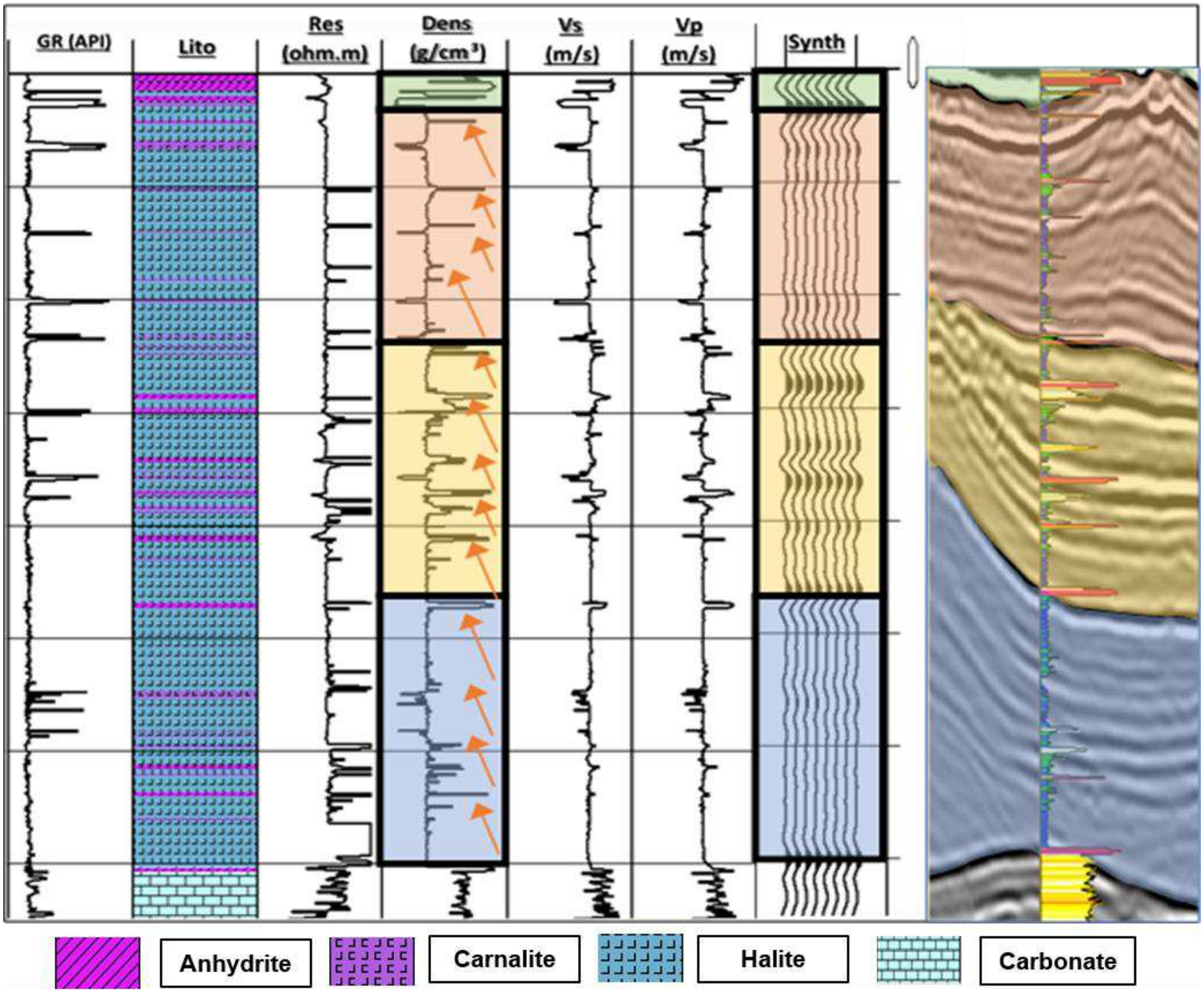

Figure 3: Basic well log suite of the well 3-BRSA-923A-SPS and the results of the seismic signal modeling analysis. It is possible to track the four major cycles as well as minor cycles within them. The colored sections are the major cycles and the arrows indicate some minor cycles identifiable in the well log. The synthetic track shows that not every minor cycle is trackable with this frequency content. Freitas (2006) suggests that these minor cycles correlate with orbital variations (Milankovitch cycles). Adapted from Pontes et al. (2018).

