UNIVERSIDADE FEDERAL FLUMINENSE
INSTITUTO DE GEOCIÊNCIAS
DEPARTAMENTO DE GEOLOGIA E GEOFÍSICA

ALEXANDRE RODRIGO MAUL

# CARACTERIZAÇÃO SÍSMICA DAS ESTRATIFICAÇÕES DA SEÇÃO EVAPORÍTICA SALINA E SUAS APLICAÇÕES NOS PROJETOS DE EXPLORAÇÃO, DESENVOLVIMENTO E PRODUÇÃO DE HIDROCARBONETOS

TESE DE DOUTORADO

PROGRAMA DE PÓS-GRADUAÇÃO EM
DINÂMICA DOS OCEANOS E DA TERRA (DOT)

**Niterói, RJ**
**2020**

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Área de concentração: Geologia e Geofísica.

**Orientador**
Marco Antonio Cetale Santos

**Coorientadores**
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**Niterói,RJ**
**2020**

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*“O impossível é apenas difícil!”*

José Alves da Luz, em seu livro:

“Zé da Luz e suas Histórias”

## RESUMO

Os estudos aqui apresentados versam sobre a caracterização sísmica detalhada da seção evaporítica salina, que se sobrepõe aos reservatórios da seção Pré-Sal na Bacia de Santos, margem sudeste brasileira, visando melhorias dos modelos de velocidades sísmicas, através de conceitos de modelagem geológica 3D de propriedades, e suas principais aplicações práticas em projetos, enfatizando o desenvolvimento de metodologias.

Os modelos de velocidades sísmicas construídos, em especial para regiões de alta complexidade geológica, como é o caso da seção evaporítica salina, influenciam nas mais diversas aplicações do segmento E&P da indústria do petróleo.

Os resultados demonstram os benefícios da caracterização sísmica detalhada da seção evaporítica salina no aprimoramento de estudos de iluminação sísmica, visando melhor definição de parâmetros para novas aquisições, melhorando a iluminação sísmica do alvo e diminuindo o esforço e a complexidade durante o processamento sísmico. Igualmente relevantes são a redução das incertezas relacionadas ao posicionamento vertical e horizontal dos eventos, e a melhoria da qualidade do sinal sísmico utilizado como parâmetro de deriva, para auxiliar na distribuição de propriedades de reservatórios, de forma mais acurada. Este conjunto de ações resulta na melhoria das estimativas volumétricas dos campos, com significativos impactos econômicos e operacionais

Durante as fases de exploração, de desenvolvimento e de produção, os resultados dos modelos aprimorados de velocidades sísmicas fornecem informações adicionais para estudos de simulação geomecânica, permitindo melhores estratégias de produção e/ou injeção, propiciando melhorias na gestão de riscos e economicidade dos projetos. As previsões otimizadas de litologias provêm ainda maior precisão para parâmetros de perfuração e de fluidos utilizados durante a construção dos poços, inclusive direcionando a escolha do tipo de sonda mais apropriada quando da perfuração de novos poços. Desta forma, importantes informações são geradas para auxiliar na tomada de decisão sobre a necessidade de equipamentos de prevenção especial, dando maior segurança e economicidade ao projeto como um todo.

Nas etapas de migração sísmica, ou mesmo durante a construção e atualização de modelos de velocidades sísmicas para este fim de migração, a inserção das heterogeneidades ou estratificações no sal, tem grande importância para as técnicas mais avançadas de processamento disponíveis. Os modelos de velocidades construídos a partir desta caracterização detalhada demandam menores esforços computacionais durante o processo de atualização por inversão tomográfica. A atualização de modelos de velocidades pela técnica *Full-Waveform Inversion* (FWI) necessita de modelos de velocidades iniciais com forte comprometimento geológico, e a técnica de Migração Reversa no Tempo - *Reverse Time-Migration* (RTM) também requer modelos de velocidades mais detalhados e menos suavisados. A aplicação da técnica de *Least-Squares Migration* (LSM) também se beneficia de modelos de velocidades mais detalhados. Até mesmo em termos de anisotropia sísmica se observa a importância destes modelos mais detalhados de velocidades sísmicas.



**Palavras-chave:** seção evaporítica salina, velocidades sísmicas, migração sísmica, incertezas sísmicas.

# ABSTRACT

The present study details the seismic characterization of evaporatic saline section above the Pre-Salt reservoirs in Santos Basin, Southeastern Brazilian margin, aiming at improving the seismic velocity models, applying concepts 3D geological property models, and its main practical applications, emphasizing the development of methodologies.

In regions of high geological complexity, such as especially the evaporatic saline section, seismic velocity models influence the main diverse applications in a wide range of routines within the E&P segment of the oil industry.

The results demonstrate the benefits of detailed seismic characterization of the evaporatic saline section to improve seismic illumination studies, aiming at better defining parameters for new acquisitions, enhancing the seismic illumination of the target, and decreasing the effort and complexity during seismic processing. Equally relevant is the reduction in uncertainties related to the vertical and horizontal positioning of the events, as well as the quality of the seismic signal to be used as a trend parameter, assisting in accurate distribution of reservoir properties. These approaches improve the volumetric field estimates, with significant economic and operational impacts.

During the exploration, development and production phases accurate seismic velocity models provide additional information for geomechanical simulation studies, allowing for better production and/or injection strategies, providing enhancements in management of project risk and economicity. Optimized lithology predictions provide even greater precision for drilling and fluid parameters during well construction, influencing the choice of the most appropriate rig type when drilling new wells. Important information is also derived for deciding the need of special prevention equipment, providing greater security and economicity to the project as a whole.

Regarding the seismic migration workflows, even for the seismic velocity models construction and updating for migration purposes, the insertion of salt heterogeneities, or stratifications, has great importance for the most advanced seismic processing techniques available. The velocity models resulted from this detailed characterization require less computational effort during the tomographic inversion updating process. Updating velocity models using the Full-Waveform Inversion (FWI) technique requires initial velocity models presenting strong geological significance, and the Reverse Time-Migration (RTM) technique also requires more detailed, less smoothed, velocity models.The application of the Least-Squares Migration (LSM) technique also benefits from more detailed velocity models. Even in terms of seismic anisotropy, the importance of these more detailed models of seismic velocities is observed.

**Keywords:** saline evaporitic section, seismic velocities, seismic migration, seismic uncertainties.

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**(Participação como Coorientador)**

*"O Sal Estratificado e sua Importância na Modelagem de Velocidades para fins de Migração Sísmica"* – Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2017. **Falcão, L.** (Orientadores: Cetale, M. & Maul, A.).

*"Uma Metodologia para a Caracterização da Formação Ariri utilizando dados de Poços e Inversão Sísmica"* – Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2019. **Yamamoto, T.** (Orientadores: Lupinacci, W. & Maul, A.).

*"Seismic Characterization of Internal Salt Cycles: A Case Study in Santos Basin, Brazil"* – Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2019. **Pontes, R.** (Orientadores: Guizan, C. & Maul, A.).

*"Novo Método para Identificação de Estratificações de Sal utilizando Machine Learning sobre Atributos Sísmicos"* – Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2020. **Mesquita, F**. (Orientadores: Cetale, M. & Maul, A.).

## ANEXO E: LISTA DOS DEMAIS ARTIGOS SOBRE O TEMA INVESTIGADO, COM PARTICIPAÇÃO DIRETA E INDIRETA DO AUTOR DESTA TESE

SUMÁRIO

# 1 INTRODUÇÃO, MOTIVAÇÃO, OBJETIVOS E ESTRUTURAÇÃO DA TESE

O imageamento sísmico em regiões de complexidade geológica é reconhecidamente um grande desafio para a indústria do petróleo (Zhang & Sun, 2009; Huang *et al.*, 2010; Jones & Davison, 2014). Significantes melhorias em imageamentos sísmicos, em especial para a aplicação em regiões próximas a corpos de sal, são observadas quando se atualizam os modelos de velocidades pela técnica de *Full-Waveform Inversion* (FWI) antes dos processos de migração sísmica (Tarantola, 1984; Zhang & Wang, 2009; Kang *et al.*, 2019). A técnica de migração *Reverse-Time Migration* (RTM) é a mais a indicada para aplicação em ambientes de geologia complexa, sendo que esta é muito dependente de modelos de velocidades detalhados e corretos no sentido de se capturar a complexidade geológica acima dos alvos, como é o caso da complexidade imposta pelo sal na Bacia de Santos (Jones & Davison, 2014; Kang *et al.*, 2019; Shadrina *et al.*, 2020). Segundo Vigh *et al.* (2019), a aplicação da técnica de *Least-Squares Migration* (LSM) (Schuster *et al.*, 1993; Nemeth *et al.*, 1999) representa um grande avanço para os processos de migração sísmica, especialmente para compensar problemas de falta de iluminação sísmica, que podem gerar respostas sub-ótimas em termos de amplitudes sísmicas (Guo & Fagin, 2002; Zdraveva *et al.*, 2011). Esta técnica é também muito dependente de modelos de velocidades detalhados para ter sucesso em sua aplicação.

Os reservatórios das seção Pré-Sal da Bacia de Santos estão localizados abaixo da seção evaporítica salina, denominada Formação Ariri. Esta seção pode variar de poucos metros até cerca de 3 quilômetros de espessura, tendo em média 2.500 m (Mohriak *et al.*, 2012). A seção evaporítica salina representa então esta complexidade geológica descrita anteriormente, nesta bacia, o implica no grande desafio de imageamento sísmico para estes reservatórios. Assim, para a utilização destas técnicas mais avançadas de imageamento sísmico se faz necessária a construção de modelos de velocidades mais detalhados. Alguns autores começam a reportar importantes resultados em termos de imagens sísmicas ao se detalhar os modelos de velocidades com a inserção de estratificações na seção evaporítica salina da Bacia de Santos (Gobatto *et al.*, 2016; Falcão, 2017; Fonseca *et al.*, 2018; Maul *et al.*, 2018c, Dias *et al.*, 2019) e quando da aplicação da técnica LSM em projetos desta mesma bacia (Pereira-Dias *et al.*, 2017; Pereira-Dias *et al.*, 2018; Shadrina *et al.*, 2020).

A principal motivação para esta pesquisa é apresentar meios para a caracterização sismica da seção evaporítica salina, visando detalhamento de suas feições geológicas (estratificações). Isto propicia a construção de modelos de velocidades sísmicas mais adequados (detalhados) que reflitam esta complexidade geológica da Bacia de Santos, com o auxílio da utilização de atributos sísmicos. A heterogeneidade interna do pacote salino apesar de nítida em seções sísmicas nem sempre está disponível em termos de propriedades (velocidades) para aplicações *a posteriori*. A Figura 1 apresenta suscintamente este problema, onde podemos observar que apesar de aparentes na resposta sísmica (amplitude) a geologia existente (estratificações da seção evaporítica) não está presente no modelo de velocidades que gerou o próprio dado sísmico.

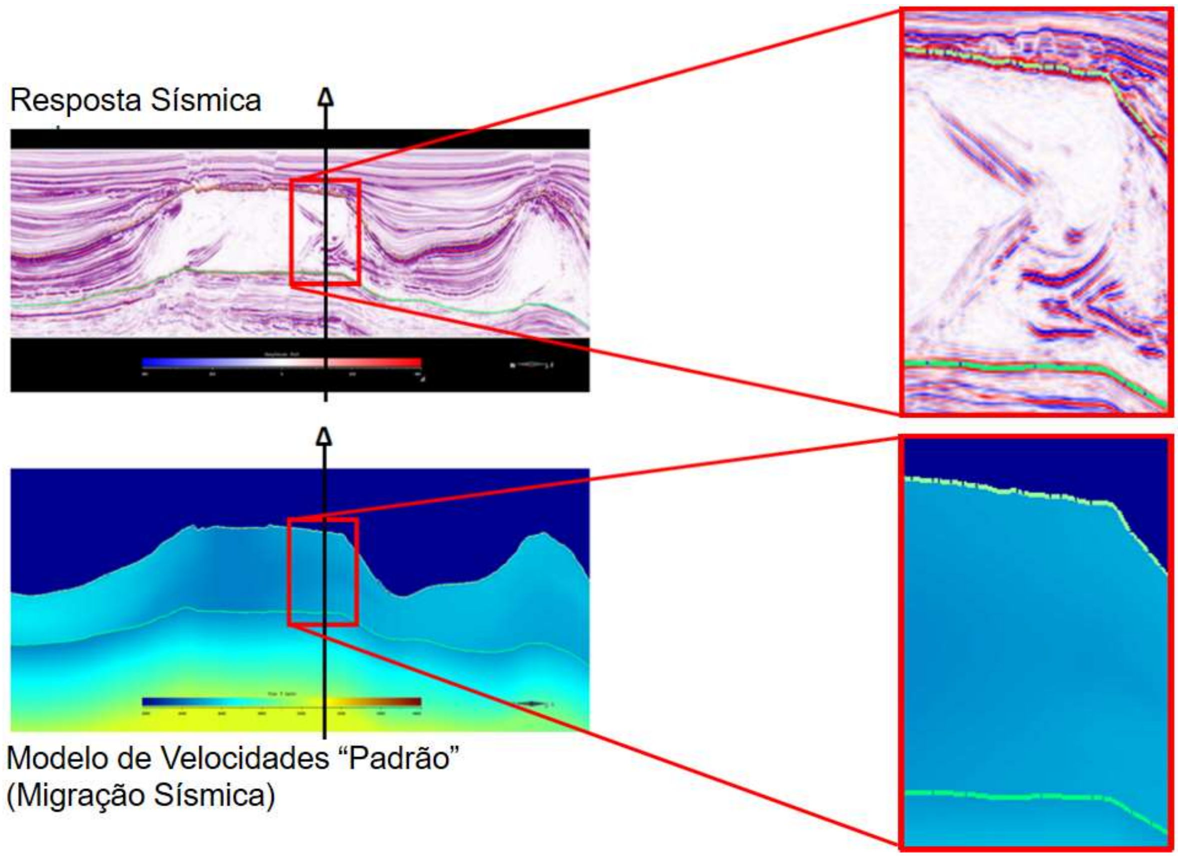


Figura 1: Apresentação do problema (motivação) a ser resolvido (objetivo). Na parte superior da figura, inclusive no detalhe, é possível se obsevar que o dado sísmico de amplitude apresenta refletores internos na seção evaporítica salina – as estratificações, e na parte inferior, no modelo de velocidades, estas feições geológicas – estratificações, não estão representadas. Adaptado de Maul *et al.* (2018c).

Assim, os principais objetivos desta tese são a caracterização destas estratificações existentes na seção evaporítica salina em termos de propriedades, utilizando informações de poços e atributos sísmicos. Isto propicia seu maior detalhamento e suas aplicações nas mais diferentes fases de projetos de exploração, desenvolvimento e produção de hidrocarbonetos. Maior ênfase será dada aos modelos de velocidades intervalares que poderão ser utilizados para estudos de iluminação sísmicas, como modelos iniciais de velocidades para atualizações junto ao fluxo de processamento sísmico – migração sísmica, estudos de incertezas em profundidade dos reservatórios, insumos para estudos de simulação geomecânica, previsão de quadros geológicos de perfuração de poços, aumentando a seguraça operacional e economicidade dos projetos, propiciando assim melhores tomadas de decisões.

Esta tese é o fruto de um longo trabalho que se iniciou antes do próprio escopo da pesquisa de doutorado, contando com a participação de diversas pessoas que participaram da "formulação inicial" do problema a ser investigado, da busca por soluções para o mesmo, de discussões sem as quais os resultados não teriam aplicações práticas, e da publicação das dezenas de artigos técnicos nos mais diversos fóruns de pesquisa, conforme pode ser consultado nos anexos. Desta forma, esta tese em si é um esforço maior para organizar todas estas informações e gerar os artigos necessários para ilustrar, complementar e confirmar a importância da caracterização sísmica da seção evaporítica salina, inserindo suas estratificações, e demonstrando suas aplicações nos projetos de exploração, desenvolvimento e produção de hidrocarbonetos.

Será apresentada uma breve revisão sobre Bacia de Santos, na porção *offshore* do Brasil e uma contextualização dos evaporitos salinos, no geral e nesta mesma bacia. Será apresentada ainda uma revisão, geral, sobre a importância dos modelos de velocidades detalhados para os desafios em termos dos processos de migração sísmica, em áreas de complexidade geológica, e o papel da técnica de inserção das estratificações na seção evaporítica salina, nas mais diversas áreas de conhecimento da indústria do segmento E&P, em especial no que tange às suas principais incertezas associadas, tendo como principal foco para os dados sísmicos, especialmente em termos destes processamentos sísmicos (migrações sísmicas e suas particularidades).

Serão apresentadas as principais contribuições para a ciência obtidas e comprovadas através desta pesquisa (em seu todo), algumas conclusões e sugestões de estudos futuros. Ao longo do texto (tese) que resume todos estes trabalhos constantes principalmente no anexo A, de forma geral, nem todas as referências bibliográficas que sustentam os mesmos, serão reapresentadas, uma vez que estas são citadas cada um dos artigos listados.

Assim, esta tese de doutorado foi estruturada em torno dos 6 artigos de periódicos (Anexo A), publicados ou em avaliação durante o período oficial em termos de doutorado, desta pesquisa. Desta forma, cada um destes pode se “caracterizar” como um dos “capítulos” de desenvolvimento da tese como um todo.

O primeiro artigo, intitulado “***Few Considerations, Warnings and Benefits for the E&P Industry when Incorporating Stratifications inside the Salt Section***”, de autoria de <u>Maul, A.</u>, Cetale, M. & Guizan, C., publicado em *Brazilian Journal of Geophysics*, 36(4): 461-477, 2018 (**Anexo A1**), versa sobre uma vasta coletânea de informações publicadas até o início desta pesquisa oficial de doutorado, cruzando-as e apresentando suas principais considerações, riscos e benefícios ao se utilizar a metodologia de inserção de estratificações na seção evaporítica salina através de atributos sísmicos. Neste artigo já é possível visualizar alguns resultados importantes com relação aos estudos de iluminação sísmica, critérios para análise de confiabilildade do sinal sísmico em função de modelos de velocidades do sal, caracterização de domínios de estratificações do sal, proposição para o agrupamento dos minerais da seção evaporítica, em especial para a construção de modelos de velocidades com finalidade de processos sísmicos.