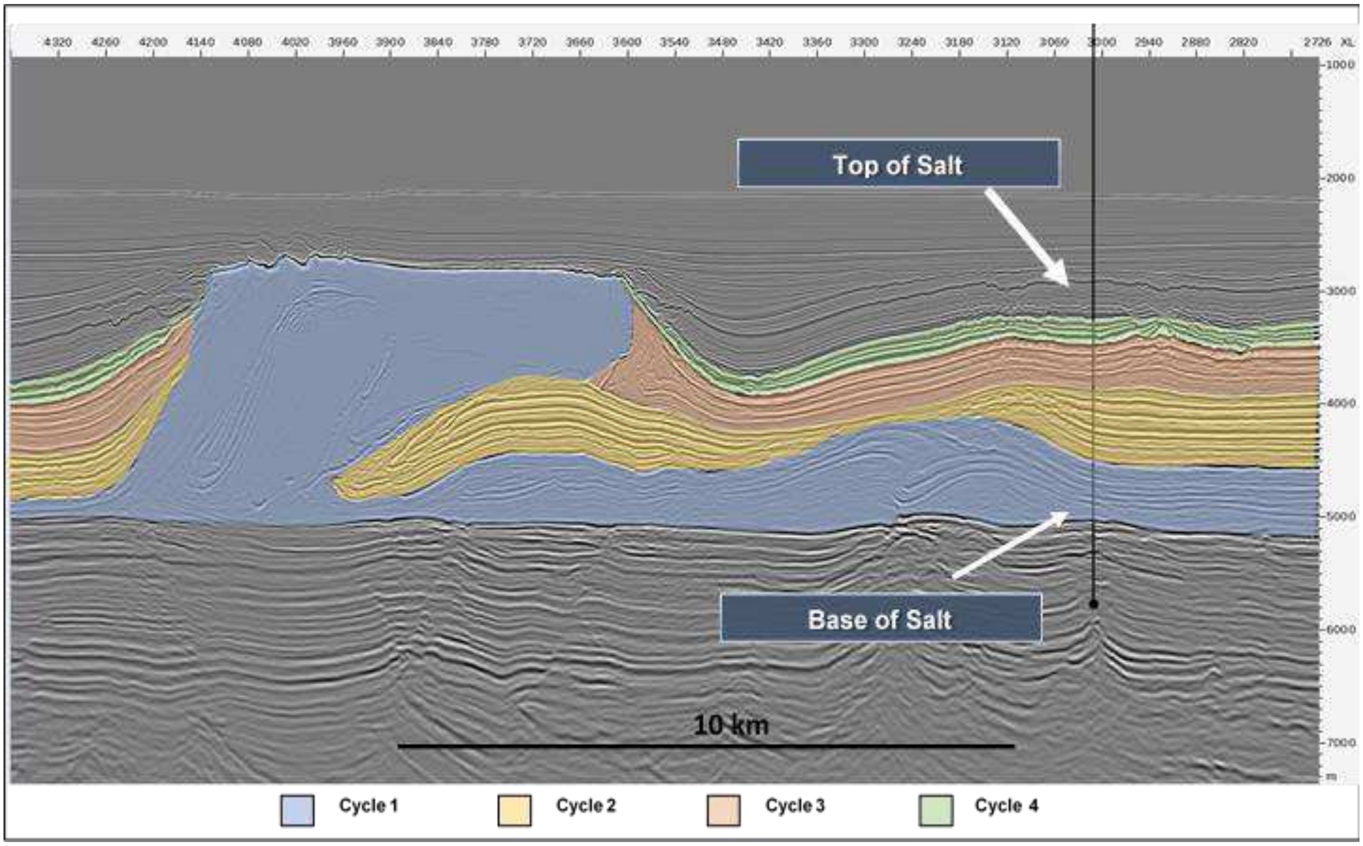

Figure 4: Seismic section in depth representing the mapped four major cycles described by Gamboa *et al.* (2009) and the well 3-BRSA-923A-SPS. It is important to notice the seismic facies variation between cycles and the structural complexity.