O segundo artigo, intitulado “***Salt Velocity Modeling Uncertainities and Variabilities: Implication for the Pre-Salt Projects in the Santos Basin, Brazil***”, de autoria de <u>Maul, A.</u>, Cetale, M., Guizan, C., González, M., Fonseca, J., Borges, F. & Abreu, C.E., publicado em *Brazilian Journal of Geophysics*, 37(2): 175-186, 2019 (**Anexo A2**), ilustra as principais incertezas para a utilização desta metodologia de inserção de estratificações na seção evaporítica salina. Estas incertezas ocorrem principalmente em função da ausência de informações que serviriam para calibrar seus resultados, ou mesmo quando presentes, do grau de confiabilidade com que as mesmas se apresentam, seja por questões de formas de aquisições (suas imprecisões), seja por suas variabilidades e/ou premissas de utilizações, ambos nem sempre bem estabelecidas, ou ainda por simplificações necessárias para a operacionalização da utilização destas informações. Através deste artigo são exploradas algumas características dos tipos de minerais existentes na seção evaporítica salina e algumas de suas respostas, como por exemplo efeitos de compactação, resistência a movimentações e correlações com espessuras.

O terceiro artigo, intitulado "***Geological Characterization of Evaporitic Section and its Impacts on Seismic Images: Santos Basin, Offshore Brazil***", de autoria de Maul, A., Cetale, M., Guizan, C., Fonseca, J., González, M., Teixeira, L., Yamamoto, T., Borges, F. & Pontes, R., publicado em *Brazilian Journal of Geophysics*, 37(1): 55-68, 2019 (**Anexo A3**), enfatiza, que mesmo considerando as incertezas descritas no artigo anterior, a importância dos estudos de inversão sísmica, *model-based*, ou seja levando em consideração as informações dos poços e horizontes mapeados na busca pela melhor caracterização da seção evaporítica salina. Ilustra a dificuldade de se inverter esta seção, em especial por sua grande espessura ou, ainda, variabilidade de espessuras, o que dificulta, por exemplo, na obtenção de uma *wavelet* média representativa para a seção como um todo. Apresenta as primeiras melhorias na geração de imagens sísmicas ao se utilizar este resultado de caracterização da seção evaporítica em termos de velocidades intervalares, a partir do estudo de inversão sísmica. Este modelo gerado foi inserido no fluxo do processo de migração sísmica fornecendo o modelo de velocidades inicial a ser atualizado por técnicas específicas, neste caso utilizando a inversão tomográfica e avaliação dos painéis de alinhamento de *gathers*.

O quarto artigo, intitulado "***Improving Pre-Salt Reservoirs Seismic Images when Considering the Stratified Evaporites Insertion in the Initial Model for the Velocity Updating Processses prior to the Seismic Migration***", de autoria de Maul, A., Cetale, M., Guizan, C., Teixeira, L., González, M., Fonseca, J., Dias, R., Boechat, J.B., Borges, F., Falcão, L., Yamamoto, T. & Pontes, R., publicado *em Brazilian Journal of Geophysics*, 37(3):235-247, 2019 (**Anexo A4**), comprova através da comparação de diversos exemplos as inúmeras melhorias ao se considerar no processo de atualização dos modelos de velocidades gerados à partir da metodologia de inversão sísmica - *model based*. Estes modelos serviram de base para o processo de atualização por inversão tomográfica dos modelos de velocidades anterior à etapa de migração sísmica. Neste caso, foram comparadas imagens sísmicas geradas a partir da atualização tomográfica - três iterações, considerando a metodologia padrão de processamento sísmico, e outras geradas a partir da atualização tomográfica - neste caso sendo necessária apenas uma iteração, quando utilizado o modelo de "sal estratificado", oriundo da inversão sísmica, conforme descrito no anexo anterior. Além do benefício em termos de ganhos computacionais – menor necessidade de iterações tomográfica, foi enfatizado o benefício em termos de qualidade das imagens sísmicas geradas.

O quinto artigo, intitulado "***Combining of Stratified Salt Velocity and Least-Squares Migration: Effects on Image Quality, Resolution, Depth Positioning and Amplitude Response***", de autoria de <u>Maul, A.</u>, Bulcão, A., Dias, R.M., Pereira-Dias, B. Teixeira, L., Borges, F., González, M., Guizan, C. & Cetale, M., submetido para *Journal of Applied Geophysics*, APPGEO-D-20-00150, em 30/10/2020 (**Anexo A5**), nos permite apresentar como a técnica de compensação das ausências de iluminação sísmica, através da utilização da *Least-Squares Migration* (LSM), associada aos modelos de velocidades que consideram as estratificações da seção evaporítica salina, sempre tendo como algorítimo de migração a técnica *Reverse Time-Migration* (RTM), permite gerar imagens sísmicas mais confiáveis. As melhorias são observadas tanto em termos de qualidade das imagens sísmicas, como em consideração à resolução dos eventos. Além disso são observadas melhores acurácias em termos de posicionamentos dos eventos, e qualidade relativa ao sinal sísmico no que diz respeito às informações de amplitude sísmica. Foram realizadas comparações dos resultados ao se considerar ou não, os modelos de sais estratificados, associados ou não, à utilização da técnica de *Least-Squares Migration*.

O sexto artigo, intitulado "***The Impact of Heterogeneous Salt Velocity Models on the Gross Rock Volume Estimation: an Example from the Santos Basin Pre-Salt, Brazil***", de autoria de <u>Maul, A.</u>, Cetale, M., Guizan, C., Corbett, P., Underhill, J., Teixeira, L., Pontes, R. & González, M., submetido para *Petroleum Geosciences*, petgeo2020-105 em 25/09/2020 (**Anexo A6**), apresenta alguns resultados práticos, em termos de volumetrias de hidrocarbonetos ao se utilizar diferentes modelos de velocidades disponíveis e/ou construídos para a seção evaporítica salina. Neste caso foram utilizados os seguintes modelos: (a) modelo com velocidade constante da seção evaporítica com valores próximos ao do mineral Halita; (b) modelo com velocidade oriunda do processamento sísmico (contendo suas atualizações por inversão tomográfica); (c) modelo de velocidades com sal estratificado construído com a inserção de estratificações na seção evaporítica a partir das informções de amplitude sísmica; (d) modelo de velocidades construído a partir da inversão acústica da seção evaporítica, utilizando o topo e base do sal como referência; e, por fim, (e) modelo de velocidades obtido a partir da inversão acústica da seção evaporítica salina onde o seu modelo *a priori*, além do topo e a base do sal, considerou mais três horizontes internos, "separando" quatro ciclos, de 4ª ordem estratigráfica, de deposição do sal. Através destes modelos, pôde-se confirmar que quanto maior o conceito geológico aplicado na construção dos modelos de velocidades melhores e mais confiáves são as previsões de profundidade dos eventos de interesse reduzindo assim as incertezas de projetos.

# 2 MATERIAIS E MÉTODOS

Para o desenvolvimento desta pesquisa a Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) disponibilizou um dado sísmico cobrindo uma área de aproximadamente 200 km², juntamente com o modelo de velocidades utilizado no processo de migração sísmica, em conjunto com 14 poços e todas as informações obtidas durante suas perfurações. Estas informações estão inseridas na área do *ring-fence*[1] do Campo de Sapinhoá na Bacia de Santos, e foram disponibilizados pela ANP através das solicitações 026285/2018, com ofício de autorização 9011/10469 de 03/16/2018, e 035695/2018, com ofício de autorização 9064/10524 de 04/20/2018.

Os dados sísmicos *streamer* apresentam os seguintes parâmetros de aquisição: total de receptores: 240; intervalo de entre receptores: 25 m; *offset* mínimo 25: m; *offset* máximo: 6.000 m; número de amostras: 2.001; profundidade dos receptores: 6 m; profundidade da fonte: 10 m; taxa de amostragem: 4 ms; frequência de corte da fonte: 45Hz; assinatura da fonte: Ricker. Em termos de processamento estes dados são classificados como sendo *Pre-Stack Depth Migration* (PSDM), obtidos através de uma migração Kirchhoff com anisotropia vertical (VTI). O modelo de velocidades utilizado na etapa de migração sísmica foi finalizado com base no método de inversão tomográfica com acompanhamento de painéis de alinhamentos de *gathers*.

Os poços disponibilizados pela ANP foram: 1-BRSA-594-SPS, 3-BRSA-788-SPS, 3-BRSA-923A-SPS, 9-BRSA-928-SPS, 9-BRSA-1037-SPS, 9-BRSA-1043-SPS, 7-SPH-1-SPS, 7-SPH-2D-SPS, 7-SPH-4D-SPS, 7-SPH-5-SPS, 7-SPH-8-SPS, 8-SPH-13-SPS, 7-SPH-14D-SPS, 8-SPH-23-SPS. Ao longo dos artigos, de forma a simplificar a apresentação dos resultados, os poços foram renomeados com letras maiúsculas de A a N, de acordo com a orientação de Norte para Sul. Os dados dos poços utilizados foram as amostras de calha e os perfis existentes, em especial: sônico, densidade, raios gama, caliper, taxa de penetração.

A figura 2 apresenta a localização da área de estudo, a dimensão do dado sísmico e a localização dos poços, de acordo com esta definição de letras maiúsculas, e a tabela 1 apresenta a relação entre esta nomenclatura e a oficial, da ANP.

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[1] *Ring-fence* é uma barreira virtual que segrega uma porção individual (um campo de petróleo, por exemplo) do todo, tanto em termos físicos como financeiros (investopedia.com).

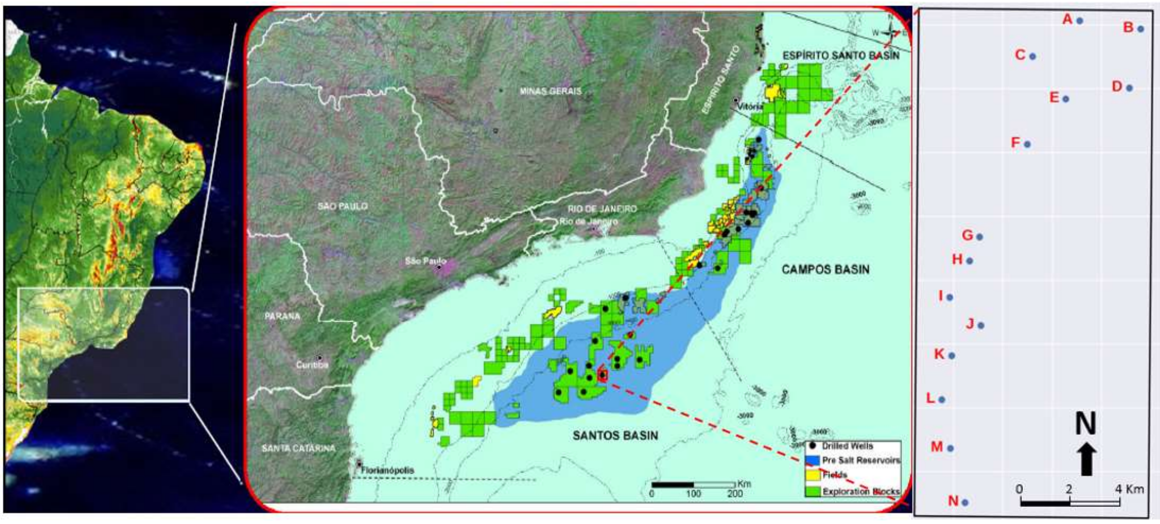


Figura 2: Localização da área de estudo. O polígono azul delimita a área de ocorrência da província Pré-Sal nas Bacias de Santos e de Campos, cobrindo uma áres de aproximadamente 380.000 km², e com lâmina d´água variando entre 2.000 to 3.000 m, e espessuras da camada de sal (seção evaporítica salina) variando de poucos metros até próximo de 3.000 m, com espessura média na ordem de 2.500 m. O painel à direita apresenta área coberta pela sísmica deste projeto e o detalhe das locações dos poços (A to N). Adaptado de Maul *et al.* (2019a), baseado de https://diariodopresal.files.wordpress.com/2010/.

Tabela 1: Correspondência entre a designação utilizada para os poços neste estudo e os nomes oficiais de acordo com a Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP).

| ANP | Este Estudo |
|---|---|
| 3-BRSA-788-SPS | A |
| 9-BRSA-1037-SPS | B |
| 8-SPH-23-SPS | C |
| 8-SPH-13-SPS | D |
| 7-SPH-14D-SPS | E |
| 7-SPH-8-SPS | F |
| 7-SPH-4D-SPS | G |
| 9-BRSA-928-SPS | H |
| 7-SPH-5-SPS | I |
| 9-BRSA-1043-SPS | J |
| 1-BRSA-594-SPS | K |
| 7-SPH-1-SPS | L |
| 7-SPH-2D-SPS | M |
| 3-BRSA-923A-SPS | N |

Para o desenvolvimento dos testes e análises desta tese foram utilizados diversos aplicativos comercias, dentre eles: SKUA-GOCAd™, Petrel©, Jason©, GeoDepth®, Excel. Além destes foram desenvolvidas rotinas em Python™, C e C++, e algoritmos implementados internamente na Petrobras (CENPES), especificamente para a execução das etapas de modelagens acústicas, migrações reversas no tempo, e aplicação de técnicas de compensação de iluminação por *Least-Squares Migration*.

As metodologias aplicadas para a obtenção dos resultados apresentados nos artigos publicados estão descritas nos mesmos. Entretanto, de forma geral a metodologia desenvolvida nesta tese perpassa por estratégias de caracterização sísmica da seção evaporítica salina, incluindo a avaliação quantitativa das informações existentes nos poços perfurados, o mapeamento de horizontes para a execução de estudos de inversão sísmica e consequentemente um detalhamento desta seção. Os produtos obtidos a partir destes estudos de inversão serviram como base para as etapas iniciais do fluxo de construção de modelos de velocidades visando a migração sísmica. Neste sentido, foram desenvolvidas e testadas diversas abordagens variando algoritmos de migração (Kirchhoff/RTM - *Reverse Time-Migration*), modelos de velocidades para a seção evaporítica (modelo de sal constante, tomográfico, baseado em amplitude, em estudos de inversão sísmica, alternativas de inversão sísmica). Estas variações foram ainda testadas à luz dos estudos de compensação da iluminação sísmica através da aplicação da técnica de *Least-Squares Migration* - LSM, onde se pode observar o incremento na qualidade dos resultados ao se associar esta técnica com os modelos de sal estratificados. De posse de alguns destes modelos, foram realizados exercícios de variações volumétricas de rochas acima do contato óleo-água e os resultados também foram apresentados.

# 3 BREVE REVISÃO SOBRE A BACIA DE SANTOS

Segundo Moreira *et al.* (2007) a Bacia de Santos situa-se na região sudeste da margem continental brasileira, entre os paralelos 23º e 28º Sul, e ocupa uma área de aproximadamente 350.000 $km^2$, abrangendo os litorais dos Estados do Rio de Janeiro, São Paulo, Paraná e Santa Catarina. Limita-se ao norte com a Bacia de Campos pelo Alto de Cabo Frio e ao Sul com a Bacia de Pelotas pelo Alto de Florianópolis (Figura 3).

Chang *et al.* (1992) advogam que a geração e a evolução da Bacia de Santos estão relacionadas ao evento de ruptura do Supercontinente Gondwana, que se iniciou no Neocomiano, culminando com a abertura do oceano Atlântico Sul e a implantação das bacias marginais brasileiras ao longo do chamado Sistema de Riftes do Leste Brasileiro. Kukla *et al.* (2018) afirmam este conceito de ruptura e datam o início desta abertura como sendo o início do Cretáceo e de forma bem clara apresentam o conceito de implantação de bacias salinas, dentre elas, a "bacia salina" da Bacia de Santos (Figura 4).

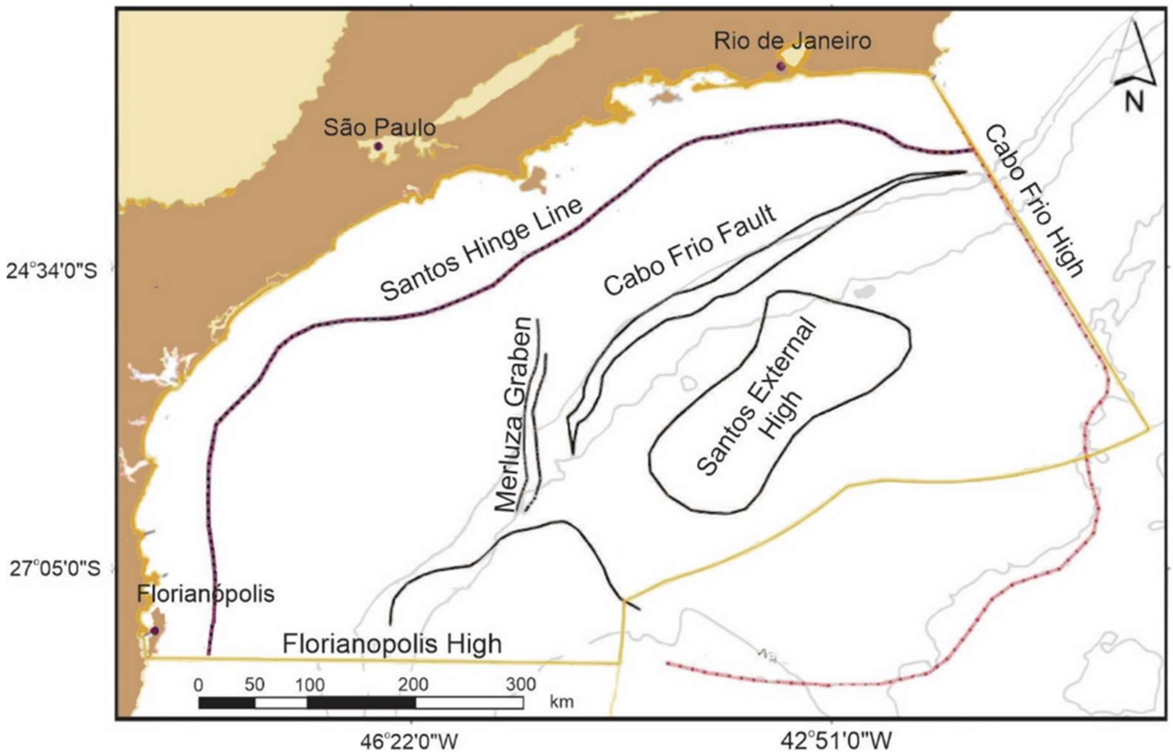


Figura 3: Localização da Bacia de Santos e seus limites estruturais. Adaptado de Garcia *et al.* (2012).

De acordo com Ponte & Asmus (1978), a Bacia de Santos apresentaria feições de uma bacia de margem passiva, contendo 4 discordâncias que controlariam megassequências tectono-sedimentares. A primeira megassequência seria marcada pelo estágio rifte com sedimentos fluviais e lacustrinos datados do Jurássico Tardio/Cretáceo Inicial; a segunda seria caracterizada por um estágio transicional ou ainda lacustre, datado do Aptiano; já terceira megassequência estaria relacionada aos depósitos de carbonatos de mares restritos, datados do Albiano; e a quarta e última megassequência seria caracterizada por sedimentos de mares abertos, datados do Cenomaniano até o presente.

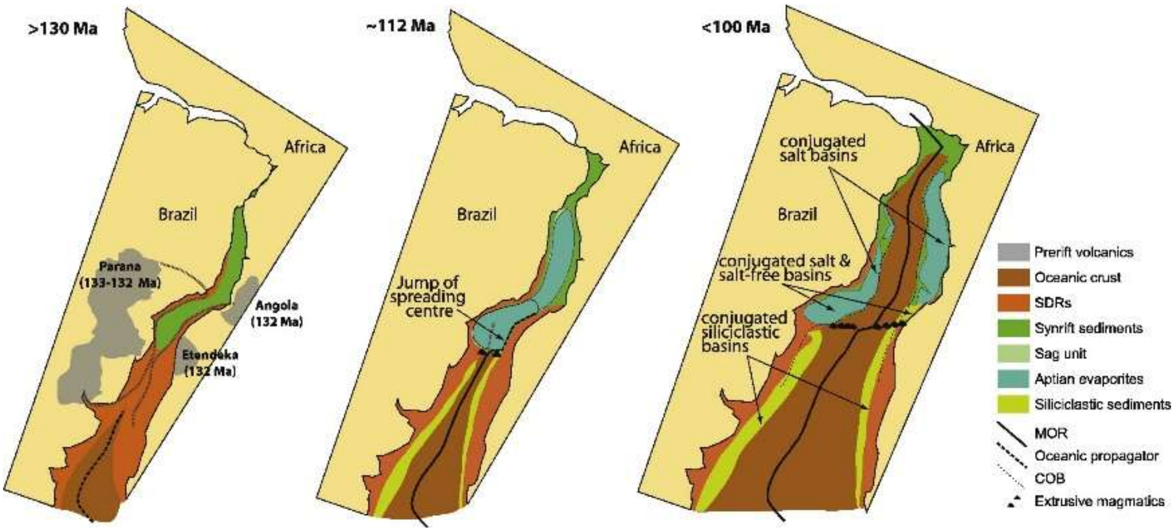


Figura 4: Esquema simplificado de evolução das bacias marginais brasileiras, com ênfase na implantação de bacias salinas, objeto deste estudo. Adaptado de Kukla *et al.* (2018).

Moreira *et al.* (2007) ao estabelecerem uma revisão da Carta Estratigráfica da Bacia de Santos (Figura 5) relatam que por sobre o embasamento pré-Cambriano, de forma discordante estão os basaltos da Formação Camboriú, do Grupo Guaratiba. Além da Formação Camboriú, o Grupo Guaratiba ainda apresenta os sedimentos carbonáticos, siliciclásticos e evaporíticos das Formações Piçarras, Itapema, Barra Velha e Ariri, e correspondem ao período anterior à fase drifte da bacia, durante períodos de maiores ou menores ativações de falhas (fase rifte). As Formações Piçarras e Itapema são caracterizadas por sedimentações continentais. De forma discordante, ocorre a Formação Barra Velha, que foi depositada durante o Aptiano, em uma relativa calmaria tectônica. Predomina nesta formação a deposição de carbonatos e folhelhos, refletindo um típico ambiente transicional, de continental à marinho raso. Tardiamente, ainda no Aptiano, foi depositada a sequência evaporítica salina, nominada de Formação Ariri, principal objeto deste estudo. Sobre o Grupo Guaratiba são encontradas 3 sequências maiores que compõem a fase drifte da bacia, os Grupos Camburi, Frade e Itamambuca. Sequências do Albiano ao Cenomaniano compreendem estes grupos. Os primeiros depósitos, do Grupo Camburi são claramente relacionados com a evolução da fase drifte. Durante o Albiano, sedimentos siliciclásticos proximais, calcáreos de águas rasas na plataforma continental, e margas e folhelhos na bacia distal foram depositados. A sequência do Cenomaniano é marcada por registros deltaicos e leques siliciclásticos proximais, com folhelhos e margas da plataforma continental até as regiões mais distais da bacia. No Grupo Frade o registro de uma grande transgressão marinha é representado pelo padrão retrogradacional (*onset*) deste pacote. No paleo-ambiente continental, principalmente no Cretáceo Tardio, sequências siliciclásticas progradacionais foram depositadas. No Grupo Itamambuca, de idade Cenozóica, os sedimentos depositados variam de leques aluviais a folhelhos distais marinhos e arenitos. Por sobre o Grupo Itamambuca está presente a Formação Ponta Aguda, que apresenta uma larga distribuição geográfica, e seu registro é datado do Paleógeno Inicial ao Médio. Finalizando o registro estratigráfico está presente a Formação Iguapé, datada do Oligoceno ao presente.

Recentemente, em função de inúmeros estudos relacionados aos principais reservatórios da seção Pré-Sal da Bacia de Santos, a influência marinha na deposição destes reservatórios é contestada (Wright & Barnett, 2015; Muniz & Bosence, 2015; Farias *et al.*, 2019; Gomes *et al.*, 2020), sendo o descarte desta influência marinha um importante marco para a compreensão do sistema deposicional da Fm. Barra Velha, uma vez que carbonatos marinhos contrastam fortemente dos lacustres (Castro & Lupinacci, 2019).

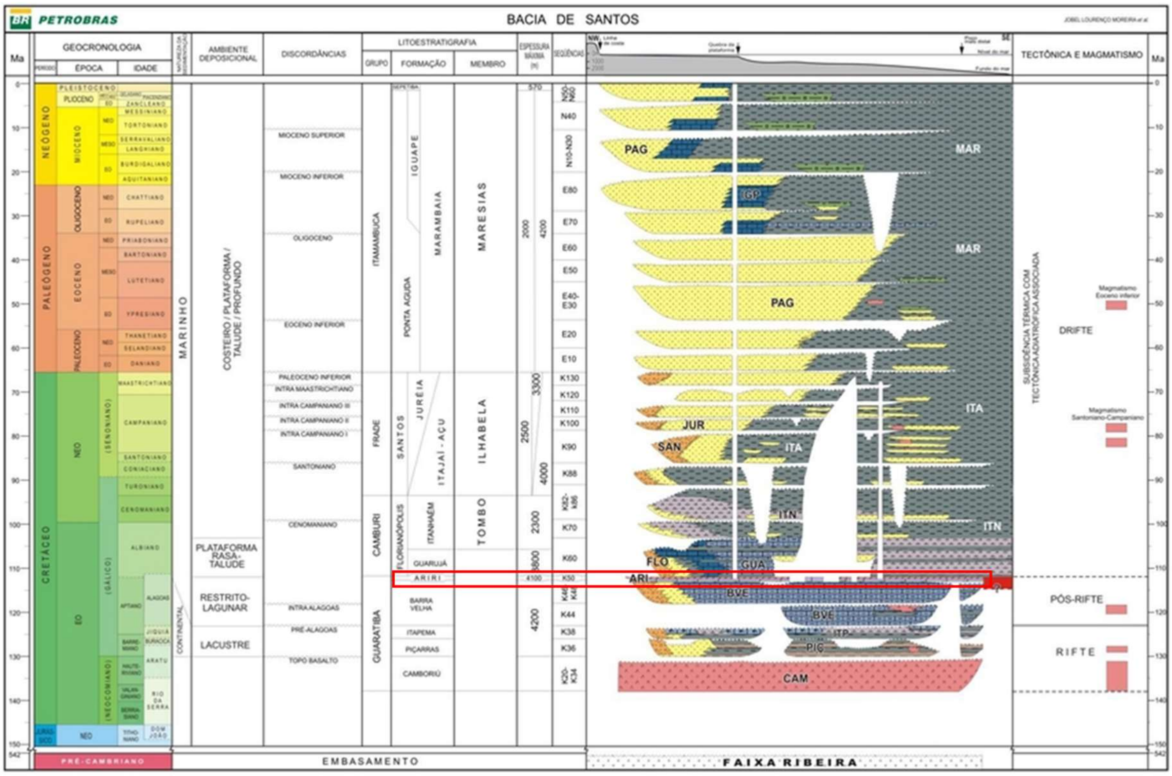

Figura 5: Carta Estratigráfica da Bacia de Santos, com destaque para o posicionamento da Formaçao Ariri - Seção Evaporítica Salina, objeto de estudo desta tese. Adaptado de Moreira *et al.* (2007).

# 4 OS EVAPORITOS SALINOS E SEU CONTEXTO NA BACIA DE SANTOS

Evaporitos salinos representam apenas 2% do registro sedimentar. Entretanto estão relacionados com aproximadamente 50% das reservas de hidrocarbonetos do mundo (Warren, 2016). Dos 120 campos de petróleo considerados gigantes, descobertos entre 2000 e 2012 no mundo, 56% tinham evaporitos salinos como selos (Bai & Xu, 2014).

A província Pré-Sal no Atlântico Sul se tornou uma das mais importantes áreas para estes recursos naturais na última década. O primeiro poço a atingir os reservatórios da seção Pré-Sal na Margem Continental Brasileira foi concluído em setembro de 2005. Em 2009, a produção destes reservatórios se iniciou no Campo de Lula (Tupi). Atualmente, após a perfuração de cerca de 250 poços, as reservas provadas da seção Pré-Sal correspondem a aproximadamente 60% dos 15 bilhões de boe[2] da reserva Brasileira, com uma taxa de produção diária superior a 2,1 milhões de barris/dia, com alguns poços produzindo mais de 40.000 barris/dia (Ávila, 2020). Desde então, vários campos gigantes foram descobertos em lâminas d´água ao redor de 2.000 m, especialmente por consórsios liderados pela Petrobras, todos produzindo das formações Barra Velha e Itapema.

Os evaporitos salinos na Bacia de Santos têm em média 2.500 m de espesssura, variando de poucos metros a quase 3.000 m (Mohriak *et al.*, 2012). Esta seção atua como o selo efetivo para reservatórios carbonáticos do Aptiano (Carminatti *et al.*, 2008). Uma análise detalhada das heterogeneidades intrasal na Bacia de Santos é possível em função da alta qualidade dos dados sísmicos e da grande quantidade de poços já perfurados e de seus perfis. A seção evaporítica da Bacia de Santos, *offshore* do Brasil, vem atraindo grande atenção de empresas de vários países nas últimas duas décadas em função da descoberta desta província carbonática de reservatórios e seus campos considerados, em alguns casos, como super-gigantes (Carlotto *et al.*, 2010).

Segundo Warren (2016) baseado em diversos autores anteriores, evaporitos são por definição rochas formadas em ambientes sedimentares com baixíssimo aporte

[2] boe: Barril de Óleo Equivalente. Unidade utilizada pela industria do petróleo para comparar volumes de óleo e gás natural. (fgvenergia.fgv.br)

de sedimentos terrígenos, sujeitos a altas taxas de evaporação em condições de climas áridos, o que propicia a formação das salmouras. Para Kendall (1988), uma sequência de precipitação química nestes ambientes é composta por carbonatos, sulfatos e cloretos, que refletem uma sucessão vertical assim como seu posicionamento lateral, conforme estabelecido pela "Lei de Walther"[3], com carbonatos e sulfatos próximos à entrada do mar, e os sais mais solúveis nas porções mais centrais e distais da bacia.

Erroneamente para muitas atividades da indústria do petróleo a seção evaporítica salina é idealizada como uma seção aproximadamente homogênea, e apresentando as características do mineral de Halita (NaCl). De fato, na maioria dos poços investigados este é o mineral predominante, com cerca de 80% de ocorrência (Maul *et al.*, 2018a; 2018c). Entretanto, os cerca de 250 poços já perfurados na Bacia de Santos visando acessar os reservatórios da seção Pré-Sal que, obviamente, atravessaram e perfilaram esta seção evaporítica salina, comprovaram que outros evaporitos estão sempre presentes. Segundo Maul *et al.* (2018b - Anexo A1), os mais comuns são: Anidrita ($CaSO_4$), Gipsita ($CaSO_4 \cdot 2(H_2O)$), Silvita (KCl), Carnalita ($KMgCl_3 \cdot 6(H_2O)$) e Taquidrita ($CaMg_2Cl_6 \cdot 12(H_2O)$). Estes minerais, em termos de velocidades sísmicas, apresentam variações em relação à Halita: Anidrita e Gipsita com velocidades maiores, e Silvita, Carnalita e Taquidrita, com velocidades menores (Maul *et al.* 2015).

De acordo com Bąbel & Schreiber (2014), ao final do ciclo de deposição dos carbonatos de uma sequência evaporítica se inicia o processo de precipitação dos evaporitos salinos. Nesta fase, até a faixa de 10% de evaporação da salmoura, apenas gipsita será depositada. Esta gipsita em função do soterramento, devido à perda de água estrutural, será convertida em Anidrita que em geral é o mineral encontrado na Bacia de Santos. Após, entre 10 e 70% de evaporação da salmoura apenas Halita será depositada. Por fim, a partir de 70% de evaporação da salmoura, os denominados "sais amargos" (Carnalita, Silvita e Taquidrita) são depositados, ou convertidos (Figura 6). Qualquer influxo de água durante este processo altera as condições da salmoura e novas sequências de precipitações são iniciadas, denotando

[3] A Lei de Walther afirma que a sucessão vertical das fácies reflete mudanças laterais no meio ambiente, e que à medida que o sistema deposicional "migra" lateralmente, os sedimentos de uma nova fase deposicinal vão se "acomodar" por sobre o anterior (Glossário Geológico – CPRM).

o caráter de ciclos para a formação dos evaporitos. O processo de aumento da concentração iônica na salmoura (*Brining Upward*) e o processo de diminuição da concentração iônica na salmoura (*Brining Downward*) nos ajudam a melhor compreender o efeito de ciclicidade na formação dos evaporitos salinos (Figura 7).

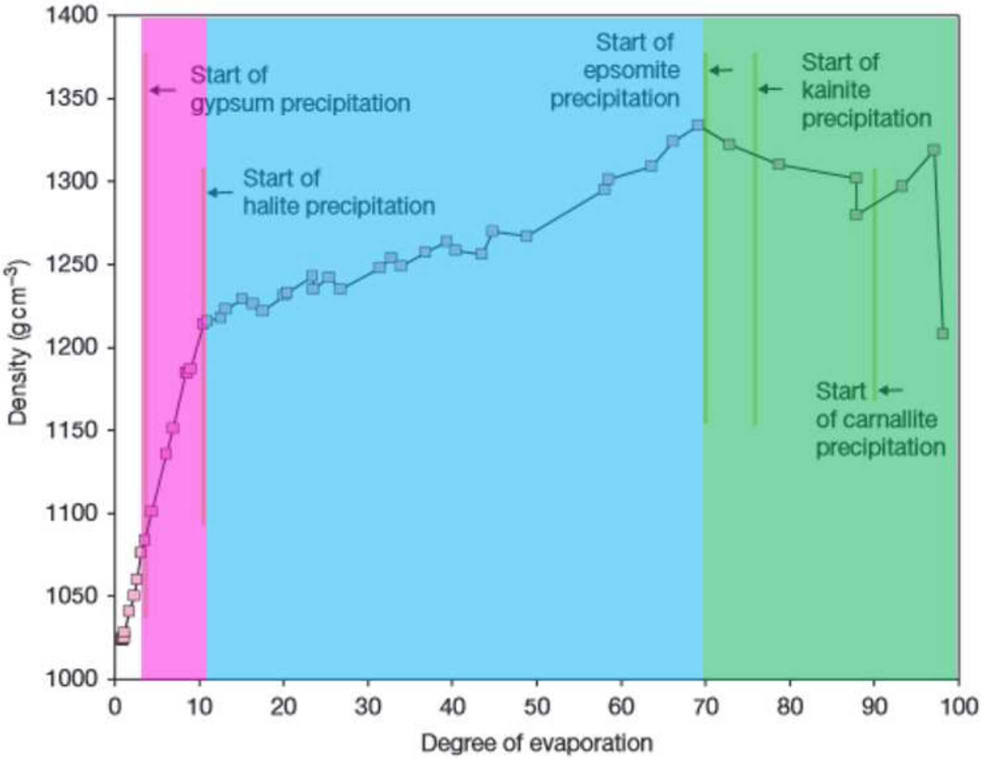


Figura 6: Sequência de deposição dos evaporitos salinos em função da taxa de evaporação/concentração iônica da salmoura. O Eixo vertical significa a densidade da salmoura. Adaptado de Pontes (2019) segundo conceitos apresentados em Bąbel & Schreiber (2014), baseados em autores anteriores.

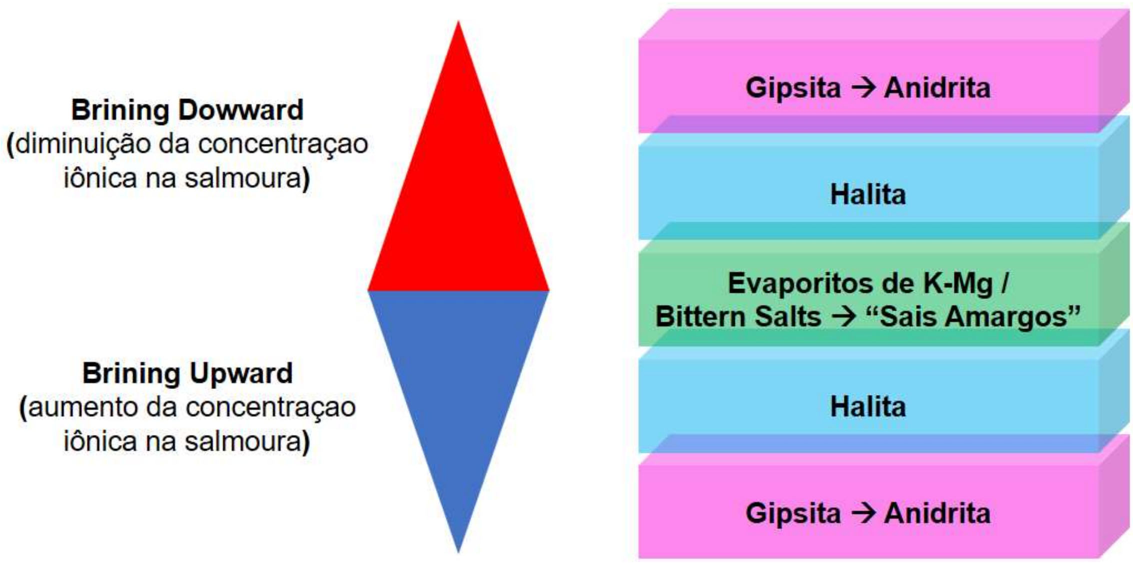


Figura 7: Modelo de aumento e diminuição da concentração iônica na salmoura favorecendo a sequência de deposição/precipitação dos evaporitos salinos. Adaptado de Pontes (2019) segundo conceitos apresentados em Bąbel & Schreiber (2014), baseados em autores anteriores.

Karner & Gamboa (2007) defendem que os evaporitos representam o estágio final de uma megassequência transgressiva. Entretanto, outros pesquisadores, por exemplo Kukla *et al.* (2018), argumentam que a formação de “lagos salgados” se dá como parte de um processo de “quebra” rápida da crosta durante a fase rifte, que causa subsidência e influxo da água do mar nos “lagos restritos” originados, iniciando-se assim o processo de evaporação e formação dos evaporitos.

Segundo Warren (2016) existem três tipos de bacias que propiciam a formação de evaporitos salinos (Figura 8). O primeiro tipo configura uma bacia profunda, com lâmina d´água profunda; o segundo tipo se configuraria como uma bacia profunda, porém com lâmina d´água rasa; e por fim, um terceiro tipo com bacia rasa e lâmina d´água também rasa. Ainda segundo este autor a Bacia de Santos se enquadra no segundo tipo, ou seja, bacia profunda, com lâmina d´água rasa.

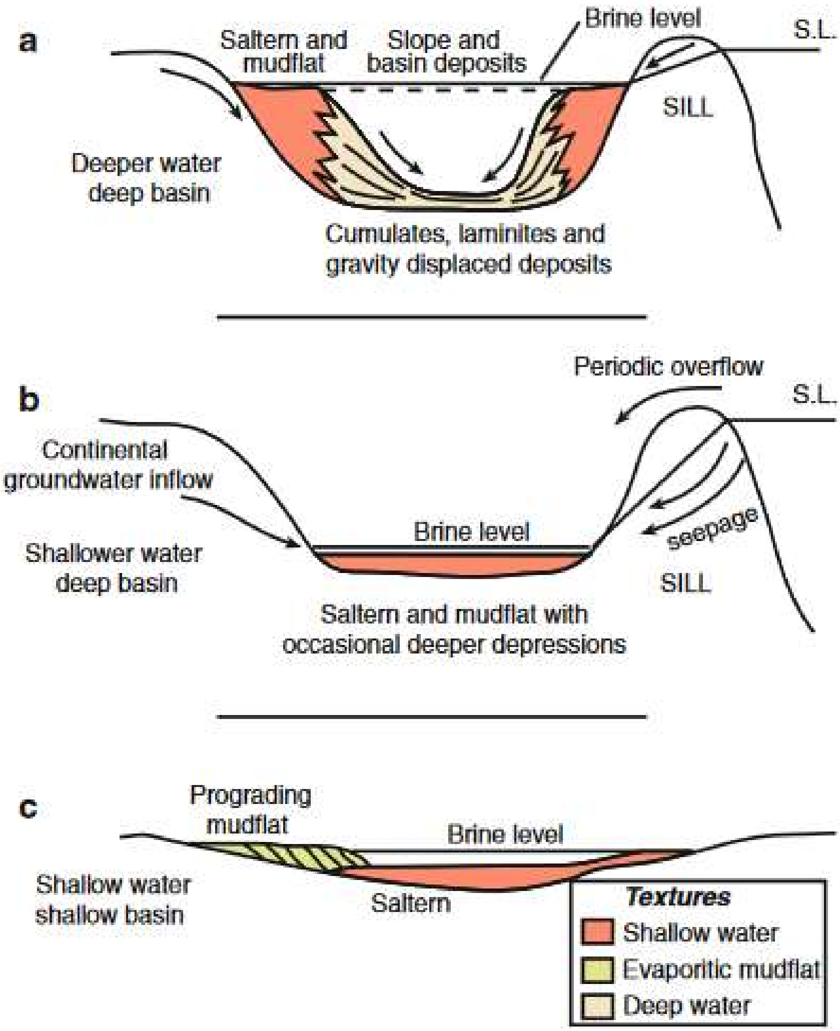


Figura 8: Tipos de bacias que propiciam a formação de evaporitos salinos. Adaptado de Warren (2016).

Caracteristicamente, a formação/precipitação/deposição dos evaporitos ocorre num período de tempo muito curto e em grandes áreas, gerando algumas biozonas bênticas (Schreiber *et al.*, 2007). Rodriguez *et al.* (2018) inferem um período inferior a 530 mil anos para toda a deposição dos evaporitos salinos na Bacia de Santos. Dias *et al.* (1994) e Davison (2007) *apud* Karner & Gamboa (2007) indicam uma idade máxima de deposição de cerca de 113Ma. Esta estimativa está em acordo com as idades dos sedimentos das porções "pré-sal" e "pós-sal", das porções proximais da bacia, que datam como sendo entre 120Ma e 110Ma (Freitas, 2006). Todos os autores chamam a atenção, entretanto, para a baixa precisão na inferência destas idades. Mesmo com este relativamente pequeno intervalo de tempo a espessura da seção evaporítica no depocentro desta bacia é superior a 2.000 m, o que confirma as altas taxas de deposição dos evaporitos. Faria (2017) menciona que no Aptiano tardio, há aproximadamente 113Ma, em função da evaporação das águas oriundas das invasões periódicas de águas do oceano Atlântico Central e Meridional, ocorreu a deposição de uma grande quantidade de Halita, com menores quantidades de gipsita, que em função do soterramento e perda de água estrutural se converteu em Anidrita, Silvita, que se transformou, em grande parte, em Carnalita, e Taquidrita.

Gonzaga (2017), em seu relatório conclui, para sua própria surpresa, e provavelmente para muitos de nós, leitores, que muitas das discussões tidas como recentes ou modernas, ou de vanguarda, relativas aos evaporitos, já vêm sendo aventadas desde o final dos anos 1960, início dos anos 1970, na Bacia de Santos. Este autor enfatiza ainda que a melhor compreensão dos gigantescos volumes de deposição envolvidos, suas estratificações, seus ambientes de deposição (evaporação), idade e assim por diante, ficaram melhores caracterizados por volta da metade da década de 1990, em especial pela possibilidade de utilização de dados sísmicos.

A utilização de interpretação sísmica e de modelos numéricos proveram melhores compreensões dos efeitos halocinéticos presentes na Bacia de Santos. Diversos autores defendem o conceito de separação da Bacia de Santos em "Províncias Halocinéticas" (Demercian *et al.*, 1993; Cobbold *et al.*, 1995; Demercian, 1996; Szatmari *et al.*, 1996; Ge *et al.*, 1997; Gemmer *et al.*, 2004; Ings *et al.*, 2004;

Guerra & Szatmari, 2009; Mohriak *et al.*, 2008; Davison *et al.*, 2012; Jackson *et al.*, 2014).

Freitas (2006) interpreta apoiado em informações de poços dúzias de ciclos menores de deposição de sais. Para este autor cada ciclo individual é composto por uma sucessão de Anidrita, Halita, sais complexos, Halita e, finalmente Anidrita novamente. Este mesmo autor ainda enfatiza que os sais mais solúveis podem não estar representados em todos os ciclos. Gamboa *et al.* (2009), apoiados por interpretação sísmica, apontam para a existência de quatro ciclos maiores de deposição de sais dentro da sequência salífera aptiana da Bacia de Santos. O primeiro ciclo, basal, composto por um pacote de Halita; o segundo, composto por uma camada de Anidrita basal, seguida por Halita e outros sais mais móveis; o terceiro composto por um pacote mais delgado de Halita; e o quarto, com as mesmas características do segundo, porém mais delgado. Este conceito de divisão da seção evaporítica em ciclos de deposição, apoiados por quantificação dos percentuais dos minerais em cada um destes vem, cada vez mais, se mostrando importante para o entendimento da seção evaporítica (Rodriguez *et al.*, 2018; Pontes, 2019). A figura 9 exemplifica esta abordagem, separando para cada um dos ciclos identificados o percentual de cada mineral/grupo mineral de acordo com a sua classificação específica proposta. Teixeira *et al.* (2020) propõem uma metodologia para a classificação quantitativa destes ciclos, de forma espacial, apresentando mapas de proporções dos tipos de evaporitos pelos principais ciclos identificados e mapeados, possibilitando a análise espacial da distribuição percentual dos minerais por cada ciclo separado.

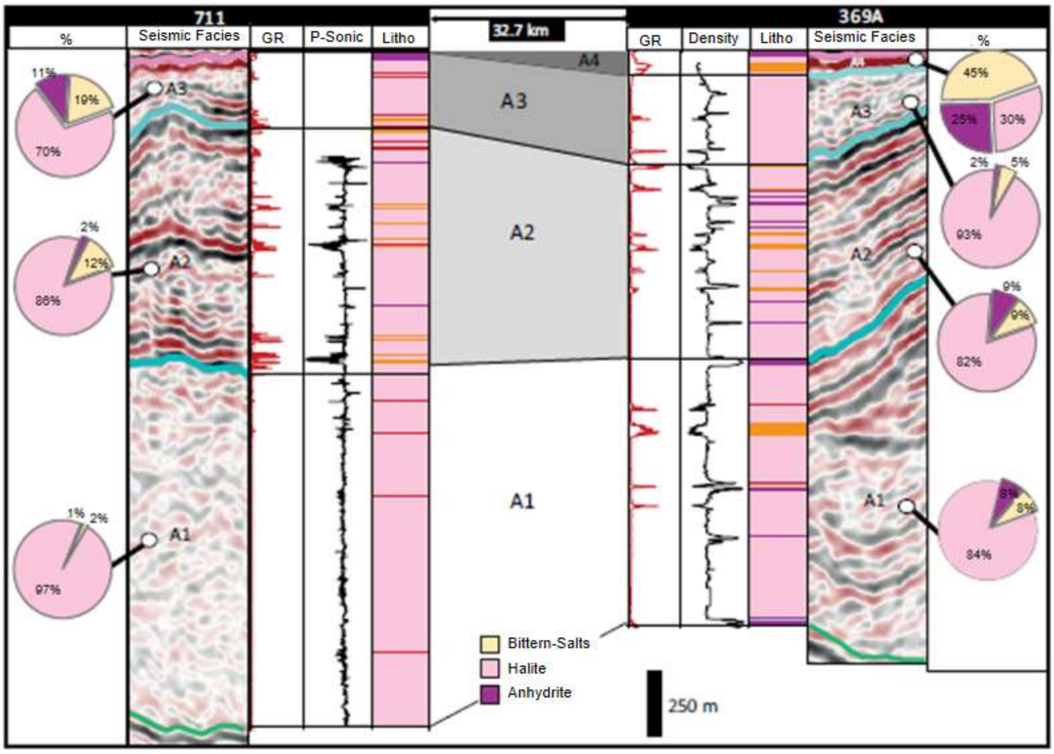


Figura 9: Exemplo dos ciclos deposicionais de evaporitos salinos na Bacia de Santos, apoiados pela quantificação (%) dos minerais presentes. A1, A2, A3 e A4 representam os ciclos deposicionais considerados. Gráficos de pizza expressam o percentual de cada mineral/agrupamento mineral por cada ciclo. *Bittern-Salts* representam Carnalita, Taquidrita e Silvita. Adaptado de Rodriguez *et al.* (2018).

Apesar de aparentemente bem aceito o conceito da ciclicidade na deposição dos evaporitos na Bacia de Santos (Freitas, 2006; Gamboa *et al.*, 2009; Rodriguez *et al.*, 2018; Pontes, 2019; Teixeira *et al.*, 2020), a expressão de cada um destes ciclos (maiores) ou mesmo a presença destes em todas as áreas da bacia ainda é um assunto controverso. Na literatura existem, ainda, outras subdivisões para estes ciclos (Fiduk & Rowan, 2012; Alves *et al.*, 2017) ou mesmo a defesa que nem sempre estes ciclos estão presentes por toda a área de análise (Alves *et al.*, 2017; Teixeira *et al.*, 2020).

No trabalho de Mohriak *et al.* (2008), a existência de um “refletor enigmático” dentro do sal na Bacia de Santos é descrita. Este refletor em termos sísmicos corresponde a uma alteração mineralógica, o que propicia uma alteração de impedância, gerando a resposta sísmica, ou simplesmente um refletor sísmico. Jackson *et al.* (2015) identificam diversos refletores, além do “enigmático” descrito por Mohriak *et al.* (2008), e criam a denominação de “estruturas enigmáticas” dentro da seção evaporítica. Estes mesmos autores enfatizam que provavelmente a existência destas “estruturas” tenha como origem a atuação de forças compressivas, conforme defendido por Dooley *et al.* (2015). A grande variabilidade mineral na seção evaporítica sugere que cada um tenha um comportamento diferente com relação à sua mobilidade. Alguns são classicamente mais móveis, outros mais dúcteis e outros mais rúpteis ou rígidos.

Maul *et al.* (2015) denominam de forma genérica qualquer intercalação ou reflexão dentro da seção evaporítica como sendo "estratificação", terminologia também adotada nesta tese. Atualmente os percentuais de ocorrência de cada mineral, sem considerar os ciclos antes mencionados, por poços ou por campos, têm amplas implicações para o conhecimento e aplicações, em especial para questões relacionadas às velocidades sísmicas. Maul *et al.* (2018a; 2019c - Anexo A4) apresentam uma tabela (Tabela 2) onde, a partir do estudo de 182 poços em 9 campos distintos do Pré-Sal da Bacia de Santos, que ilustra como variam os percentuais de ocorrências dos agrupamentos minerais. Estes mesmos autores enfatizam como as velocidades intervalares da seção evaporítica variam, sugerindo ser um equívoco a consideração de homogeneidade da seção evaporítica, com características monominerálicas similares às da Halita. Neste inventário os autores se referem aos agrupamentos em termos de velocidades, conforme apresentado por Maul *et al.* (2015): Sais de Baixas Velocidades (em inglês *Low Velocity Salts*, ou LVS), com velocidades menores que a Hallita e Sais de Altas Velocidades (em inglês *High Velocity Salts*, ou HVS), com velocidades maiores que a Halita. Os percentuais descritos nesta tabela estão em concordância com trabalhos anteriores que, com base em estudos de poços, afirmam que o percentual de Halita na seção evaporítica salina da Bacia de Santos, em geral, supera os 80% (Fiduk & Rowan, 2012; Jackson *et al.*, 2014).

Tabela 2: Proporções de Sais e velocidades intervalares (m/s) para nove campos distintos dentro da Bacia de Santos (considerando como "corte" no tempo, o final de 2018).

| Campo | # Poços | % LVS | LVS ACV (m/s) | % Halita | Halita ACV (m/s) | % HVS | HVS ACV (m/s) | WCV (m/s) |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 8 | 4.018,56 | 83 | 4.480,88 | 8 | 5.210,27 | 4.462,56 |
| 2 | 29 | 9 | 4.218,47 | 82 | 4.563,69 | 9 | 4.975,84 | 4.567,53 |
| 3 | 17 | 11 | 4.054,42 | 77 | 4.498,25 | 12 | 4.989,92 | 4.505,66 |
| 4 | 3 | 13 | 3.971,00 | 71 | 4.507,09 | 16 | 4.927,59 | 4.505,04 |
| 5 | 5 | 3 | 4.167,00 | 84 | 4.538,00 | 13 | 5.123,33 | 4.576,00 |
| 6 | 7 | 3 | 4.264,19 | 80 | 4.509,87 | 17 | 5.061,36 | 4.596,05 |
| 7 | 72 | 8 | 4.122,33 | 81 | 4.526,47 | 11 | 5.105,84 | 4.560,03 |
| 8 | 25 | 4 | 4.182,53 | 88 | 4.533,59 | 8 | 5.003,35 | 4.547,16 |
| 9 | 4 | 6 | 4.055,63 | 81 | 4.486,58 | 13 | 5.077,49 | 4.535,67 |
| **TNW** | **182** | | | | | | | |
| **AVG** | | **7** | **4.117,13** | **81** | **4.516,05** | **12** | **5.052,78** | **4.539,52** |

LVS: *Low Velocity Salt* - Sais de Baixas Velocidades; HVS: *High Velocity Salt* - Sais de Altas Velocidades; ACV: *Average Compressional Velocity* - Velocidade Compressional Média dos agrupamentos, por campo, considerando todos os poços; WCV: *Weighted Compressional Velocity* - Velocidade Compressioal Ponderada pela Percentual de Ocorrência; TNW: *Total Number of Wells* - Número Total de Poços; *Compressional Velocity* - Velocidade Compressioal (m/s); AVG: *Average* - Velocidade Compressional Média da Seção, considerando todos os poços do Campo. Modificado de Maul *et al.* (2018a; 2019c).

O mecanismo de movimentação do sal, especificamente para a Halita e os demais sais considerados móveis (Carnalita, Taquidrita e Silvita), resulta em várias estruturas como almofadas de sal, domos, paredões, jangadas e falhas de crescimento. Segundo Fossen (2012), diversas feições geológicas resultam dos processos de halocinese, e suas dimensões variam tanto da escala local, com poucos metros, até a escala regional, com dezenas de quilômetros (Figura 10). O movimento vertical é atribuído à instabilidade de *Rayleigh-Taylor* (R-T), conforme descrito por Lachmann (1910) e Arrhenius (1913) ambos referenciados em Dooley *et al.* (2015). De forma complementar, Ge *et al.* (1997) discutem o efeito da sobrecarga de sedimentos sobre a seção evaporítica sobrejacente a um embasamento considerado irregular. De acordo com estes autores o peso dos sedimentos força o sal a subir em estruturas almofadadas formando anticlinais. Com a continuidade da sobrecarga estas estruturas são convertidas em domos e paredões de sal. Guerra & Underhill (2012) defendem a hipótese de que a força da gravidade atuando por diferenças de pressão move os evaporitos em conjunto das porções mais pressurizadas para as menos pressurizadas na Bacia de Santos.

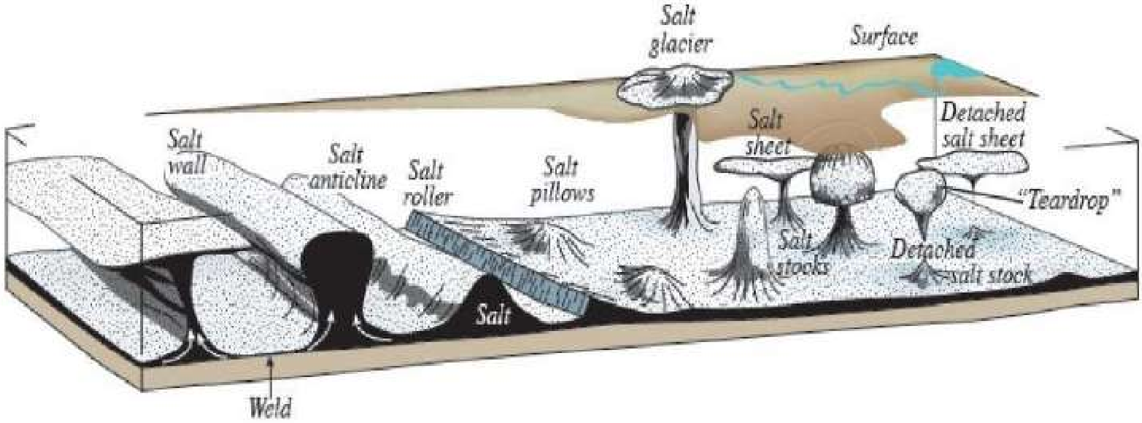

Figura 10: Exemplos de estruturas formadas em ambientes evaporíticos. Adaptado de Fossen (2012).

Zambrini (2020) e Zambrini *et al.* (2020) em seus trabalhos voltados para estudos de iluminação sísmica focados em alvos do Pré-Sal da Bacia de Santos, ao se depararararem com estruturas de multi-z (*overhang*) do sal, concluem que tais estruturas devem ser mapeadas e inseridas no estudo, pois do contrário comprometeriam todo o resultado. Esta análise está em total consonância com o apresentado por Etgen (2013), que exemplifica os problemas no imageamento sísmico em regiões de complexidade geológica impostas pela presença de corpos de sais e a utilização de modelos de velocidades simplificados.

Todas as informações até aqui descritas não podem ser consideradas de forma isolada para entendimento do comportamento da seção evaporítica salina em termos de propriedades e mais, sobre qual o impacto desta complexidade nos modelos sísmicos. De forma simplificada, o modelo apresentado na figura 11, se apresenta como um caminho interessante, adaptando-se para cada área específica, nos modelos de propriedades para a seção evaporítica salina, em especial para a Bacia de Santos. Através deste modelo é possível observar a complexidade geológica relacionada aos ciclos salinos (Figura 9), das movimentações internas das unidades depositadas nos diferentes ciclos (Figura 11), e que estes elementos devem ser contemplados na caracterização em detalhe da seção evaporítica salina, refletindo assim suas propriedades, como por exemplo a velocidade sísmica. Uma abordagem similar a essa tem seus resultados, abrangendo variações volumétricas (rochas) do campo em questão, e as mesmas são explorados no Anexo A6 desta tese.

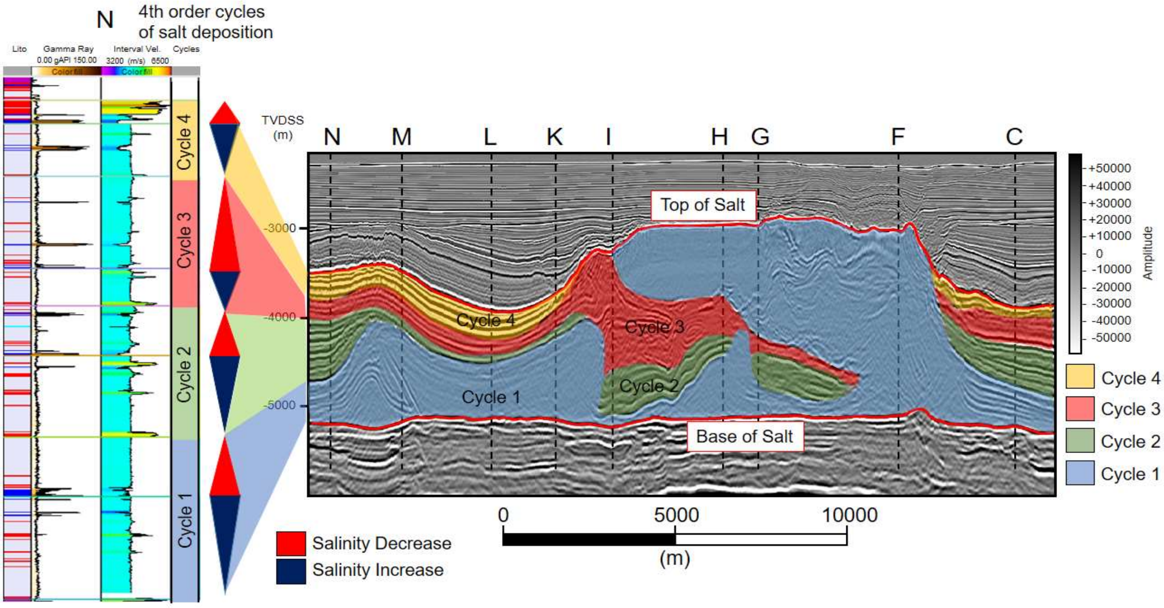


Figura 11: Alguns dos aspectos geológicos considerados como sendo os mais relevantes para se pensar em modelos de propriedades para a seção evaporítica salina na Bacia de Santos: presença dos ciclos de deposição dos evaporitos salinos e suas movimentações. Maul *et al.* (2020a – submetido).

# 5 IMPORTÂNCIA DOS MODELOS DE VELOCIDADES DETALHADOS PARA OS PROCESSOS SÍSMICOS (MIGRAÇÃO) E O PAPEL DAS ESTRATIFICAÇÕES DA SEÇÃO EVAPORÍTICA SALINA NESTE CONTEXTO

Segundo Mohriak *et al.* (2012), os reservatórios da seção Pré-Sal das Bacias de Santos e de Campos, na margem sudeste do Brasil, estão situados em lâminas d´água que podem passar de 2.000 m, e suas profundidades variam de 3.000 m até mais de 5.000 m. Além destas variações de lâmina d´água e de profundidades, que já imporiam relativa complexidade para os modelos de velocidades, estes reservatórios podem ainda estarem situados abaixo de *rafts* ("cascos" de tartarugas) carbonáticos de idade albiana e da seção evaporítica (vulgarmente denominada de sal) de idade aptiana. Estas seções albianas e aptianas (carbonatos e sal) geram variações laterais de velocidades, tanto entre si, como com os sedimentos mais jovens, e são importantes para os modelos de velocidades até mesmo para as porções mais superiores. Estas duas seções (*rafts* do albiano e sal do aptiano) apresentam variações muito significativas em termos de espessuras. Na Bacia de Santos o sal da seção aptiana é muito mais proeminente que os *rafts* carbonáticos da seção albiana. Já na Bacia de Campos, os *rafts* carbonáticos do albiano, em geral, predominam, em termos de espessura e de complexidade quando comparados com a seção salífera do aptiano (Mohriak *et al.*, 2012). Como este estudo está inserido na Bacia de Santos, a ênfase das informações será sempre esta bacia, ou melhor seus evaporitos salinos e suas estratificações.

O processamento sísmico necessita gerar informações de amplitude e em frequências altas, o que permite melhores chances de resolver questões de ambiguidades na carcaterização detalhada dos reservatórios, em especial para a seção Pré-Sal da Bacia de Santos (Teixeira *et al.*, 2017; Teixeira *et al.*, 2018; Penna *et al.*, 2018; Dias *et al.*, 2019; Kneller *et al.*, 2019; Teixeira & Lupinacci, 2019; Penna & Lupinacci, 2020; Mello, 2020; Teixeira *et al.*, 2020). E o papel da interpretação do atributo velocidade sísmica, especialmente se este atributo estiver bem detalhado, tem um papel fundamental neste sentido.

A informação sísmica, desde suas primeiras seções em duas dimensões (2D), sempre foi construída a partir de um experimento que registra o tempo de trânsito entre sua emissão (fonte) e seu retorno (receptor), ou seja, tempo-duplo (em inglês

*Two-Way-Time*, TWT) assumindo uma determinada geometria em profundidade (Yilmaz, 2001; Etris *et al.*, 2001; Robein; 2003, Rosa, 2018). Segundo estes mesmos autores, quanto melhores forem os modelos de velocidades, no sentido de representatividade da geologia existente em sub-superfície, maiores serão as chances de se obter sucesso nos projetos de E&P que se baseiam no método sísmico.

Estudos relativos às melhorias dos modelos de velocidades sísmicas para as mais diversas aplicações da indústria do petróleo, em especial no segmento de E&P, sempre se mostraram de grande valia (Sexton, 1998). Consequentemente, o elo entre este registro de tempo e a profundidade é a velocidade. A precisão desta informação de velocidade é função direta do modelo concebido para esta geometria em sub-superfície, uma vez que o arranjo (fonte-receptor) é conhecido (Etris *et al.*, 2001). Daí a importância dos modelos de velocidades para o método sísmico.

O imageamento sísmico em ambientes geológicos complexos é reconhecidamente um grande desafio para a indústria do petróleo (Zhang & Sun, 2009; Huang *et al.*, 2010; Jones & Davison, 2014). Jones & Davison (2014), especificamente estudando a Bacia e Santos, reportam a dificuldade de se construir uma boa imagem sísmica em regiões próximas aos flancos de sal, ou mesmo dentro dos corpos de sal. Para o caso de imageamento em regiões próximas a corpos de sal é sugerida a inserção de heterogeneidades de forma a melhorar os modelos de velocidades, como por exemplos, utilizando a técnica de FWI ou da inversão tomográfica intra-sal (Tarantola, 1984; Zhang & Wang, 2009; Jones & Davison, 2014; Kang *et al.*, 2019; Penna *et al.*, 2019).

Segundo Johann *et al.* (2013), uma porção significante dos dados sísmicos utilizados para a caracterização sísmica dos reservatórios da seção Pré-Sal da Bacia de Santos foi processada utilizando-se da técnica de atualização por inversão tomográfica do modelo de velocidades. Em termos de anistropia inicialmente era utilizada a *Vertical Transverse Isotropic* (VTI) e, atualmente, a técnica *Transverse Transverse Isotropic* (TTI) é mais utilizada (Langlois *et al.*, 2013; Johann *et al.*, 2013; Lebit *et al.*, 2018).

Os modelos de velocidades iniciais a serem atualizados pela inversão tomográfica podem assumir para a seção evaporítica valores aproximadamente constantes, muito próximos de homogêneos (com cerca de 4.500 m/s), o que reflete basicamente a velocidade do mineral Halita, que é o mineral mais abundante na seção evaporítica (por volta de 80% de ocorrência). Ao consultar a literatura se percebe, de forma bem ampla, que a anisotropia sísmica do sal é considerada como sendo desprezível ou mesmo associada, apenas à anisotropia extrínseca, ao se medir este efeito tendo como base o acamamento das estratificações de amostras coletadas em minas de sal (Yan *et al.,* 2016). Ainda como suporte a esta premissa, alguns autores, partindo de medições em laboratório, especificamente considerando a Halita, afirmam que anisotropia observada é da ordem de 7% (Raymer *et al.,* 1999; 2000), ou com uma diferença inferior a 5%, ao se considerar o eixo principal de evaporação como sendo o eixo principal de anisotropia (Landrø *et al.*, 2011). Neste trabalho não se pretende discorrer sobre este fato, nem no sentido de concordar, como também no de não concordar. Apenas é importante introduzir este ponto de investigação futura, para se discutir, ao menos, se estas interpretações não teriam consigo o viés da Halita, que tem percentuais de ocorrência da ordem de 80%, ao menos na Bacia de Santos, e que, de fato, aparentemente teria anisotropia irrelevante para o método sísmico.

Em termos de migração sísmica, os primeiros projetos migrados em profundidade utilizavam a técnica Kirchhoff e atualmente a técnica *Reverse-Time Migration* predomina, começando a aumentar a aplicação da técnica *Full-Waveform Inversion* (FWI), ao menos em termos de atualização dos modelos de velocidades. Mais recentemente, a aplicação da *Least-Squares Migration* (LSM) (Schuster, 1993) vem sendo mais comumente empregada (Pereira-Dias *et al.*, 2017; Wang *et al.*, 2017; Pereira-Dias *et al.*, 2018; Vigh *et al.*, 2019; Shadrina *et al.*, 2020).

De acordo com Guo & Fagin (2002), a atualização do modelo de velocidades pelo processo de inversão tomográfica apesar de apresentar bons resultados não tem compromisso com a geologia existente, apenas se compromete em buscar uma resposta matemática para atualizar este modelo, tendo como base o acompanhamento de painés de alinhamentos de *gathers*. Em geral esta técnica parte de um modelo de velocidades aproximadamente constante, como o descrito anteriormente, ou seja, com velocidade inicial na ordem de 4.500 m/s, ou ainda buscando a regularização através do emprego vínculos estruturais (Costa *et al.*, 2008; Chen & Hu, 2014; Santos *et al.*, 2019). Importantes trabalhos ilustram a importância de se construir modelos de velocidades sísmicas com forte compromisso geológico, especialmente em áreas de grande complexidade geológica, visando aprimorar a qualidade das imagens sísmicas geradas (Clapp *et al.*, 2004; Bakulin *et al.*, 2010). Ji *et al.* (2011) apresentam um estudo onde um modelo de velocidades considerando uma inversão sísmica simples possibilita a criação de modelos mais heterogêneos para o sal, melhorando assim a qualidade das imagens sísmicas geradas.

Segundo Sheriff (2002), os principais objetivos do processo de migração sísmica são o posicionamento correto dos refletores sísmicos em suas profundidades próximas, de forma mais real e principalmente a correspondência entre as amplitudes de reflexão e o coeficiente de reflexão em si. Este mesmo autor enfatiza ser muito importante o conhecimento do campo de velocidades que muitas vezes é estimado do próprio dado sísmico da área para se ter sucesso neste processo de migração. Assim, seguindo este raciocínio deve-se criar modelos de velocidades a partir do próprio dado sísmico.

Posteriormente às descobertas dos reservatórios da seção Pré-Sal da Bacia de Santos e em conjunto com o crescimento da capacidade computacional, os processamentos sísmicos do tipo *Pre-Stack Depth Migration* (PSDM) se tornaram cada vez mais, comuns. Dentro dos limites das técnicas PSDM´s existe uma grande variedade de métodos, desde migração Kirchhoff até RTM. O estado da arte em termos de técnicas de processamento sísmico, ainda contempla as técnicas de atualização dos modelos de velocidades sísmicas por FWI (Ben-Hadj-Ali *et al.,* 2008; Barnes & Charara, 2009; Operto *et al.*, 2013; Vigh *et al.*, 2014) e a aplicação de compensação de amplitudes por LSM (Schuster, 1993; Nemeth *et al.*, 1999; Hu *et al.*, 2001; Pereira-Dias *et al.*, 2017; Wang *et al.*, 2017; Pereira-Dias *et al.*, 2018; Vigh *et al.*, 2019; Shadrina *et al.*, 2020).

Potencialmente, a atualização do modelo de velocidades pela técnica FWI possibilita a geração de modelos de velocidades de alta resolução que quando associado de forma apropriada à migração RTM tem maiores chances de lograr sucesso na geração de imagens sísmica de qualidade, especialmente em ambientes geológicos complexos (Vigh & Starr, 2008). Entretanto, de acordo com Vigh *et al.* (2009), um dos maiores desafios da técnica FWI é justamente produzir (ou reproduzir) bons modelos iniciais de velocidades, que melhor representem a geologia existente, para gerar boas imagens sísmicas, com sua respectiva relevância geológica.

Maul *et al.* (2015) apresentam os primeiros resultados versando sobre o conceito de inserção de estratificações na seção evaporítica, utilizando atributos sísmicos. Segundo estes mesmos autores, estas estratificações já seriam uma boa representação de feições geológicas dentro da seção evaporítica salina (Figura 12). De acordo com este estudo é indicada uma simplificação (ou "agrupamento mineralógico") para as velocidades sísmicas dos evaporitos salinos: Sais de Altas Velocidades (em inglês *High Velocity Salts*, ou HVS), compostos por Anidrita e Gipsita); a própria Halita (que pode ser considerada com *Background*) e Sais de Baixas Velocidades (em inglês *Low Velocity Salts*, ou LVS), compostos basicamente por Silvita, Carnalita e Taquidrita.

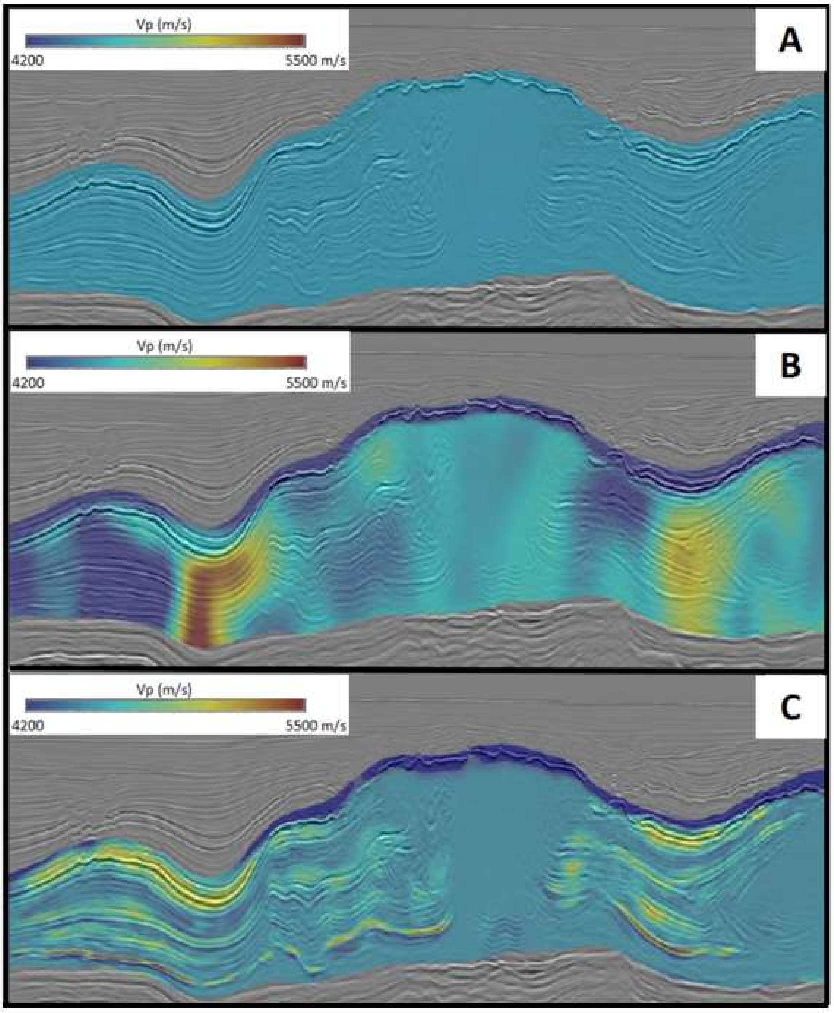


Figura 12: Seção sísmica na Bacia de Santos com a sobreposição de modelos de velocidades intervalares na seção evaporítica salina.
A - Modelo de velocidades constantes (V = 4.500 m/s);
B - Modelo de velocidades com atualização tomográfica (atualização do modelo apresentado em "A";
C - Modelo de velocidades com inserção de estratificações no sal, baseado na metodoligia de uso de atributos sísmicos.
Observar a melhor coincidência entre a geologia (repostas de amplitude) e as respectivas variações do modelo de velocidades em "C", o que não ocorre em "A" e em "B". Adaptado de Maul *et al.* (2015).

A comparação entre o comportamento das velocidades dos agrupamentos pode ser consultada na figura 13, onde são analisadas, somente as informações existentes nos perfis. Isto não ocorre na tabela 2 onde também são consideradas as amostras de calha para o cálculo das velocidades onde não há perfil e, portanto, apresentando diferenças. Diversos resultados considerados como de sucesso ao se adotar o modelo de sal estratificado como modelo inicial para o fluxo de atualização e consequente processo de migração sísmica foram apresentados (Gobatto *et al.*, 2016; Falcão, 2017; Fonseca *et al.*, 2018; Dias *et al.*, 2019; Maul *et al.*, 2019c - Anexo A4; Fonseca *et al.*, 2019). O"agrupamento" proposto é responsável por produzir os padrões sísmicos identificados na seção evaporítica, denominados pelos mais diversos autores, tais como: refletor enigmático, estruturas enigmáticas, sal acamadado, sal estratificado (Mohriak *et al.*, 2008; Jackson *et al.*, 2015, Maul *et al.*, 2015).

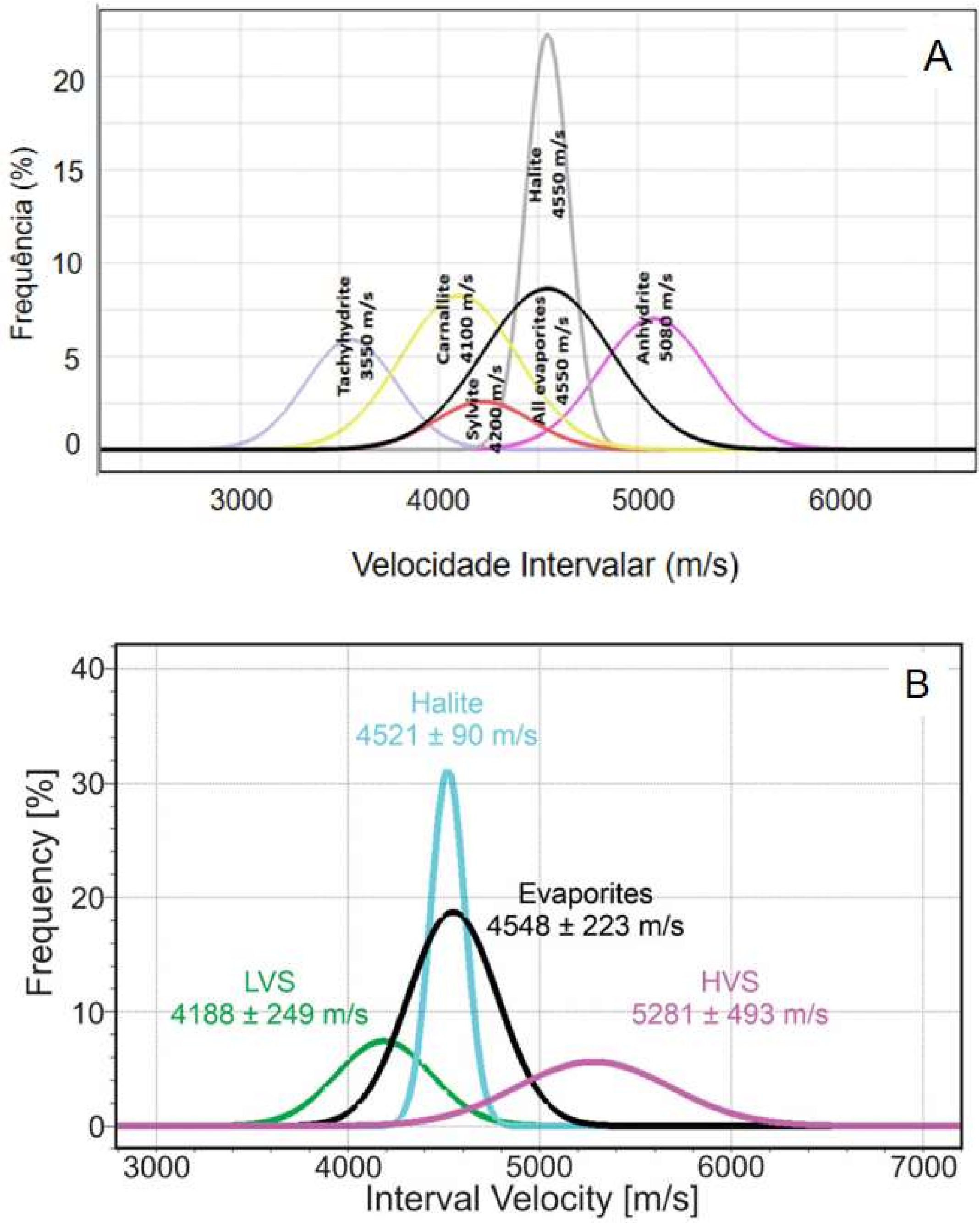


Figura 13: Frequência de ocorrências dos minerais e “agrupamentos minerais”.
A - Considerando os 182 poços perfurados até o final de 2018 e todos os minerais salinos individualizados. Adaptado de Maul et *al.* (2018c);
B - Considerando os 14 poços utilizados nesta tese, com os agrupamentos propostos. Adaptado de Maul *et al.* (2019b).

De forma complementar, tendo como base o “agrupamento” proposto, foram constados em alguns dos poços perfurados, fragmentos de rochas ígneas e de carbonatos que, ainda, em termos sísmicos, poderiam ser “agrupados” nos “HVS”; e outras rochas sedimentares, além de outros evaporitos de baixas velocidades que também em termos sísmicos, podem ser “agrupados” nos “LVS” (Oliveira *et al.,* 2015).

O agrupamento proposto (LVS, Halita e HVS) vem se apresentando como de grande valia em todos os projetos identificados. Entretanto ainda possuem suas limitações. Uma das grandes limitações está na resolução do método sísmico. Muitas das estratificações identificadas em poços apresentam espessuras métricas, até mesmo centimétricas. De acordo com a teoria do método sísmico, não seria possível de resolver, na melhor das hipóteses, nada inferior à 25-40 metros de espessura, neste ambiente, em função de sua profundidade, comportamento das rochas e frequência ainda presente antes de suas atenuações e absorções adotando-se um critério de resolução sísmica, como por exemplo o apresentado por Widess (1973). Além disso, tais estratificações, principalmente, em função de suas movimentações, conforme já mencionado anteriormente, podem estar situadas em ângulos tais que as colocam em posições que as tornam não passíveis de registro por um dispositivo de aquisição sísmica convencional do tipo *streamer* (Yilmaz, 2001). Em ocorrendo isto, simplesmente não são recuperadas reflexões sísmicas originadas destas estratificações. As regiões dos flancos das seções evaporíticas são então candidatas perfeitas para esta situação. E este fato é caracterizado como um dos maiores riscos de imprecisões a partir dos resultados oriundos desta metodologia como um todo. Mesmo com a associação da técnica de inserção de estratificações e com a compensação de iluminação sísmica por *Least-Squares Migration* ainda não foi obtido nenhum resultado considerado sendo plenamente satisfatório (Anexo A5).

Para contornar parte destes problemas a metodologia de inserção de estratificações na seção evaporítica salina (Maul, 2020 – esta tese) vem se desenvolvendo no sentido de buscar a recuperação de maiores faixas de frequências, seja pelo simples processo de deconvolução, seja por processos de derivação do sinal (Seifert *et al.*, 2017, Falcão, 2017, Maul *et al.*, 2018b - Anexo A1), ou ainda por processos de inversão sísmica absoluta (Meneguim *et al.*, 2015; Teixeira *et al.*, 2017; Maul *et al.*, 2019a - Anexo A3), uma vez que ao se aumentar a faixa de frequência recuperada se aumentaria a resolução do método, nos permitindo melhor identificar e caracterizar eventos de espessuras mais delgadas. Em especial, os estudos de inversão sísmica, principalmente os denominados *model-based*, têm apresentado resultados muito promissores, inclusive na tentativa de "desagrupar" os "agrupamentos" propostos para os HVS´s e LVS´s (Teixeira *et al.*, 2017; Teixeira & Lupinacci, 2019; Mesquita, 2020; Mesquita *et al.*, 2020; Teixeira *et al.*, 2020). Neste processo de inversão sísmica *model-based* outra grande vantagem é a calibração do modelo com as informações dos poços perfurados. Entretanto, é necessário enfatizar que um dos principais desafios ao se trabalhar com a inversão *model-based* para a seção evaporítica está na grande espessura desta, ou mesmo a variabilidade de sua espessura o que implica diretamente na dificuldade de se escolher uma *wavele*t única e que seja representativa para o todo, necessária no processo de inversão (Maul *et al.*, 2019a - Anexo A3; Yamamoto, 2019).

Durante o desenvolvimento desta metodologia de inserção das estratificações na seção evaporítica foi identificada a possibilidade de considerar porções distintas da seção em função do tipo de resposta sísmica observada, sendo possível se estabelecer “Domínios de Estratificações” (Maul *et al.*, 2018b - Anexo A1). A classificação proposta (Figura 14) visa estabelecer as porções do dado onde se deve trabalhar com incertezas quanto às conclusões de suas respostas, e se apresenta da seguinte forma: 1) Domínio Sem Estratificação (em inglês *Without Stratification Domain*, ou WSD) que é caracterizado pela ausência quase que total de estratificações, com amplo predomínio de Halita e pequenas porções de LVS. Este domínio ocorre, geralmente, nas porções centrais das grandes “almofadas” de sal; 2) Domínio com Estratificação Evidente (em inglês *Evident Stratification Domain*, ou ESD), onde o conteúdo de Halita diminui para cerca de 70% e aumenta o percentual dos HVS. A região onde este domínio predomina se caracteriza em geral pelas menores espessuras da seção evaporítica. Esta diminuição de espessura pode em parte ser explicada pela sobrecarga dos *rafts* e sedimentos acima do sal, formando as mini-bacias (ou *mini-basins*, em inglês). Devido ao caráter “mais móvel” tanto a Halita quanto os LVS tendem a buscar porções de menores sobre-pressão: as “almofadas”. Ainda seguindo esta analogia observa-se que com a diminuição da espessura da seção evaporítica, ocorre o aumento da velocidade compressional (intervalar), uma vez que aumenta, proporcionalmente o percentual de HVS, diminuindo as quantidades de Halita e LVS; 3) Domínio de Estratificações Aleatórias (em inglês *Random Stratification Domain*, ou RSD), que são “porções” de estratificações que ocorrem de forma errática, dentro do WSD. Nestas “porções” há diminuição do percentual de Halita e, consequemente, um ligeiro aumento da velocidade compresisonal. Estas estratificações aleatórias são interpretadas por diversos autores como sendo consequência da movimentação do sal mais móvel. Neste processo são “arrastados”, “dobrados” ou mesmo “quebrados”, porções de sais menos móveis, como por exemplo, partes de intercalações de Anidritas com sais mais móveis; 4) Domínio de Estratificações Escondidas (em inglês *Hidden Stratification Domain*, ou HSD), que podem ser encontradas, principalmente, nos flancos da seção evaporítica, onde não é passível de registro nenhuma reflexão – estratificação – por um dispositivo de aquisição sísmica convencional do tipo *streamer* , como em outras porções, em função da falta de resolução do método. Este último domínio (HSD) é o mais crítico (perigoso) em se tratando de aspectos operacionais quando da perfuração de poços, podendo implicar em aprisionamento de colunas de perfuração e perda de fluidos de perfuração. Há relatos de perdas de poços por conta de se perfurar sem o devido cuidado este domínio. Neste último domínio, mesmo utilizando-se as técnicas mais avançadas de processamento, como por exemplo a associação de *Reverse Time-Migration* e *Least-Squares Migration* não há garantia de sucesso de imageamento, conforme veremos mais adiante (Anexo A5).

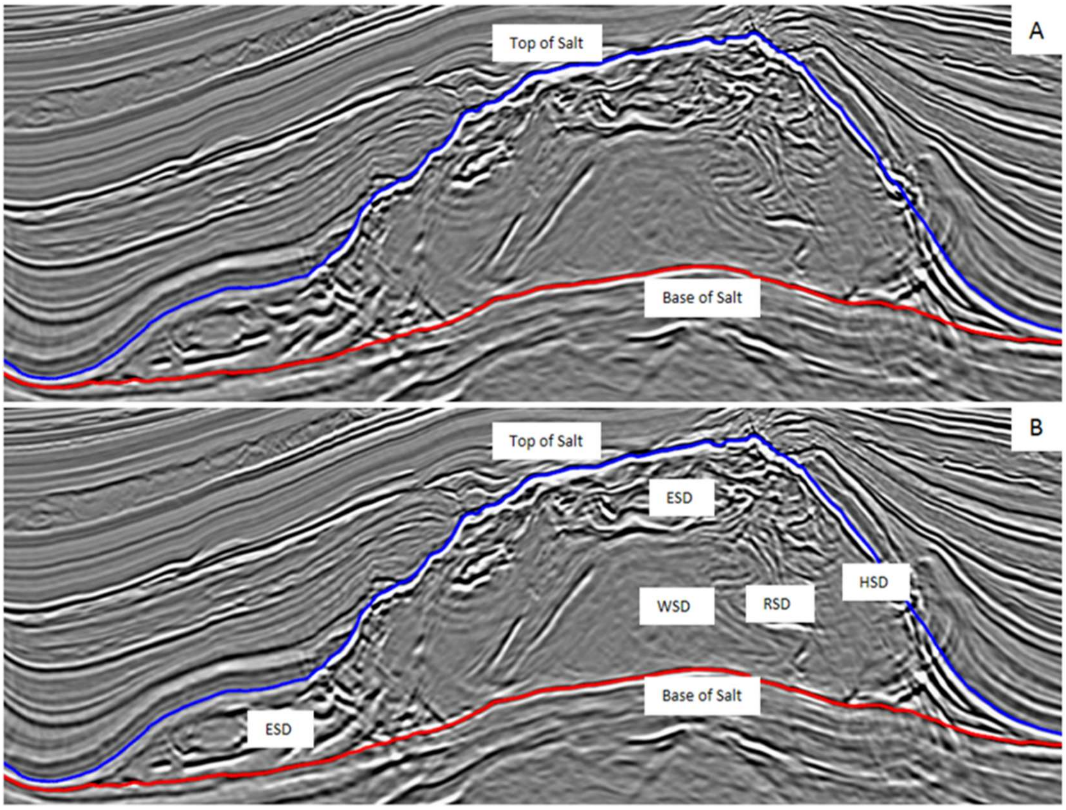


Figura 14: Exemplos de interpretações sísmicas e seus domínios de estratifiações:
A - Sem a presença dos domínios de estratificações;
B - Com a presença dos domínios de estratificações;
WSD - *Without Stratification Domain* (Domínio Sem Estratificações);
ESD - *Evident Stratification Domain* (Domínio de Estratificações Evidentes);
RSD - *Random Stratification Domain* (Domínio de Estratificações Aleatórias);
HSD - “*Hidden”Stratification Domain* (Domínio Com Estratificações “Escondidas”).
Adaptado de Maul *et al.* (2018b).

Visando auxiliar na minimização destes dois problemas citados anteriormente (falta de resolução e situações onde as possíveis reflexões estariam situadas em ângulos não passíveis de registro por um dispositivo de aquisição sísmica convencional do tipo *streamer*) o trabalho de classificação de fácies – método *bayesiano* – (Doyen, 2007), vem se apresentando promissor para esta finalidade (Meneguim *et al.*, 2015; Teixeira *et al.*, 2017; Teixeira & Lupinacci, 2019; Teixeira *et al.*, 2020). Através deste método é possível gerar um "cubo" do evaporitos mais provável, bem como os "cubos" de probabilidade de ocorrência de cada um dos evaporitos, de acordo com o critério de agrupamento de fácies indicado. Nesta metodologia a combinação de atributos sísmicos incluindo os dados de inversão sísmica, são as entradas para a classificação das fácies de acordo com as informações existentes nos poços.

Atualmente, além dos estudos de inversão e de classificação de fácies, a metodologia de *Machine Learning* aparenta ser, potencialmente, um caminho com "menos" interferência humana na busca das fácies dos sais estratificados (Mesquita *et al.*, 2019; Mesquita, 2020; Mesquita *et al.*, 2020). Desta forma, este ainda é um vasto campo a ser explorado.

Além da qualidade do dado sísmico para a aplicação da metodologia de inversão sísmica *model-based* se faz necessário utilizar os perfis de densidade e sônico disponíveis, devidamente corrigidos e emendados. Infelizmente estes perfis não estão, em sua totalidade, disponíveis na maioria dos poços, mais especialmente na seção evaporítica. Apenas os poços denominados como exploratórios "clássicos" apresentam a seção evaporítica, em sua maior parte, com estes perfis adquiridos. Mesmo estes poços, por questões de segurança operacional, tanto no início quanto no fim da seção evaporítica, onde ocorrem as denominadas Anidritas "superior" e "basal", são assentadas as sapatas para alteração das fases de perfuração dos poços. Nestes intervalos não são corridas as perfilagens geofísicas, pois não faz sentido se registrar informações de cimentos. Já os poços de desenvolvimento, de produção ou de injeção, em geral não têm perfilagem na seção evaporítica salina, principalmente por questões de economicidade dos projetos. Na Tabela 3, considerando os 14 poços deste estudo (detalhes no Anexo A2), é possível se observar como varia em termos percentuais o registro de perfis nos poços perfurados.

Este problema de falta de perfis além de dificultar os processos de inversão sísmica *model-based*, de classificação de fácies e de *Machine Learning*, inviabiliza a própria determinação mais próxima da realidade em termos percentuais de cada ocorrência mineral ou de seus “agrupamentos” na seção evaporítica. Isto, consequentemente não permite quantificar o quão próximo ou distante, estaria o modelo de velocidades, por exemplo utilizado no processo de migração sísmica, de sua realidade geológica.

Para lidar com parte deste problema utiliza-se a descrição das litologias durante a perfuração dos poços (as amostras de calha) com o auxílio de qualquer perfil que esteja disponível (Amaral *et al.*, 2015, Maul *et al.*, 2018a, 2018b - Anexo A1, Cunha *et al.*, 2019). Até mesmo o perfil de taxa de penetração (em inglês *Rate of Penetration*, ou ROP), já é um indicativo de qual mineral (agrupamento) está sendo perfurado: no caso de baixas taxas de penetração sugere-se um mineral de mais densidade, ou de maior velocidade, possivelmente um mineral dos HVS; caso sejam altas as taxas de penetração, infere-se um dos minerais do LVS pois, intuitivamente, sais de baixas velocidades estão associados às menores densidades e, consequentemente, a menores esforços para sua perfuração (Cunha *et al.*, 2019). O suporte da descrição litológica permite uma interpretação mais próxima da realidade geológica. Com esta metodologia, na Bacia de Santos já foram estudados cerca de 250 poços (nos trabalhos publicados - Anexos, são citados 182, considerando como *data de corte* o final do ano de 2018), cobrindo 9 campos distintos da seção Pré-Sal da Bacia de Santos, permitindo uma clara ideia de como seria o comportamento das velocidades da seção evaporítica, por cada um destes campos, por poço, e assim por diante. Os 14 poços deste projeto fazem parte deste conjunto maior, e seus resultados específicos são apresentados conforme anexos (Maul *et al.*, 2019b - Anexo A2, 2019c - Anexo A3).

Tabela 3: Percentuais de perfis registrados e ausentes em um espaço amostral (14 poços), de um projeto/campo específico na Bacia de Santos, dentre os cerca de 250 poços já perfurados (neste caso considera-se qualquer perfil adquirido no comprimento total do poço, ou seja, muitas vezes, perfis distintos em posições distintas e, não necessariamente aqueles mais comuns de serem utilizados no método sísmico).

| Nome do Poço | Perfil Registrado (%) | Perfil não Registrado (%) |
|---|---|---|
| A | 91,90 | 8,10 |
| B | 87,60 | 12,40 |
| C | 91,10 | 8,90 |
| D | 87,30 | 12,70 |
| E | 77,90 | 22,10 |
| F | 87,20 | 12,80 |
| G | 92,00 | 8,00 |
| H | 91,80 | 8,20 |
| I | 91,40 | 8,60 |
| J | 96,00 | 4,00 |
| K | 100,00 | 0,00 |
| L | 95,60 | 4,40 |
| M | 94,30 | 5,70 |
| N | 94,00 | 6,00 |
| **Média** | **91,30** | **8,70** |

A interpretação destas litologias além de permitir de forma rápida estimar o percentual real dos minerais ou seus “agrupamentos”, possibilita a inferência de valores de propriedades, como por exemplo a velocidade intervalar média, para cada poço estudado. Isto, por si só já é de grande valia para a construção dos modelos de velocidades a serem utilizados nos processos de atualização por inversão tomográfica visando futuras migrações sísmicas. Entretanto, uma vez que as litologias são interpretadas para cada profundidade, é possível se analisar quais seriam os valores mais adequados das propriedades de acordo com a sua posição vertical. Os estudos realizados nos mais diversos poços onde existem perfis registrados indicam que apenas o “agrupamento” denominado HVS aparenta ter algum tipo de resposta à compactação (Maul *et al.*, 2019b - Anexo A2), ou seja, os HVS´s interpretados nas maiores profundidades apresentam velocidades maiores que os interpretados nas poções mais rasas. Este comportamento não é observado nem para a Halita nem para o “agrupamento” LVS.

No Anexo A2 é possível se observar que o aumento da velocidade intervalar está relacionado de forma inversa com o aumento da espessura da seção evaporítica. Em outras palavras, quanto mais delgada for a seção evaporítica analisada, maior será a probabilidade de se aumentar a velocidade intervalar média desta porção. Este conceito já mencionado por Oliveira *et al.* (2015), reportava que os evaporitos mais móveis (LVS e Halita) se moveriam para regiões de menores pressurizações (maiores espessuras), enquanto que os HVS, por serem mais rígidos e menos móveis, se manteriam em suas localizações originais (ao final do processo de movimentação, nas regiões de menores espessuras). Este conceito está em total concordância com as conclusões apresentadas por Dooley *et al.* (2015), em função da instabilidade *Rayleigh-Taylor* (R-T), ou a Ge *et al.* (1997) que discutem sobre o efeito da sobrecarga de sedimentos sobre a seção evaporítica sobrejacente a um embasamento considerado irregular, inferindo que o peso dos sedimentos força o sal a subir. De forma semelhante, Guerra & Underhill (2012) sugerem que a força da gravidade atuando por diferenças de pressão move os evaporitos em conjunto das porções mais pressurizadas para as menos pressuriozadas na Bacia de Santos.

Diversas abordagens tentando se gerar uma propriedade de outra existente, especificamente com relação aos perfis de poços adquiridos estão presentes na literatura (relações empíricas). Muitas destas estabelecem correlações suportadas por informações de laboratório, com amostras de locais específicos, sejam de afloramento, sejam de informações de poços. Neste trabalho propomos a utilização de correlações baseadas nos perfis existentes (Maul *et al.*, 2019b - Anexo A2, 2019c - Anexo A4), uma vez que temos, por cada campo, sempre alguns poços que possuem suíte de perfilagem próximas da completa. Entretanto, é importante enfatizar que isto é também uma forma de introduzir incertezas ou mesmo de imprecisão da metodologia (Maul *et al.*, 2019b - Anexo A2).

Como já mencionado anteriormente a qualidade do dado sísmico que serve de entrada para a aplicação da metodologia desenvolvida é mandatória, uma vez que o dado sísmico é a base para a caracterização da seção evaporítica. Assim, é importante a correção da fase do dado, estudos de pré-condicionamento e filtragens de ruídos. Tanto o estudo de inversão sísmica, quanto o estudo de fácies sísmicas e das abordagens por *Machine Learning* dependem da qualidade do dado sísmico, sobre o qual serão realizados eventuais estudos. A metodologia adotada prevê a recursividade dos processos (Maul *et al.*, 2018b - Anexo A1; 2019b - Anexo A2; 2019a - Anexo A3, 2019c - Anexo A4; 2020a - Anexo A5). A partir da imagem sísmica inicial, são efetuados os processos de migração sísmica, considerando-se o modelo de sal estratificado e, subsequentemente, sobre a nova imagem sísmica gerada são realizados novos processos de migração, com algoritmos mais adequados e assim por diante (Gobatto *et al.*, 2016; Falcão, 2017; Fonseca *et al.*, 2018; Dias *et al.*, 2019; Maul *et al.*, 2019c - Anexo A4; Fonseca *et al.*, 2019; Maul et al., 2020a - Anexo A5). Os melhores exemplos desta abordagem considerando aplicação da recursividade estão amplamente expostos nos Anexos A4 e A5 desta tese, sendo que no Anexo A5, inclusive já se observam os resultados, de forma recursiva, da inserção de estratificações com a técnica de *Least-Squares Migration* (LSM), e seus benefícios, conforme pode ser exemplificado na Figura 15.

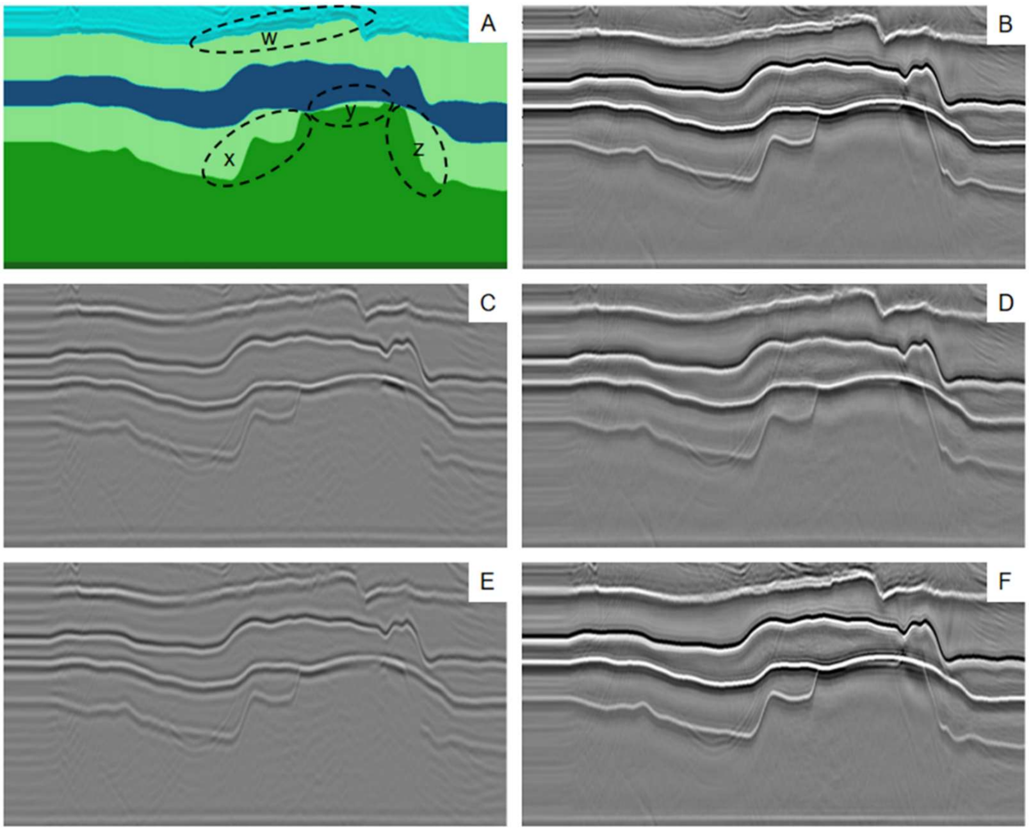


Figura 15: Painéis para a inspeção do ganho de qualidade da imagem sísmica quando se combina a técnica de inserção das estratificações no sal no modelo de velocidades e *Least-Squares Migration*.
A: Modelo geológico de propriedades usado para a geração da aquisição sísmica sintética, utilizando o método de diferenças finitas e algumas feições geológicas de interesse: elipse "w" ilustra uma porção da base do sal com duas interfaces; elipse "x" indica uma feição de rifte; elipse "y" apresenta uma camada delgada; e elipse "z" reoresenta uma superfície de grande mergulho.
B: Migração (RTM) da "aquisição sintética" e aplicação do LSM utilizando o próprio modelo de propriedades (velocidades) como modelo de velocidades para a migração, gerando o modelo de referência.
C: Migração (RTM) da "aquisição sintética" utilizando o modelo de velocidades padrão (tomografia).
D: Aplicação do LSM sobre a migração (RTM) apresentada em "C".
E: Migração (RTM) utilizando um novo modelo de velocidades pela inversão sísmica, a partir da imagem apresentada em "C".
F: Aplicação do LSM sobre a migração (RTM) apresentada em "E".
Observar a grande melhoria da imagem "F" em função da combinação das técnicas de inserção das estratificações no sal no modelo de velocidades e de *Least-Squares Migration* (Maul *et al.*, 2020b – Submetido).

Mesmo com todas estas informações disponíveis, a amostragem de poços é consideravelmente muito pequena em relação à cobertura espacial dos projetos sísmicos. Além do mais, os poços são em geral situados nas melhores posições de reservatórios prioritariamente e, secundariamente, nas regiões de menores riscos operacionais para sua perfuração, o que geralmente cria vieses específicos para os resultados obtidos, não necessariamente sendo representativos para o todo. As próprias considerações de Alves *et al.* (2017) e Teixeira *et al.* (2020) refletem de forma bem clara este aspecto de falta de representativade dos dados de poços existentes para o todo.

Desta forma, nem sempre todas as porções da seção evaporítica salina são de fato amostradas por poços, e isto pode ser crucial nos processos de caracterização desta seção como um todo, pois podem não contemplar situações específicas a serem investigadas e, a depender, calibrar seus modelos gerados (inversão sísmica *model-based*, por exemplo) de forma equivocada, uma vez que estes estudos dependem das informações de poços para a construção dos modelos de baixa frequência. Estes modelos podem ser definidos como o resultado da interpolação das informações oriundas dos poços, obedecendo às geometrias impostas pelos modelos interpretados (daí o nome *model-based*) que no caso da seção evaporítica são o topo e base do sal, normalmente. Assim, a escassez de poços, ou mesmo a falta de poços em determinadas situações pode ser um impacto muito grande para este processo de construção dos modelos de baixa frequência, que balizam os estudos de inversão e, consequentemente, comprometer seus resultados. Um dos maiores problemas já identificados é a extrapolação de eventuais respostas típicas de estratificações, existentes nos poços, para porções nitidamente homogêneas na sísmica.

Tentando contornar este tipo de problema foram desenvolvidas duas rotinas relativamente simples, mas que se mostraram muito eficazes. Na primeira, ao se perceber a extrapolação equivocada de informações de poços para respostas sísmicas, onde estas não eram nítidas, foram inseridos pseudo-poços para controlar este efeito de extrapolação equivocada (Teixeira *et al.*, 2016; Toríbio *et al.*, 2017). Na segunda rotina, que pode ser considerada até mesmo como um passo seguinte à primeira, foram criadas e inseridas “máscaras” utilizando-se de combinação de atributos sísmicos, para realçar as regiões domadas, impedindo assim a extrapolação das interpolações nestas regiões (Fonseca *et al.*, 2019). Em projetos anteriores, nas etapas de processamento sísmico não eram incomuns as solicitações de mapeamentos de um horizonte sísmico interno à seção evaporítica, que separasse o que era entendido como "domínio estratificado" do "domínio domado". Esta tarefa se apresentava como sendo muito dispendiosa, consumindo um tempo muito grande de execução. As "máscaras" calculadas por atributos de uma certa forma geram resultados muito semelhantes.

Entretanto, um ponto importantíssimo oriundo destas duas rotinas anteriormente descritas está na questão de se fazer a inversão no que foi denominado como sendo "em duas passadas" (Teixeira *et al.*, 2016; Toríbio *et al.*, 2017). Em linhas gerais, na "primeira passada" os resultados são os mais parecidos com a inversão tradicional, inclusive apresentando os eventuais problemas de extrapolações. Na "segunda passada" estes condicionantes (pseudo-poços + "máscaras") são inseridos antes da construção dos modelos de baixa de frequência, tornando os os resultados muito mais confiáveis.

A partir dos estudos de inversão sísmica é possível a caracterização, em maior detalhe, das estratificações presentes na seção evaporítica. Originalmente, pelos estudos de amplitude sísmica, em função da menor resolução e do processo convolucional inerente ao método sísmico, a melhor caracterização se dava para os evaporitos de alta velocidade (HVS). Para os evaporitos de baixa velocidade (LVS) esta caracterização se tornava arriscada, uma vez que muitas vezes o evento sísmico que representaria o sal de baixa velocidade se confundia com o lobo lateral do sinal representativo do sal de alta velocidade (HVS). Esta confirmação se tornou possível em função dos estudos estatísticos dos tipos de sais (de baixa - LVS ou de alta - HVS) identificados nos poços, pois não era compatível com a informação adquirida com a metodologia de amplitude sísmica. Ao se utilizar os processos de inversão sísmica, os resultados comparativos (estudos estatísticos dos poços, por "agrupamentos" e a quantificação 3D da inversão, dos mesmos "grupos") se mostraram muito mais compatíveis e, portando mais confiáveis.

Um outro aspecto a ser considerado nos estudos de inversão sísmica *model-based* está no conceito do que seriam os ciclos salinos. Conforme descritos na literatura, na escala sísmica, os ciclos de 4ª ordem estratigráfica (Freitas, 2006;

Gamboa *et al.*, 2009; Fiduk & Rowan, 2012; Jackson *et al.*, 2015; Alves *et al.*, 2017; Rodriguez *et al.*, 2018; Pontes *et al.*, 2019; Teixeira *et al.*, 2020), são utilizados como entrada para a construção do modelo de baixa frequência dos mesmos Pontes *et al.*, 2019; Teixeira *et al.*, 2020). A inserção do detalhamento de horizontes internos (representativo destes ciclos de 4ª ordem estratigráfica) na construção dos modelos de baixa frequência para o processo de inversão sísmica foi, então, proposta e testada por Pontes (2019), e os resultados minimizam os problemas de extrapolações de informações dos poços, conforme descrito anteriormente. Mesmo sendo ainda iniciais os testes com relação a esta abordagem, importantes aspectos em termos de qualidade de resultados a partir de estudos de inversão sísmica, incluindo os "ciclos salinos" podem ser verificados no Anexo A6, em especial no que tange à análise de incertezas volumétricas do reservatório em função deste maior detalhamento do modelo de velocidades da seção evaporítica salina.

Ainda que os estudos de inversão sísmica propiciem uma melhor caracterização da seção evaporítica, tanto pela melhora da resolução, quanto pelo processo de calibração dos poços, a questão da resolução vertical ainda é uma fragilidade de qualquer processo que utiliza os dados sísmicos como base. Na profundidade das ocorrências das estratificações, bem como em função das propriedades acústicas de cada mineral que compõem estas estratificações, qualquer critério de resolução sísmica, ou mesmo de detecção sísmica, conseguirá assegurar apenas a caracterização de eventos que tenham de 25 a 40 metros de espessura, no mínimo. Nos mais diversos poços estudados (cerca de 250 poços) as espessuras muitas vezes são métricas, ou mesmo centimétricas, sendo impossível sua resolução ou até mesmo sua detecção sísmica. Para diversos processos esta ordem de resolução (25-40 metros) de eventos pode ser mais do que suficiente, mas para outros não, como é o exemplo do risco operacional na perfuração de poços (Teixeira *et al.*, 2017). Nestes casos, mesmo poucos metros de espessura, mas com uma considerável área de abrangência, podem aumentar o risco de colapso de coluna de perfuração, perda de circulação de fluidos, aprisionamento de coluna e até mesmo ocasionar acidentes com pessoas (Maul *et al.*, 2018b - Anexo A1).

Complementarmente, a identificação de pequenas espessuras de estratificações vem se tornando cada vez mais frequente e necessária. Em especial estudos de classificação *bayesiana* de fácies vem se tornando padrão nestes estudos (Meneguim *et al.*, 2015; Teixeira *et al.*, 2017; Teixeira & Lupinacci, 2019, Teixeira *et al.*, 2020). Através desta abordagem, combinando atributos sísmicos e informações de poços, em especial agrupamento de fácies geológicas, é possível se gerar cubos de probabilidade de ocorrência de cada mineral ou seus agrupamentos. Isto nem de longe encerra a discussão sobre a questão da resolução, tão necessária para a segurança operacional na perfuração dos poços, mas ao menos pode sinalizar para potenciais riscos para perfuração.

A metodologia de caracterização das estratificações da seção evaporítica salina (Maul, 2020 – esta tese), e suas mais diversas aplicações nos projetos de exploração, desenvolvimento e produção de hidrocarbonetos, tendo como base (*input*) e resultados (*output*) o dado sísmico é uma realidade. Diversos resultados podem ser consultados e confirmados no Anexo A (A1, A2, A3, A4, A5 e A6). De forma resumida é possível se categorizar suas utilizações como uma variação de "simples" a "complexas", conforme apresentado na figura 16.


Figura 16: Exemplos de áreas de aplicação dos resultados obtidos pela metodologia de caracterização da seção evaporítica salina.

## 6 PRINCIPAIS CONTRIBUIÇÕES PARA A CIÊNCIA E SUAS APLICAÇÕES

A utilização das descrições das amostras de calhas com o auxílio de algum tipo de perfil existente propicia uma melhoria da quantitifação das porcentagens dos minerais existentes no poço, e permite atribuir o valor de propriedade em uma determinada posição. As descrições “discretizadas” das amostras de calha permitem gerar pseudo-perfis: com atribução de valores constantes, oriundos de tabelas (que podem ser provenientes de estudos de laboratórios ou de estudos de perfis de outros poços/áreas). A partir destas informações podem ser adotadas equações empíricas, de preferência para a própria área, que muito embora possam ser fonte de incertezas (imprecisões) trazem grandes benefícios para a intepretação, sobretudo se realizada com rigor geológico. Com base nestas informações foi possível agrupar os minerais em “famílias de velocidades”: Sais de Altas Velocidades (em inglês *High Velocity Salts*, ou HVS) composto basicamente por Anidrita e Gipsita), a própria Halita (que pode ser considerada como *Background*) e os Sais de Baixas Velocidades (em inglês *Low Velocity Salts*, ou LVS), composto basicamente por Silvita, Carnalita e Taquidrita.

A utilização de atributos sísmicos instantâneos e geométricos, tendo como base o próprio atributo da amplitude sísmica, para se identificar e alterar o modelo de velocidades da seção evaporítica salina permitiu separar regiões com ou sem sem estratificações e, inferir se as estratificações são oriundas de interfaces de aumento ou de diminuição de velocidades.

A sistematização dos estudos de inversão sísmica (*model-based*) e de classificação de fácies se apresentam como as melhores alternativas para carateризação das estratificações no interior da seção evaporítica salina. A grande espessura desta seção, ou mesmo sua grande variabilidade de espessuras, devem ser considerandas nos estudos para a seleção de uma única *wavelet* representativa para o todo, primordial para o estudo de inversão. Na inversão sísmica *model-based*, as informações dos perfis de poços são essenciais para a construção do modelo de baixa frequência. Este modelo de baixa é construído a partir da interpolação das informações dos perfis, seguindo as estruturas (*layers*) construídas a partir dos horizontes identificados como representativos da seção evaporítica salina, num primeiro momento, o topo e a base do “sal”. A observação das informações de amostras de calhas permite atribuir valores em áreas não perfiladas, e se obter um perfil “mais completo” para ser utilizado no processo de inversão. A inserção de pseudo-poços e “máscaras” no processo, permite melhor controle dos modelos de baixa e se for o caso pode-se realizar a inversão em mais de uma “passada”. A inclusão de horizontes representativos dos ciclos salinos, interpretados na escala sísmica, além do topo e base do sal, na construção do modelo de baixa frequência, apresentou excelentes resultados, sendo estes muito mais preditivos em qualquer aspecto quando comparados com a inversão que considera apenas o topo e a base do sal como condicionantes para a construção do modelo de baixa frequência.

A classificação *bayesiana* de fácies, combinando atributos sísmicos, propicia a geração de volumes de probabilidade de ocorrência dos agrupamentos minerálicos, apresentando cenários de probabilidades de ocorrência de um ou outro agrupamento mineral, o que propicia um melhor processo decisório durante a etapa de perfuração dos poços.

Foram apresentados alguns critérios que permitem a idealização de equações empíricas para a transformação de uma propriedade em outra. Como exemplo, foi ilustrada como a propriedade de impedância acústica, resposta dos estudos de inversão sísmica foi convertida para a velocidade intervalar. Neste caso, os critérios em termos de intervalos a serem correlacionados e o grau de incerteza dos resultados são também de grande valia.

Foi comprovado que é possível fazer análise do comportamento da velocidade em relação à espessura da seção evaporítica salina. Em geral, com o aumento da espessura da seção evaporítica a velocidade intervalar média tende a domininuir. A compressão exercida pelos *rafts* carbonáticos e/ou sedimentos acima da seção evaporítica salina tende a expulsar os minerais mais dúcteis (móveis) e que possuem menores valores de velocidade para regiões de mais baixas pressões, onde se situam as espessas almofadas de sal e diápiros. A consequência é que na região mais delgada haverá uma maior concentração de minerais de velocidades mais altas (HVS) que são mais resistentes à movimentação, ou seja, quanto menor a espessura, maiores as velocidades intervalares médias observadas. Este é um critério simples, mas que deve sempre ser observado.

A confirmação de que a “separação” da seção evaporítica em quatro grandes domínios sísmicos (Domínio Sem Estratificação; Domínio com Estratificação Evidente; Domínio de Estratificações Aleatórias e Domínio de Estratificações Escondidas) tem impactos nas modelagens.

O desenvolvimento da metodologia aplicada nesta tese e seus resultados contribui ainda para a simulação geomecânica de reservatórios, construção de poços, prevenção e combate a problemas de perfuração e segurança operacional. Anteriormente considerava-se a seção evaporítica basicamente composta por Halita e com uma delgada camada de Anidrita basal (variando de 10 a 20 metros em média), correspondente à média dos valores amostrados pela maioria dos poços perfurados na Bacia de Santos. A esta seção (Halita + Anidrita basal) eram atribuídas propriedades constantes como densidade, módulo de Young, coeficiente de Poisson, coesão, ângulo de atrito, e assim por diante, de forma discreta, ou seja, com valores únicos. A metodologia aplicada nesta tese permite a caraterização da seção evaporítica salina com diversas estratificações, espacialmente e geologicamente bem distribuídos incluindo, até mesmo, a Anidrita basal, porém aqui com variação de espessura. Cabe destacar que, em alguns poços já foram observadas Anidritas basais com espessuras superiores (30-50 metros) e mesmo repetições de camadas de Anidrita na base, entremeadas por Halita, ilustrando que a simplificação da consideração de uma Anidrita basal, com uma espessura única e média, é um grande risco de projeto.

A partir das posições bem definidas de estratificações da seção evaporítica salina (em especial das Anidritas basais), foram atribuídos valores de propriedades, por exemplo, segundo o que foi calculado para cada poço do projeto, em função dos perfis disponíveis, obedecendo, regras de compactação, alterações inerentes dos processos geológicos. Ou seja, propiciando a geração de um modelo 3D de propriedades para a seção evaporítica muito mais próximo da realidade geológica.

A informação sísmica é utilizada para se prever quais litologias seriam perfuradas pelos poços construindo-se o “Quadro de Previsões Geológicas” - QPG. A partir deste quadro, baseando-se em interpolações matemáticas das informações de poços e análises qualitativas das informações sísmicas, são definidos os equipamentos, parâmetros e insumos utilizados para perfuração. As inversões sísmicas e classificações de fácies conforme mencionadas nesta tese permitem de forma quantitativa e em modelos 3D, agregar muito valor aos projetos, com a previsão do potencial de aprisionamento de broca, regiões de "cavernas" ou propícias à dissolução em função do tipo de fluídos, o que causaria desabamento de toda a coluna de perfuração, perda de fuidos de circulação e, eventualmente do próprio poço, causando enormes prejuízos para o projeto.

Na maioria das vezes assume-se que a anisotropia do sal seja muito pequena ou mesmo desprezível para os processos de migração sísmica. Entretanto, ao se analisar de forma isolada cada agrupamento mineral, foi possível se identificar que, o comportamento dos HVS é diferente dos LVS e da Halita, ao menos em termos de respostas à compactação. Os HVS por serem rúpteis e menos móveis tendem a responder aos efeitos de compactação, e os LVS e a Halita, de características mais dúcteis e, consequentemente, mais móveis, tendem a se mover para regiões sob menores esforços o que, ao menos, mascararia qualquer possível efeito de compactação. Isto pode ser um indicativo de diferenças, também, em termos de anisotropia mineral e, mais ainda, anisotropia sísmica.

Para os estudos de iluminação sísmica, onde se busca melhor definir os parâmetros de aquisição de um novo dado sísmico, existe a necessidade de se representar da forma mais realística possível o caminho a ser percorrido pela onda sísmica, para se construir a informação na base do sal, que representa o topo dos reservatórios da seção Pré-Sal. Ao não se representar as estratificações da seção evaporítica salina, ou seja, ao se considerar o sal como uma seção homogênea e com propriedades aproximadamente constantes e similares às da Halita, o caminho assumido percorrido pela onda sísmica não deverá ser próximo ao da realidade geológica. Consequentemente, as respostas das simulações dos resultados na base do sal estarão comprometidas. Nos mais diversos projetos de estudos reais de iluminação sísmica as inserções das estratificações do sal resultaram em definições muito mais próximas da realidade geológica.

Com relação ao processamento sísmico, em especial em áreas consideradas como de elevada complexidade geológica, o que é representado pela seção evaporítica salina da Bacia de Santos, os modelos de velocidades iniciais a serem atualizados pela inversão tomográfica atingem seus melhores resultados, de forma muito mais rápida e precisa, quando apresentam as estratificações com algum grau de suavização, conforme demonstrado nos artigos desta tese. A diferença em termos de iterações tomográficas, chega a ser de 1 a 2 iterações para os projetos com as estratificações na seção evaporítica salina para algo entre 4 e 6, nos projetos sem estas estratificações. Esta validação é sempre realizada pela avaliação dos alinhamentos dos *gathers* e pela construção da imagem (focalização dos eventos). Ou seja, além do ganho computacional (redução do custo computacional ao se considerar os modelos de sal estratificado no processo de atualização dos modelos de velocidades por inversão tomográfica), os resultados em termos de imagens sísmicas são superiores, mesmo quando se utiliza migração Kirchhoff.

Algorítmos que requerem modelos de velocidades ainda mais detalhados/precisos, tais como as migrações *Reverse Time-Migration* (RTM), ou mesmo as atualizações de modelos pela técnica de *Full-Waveform Inversion* (FWI), sempre terão melhores resultados quando partindo de modelos de velocidades iniciais mais próximos da realidade geológica, o que é o caso dos modelos com inserções de estratificações na seção evaporítica salina. Apesar disto, ainda persiste o impacto da complexidade do topo sal, em especial em regiões de multi-Z (*overhangs*) e/ou grandes mergulhos dos paredões de sal na construção de modelos. Neste sentido, a aquisição em diferentes azimutes tem muito valor na melhoria do imageamento em áreas geológicamente complexas.

A construção de modelos de sal estratificados na seção evaporítica salina, aliada à técnica de *Least-Squares Migration* (LSM) foi realizada e os resultados são extremamente promissores (Anexo A5). Realizando-se migrações do tipo RTM com anisotropia vertical (VTI), se observou um grande ganho em termos de qualidade de imagem, conteúdo de frequência, preditividade de profundidades e melhor precisão em termos de respostas de amplitude sísmica. Para tal, a partir de um modelo “teórico” de propriedades, em especial a velocidade, (incluindo as estratificações no sal) foi simulada uma aquisição sísmica que foi migrada utilizando-se a combinação do RTM com o LSM, tendo como modelo de velocidades o próprio modelo “teórico”. Na sequência foram realizadas quatro migrações, duas considerando o modelo tomográfico (padrão da indústria), sendo uma sem LSM e outra com; e duas migrações considerando um novo modelo de sal estratificado, obtido pela inversão, a partir da imagem construída pelo modelo tomográfico, sem LSM. Para estes dois últimos modelos, em um não foi considerada aplicação do LSM e no outro sim. Ao fim, todos os modelos foram comparados com o modelo inicial (em termos de propriedades e de imagem sísmica) e, em todas as comparações, o modelo que considera a nova inversão e o LSM ficou muito mais próximo do modelo inicial (Figura 15), dando a certeza de que esta combinação é um grande passo, provavelmente sendo a maior contribuição desta tese.

Partindo-se do pressuposto de que todos os modelos são apenas uma representação matemática da natureza, é possível se afirmar que todos são, portanto, errados por definição, mesmo que muitas vezes úteis. As diferenças encontradas ao se adotar um ou outro modelo, por exemplo em termos de posicionamento de eventos, permitem estudos de variações volumétricas, tanto de rochas acima de uma eventual referência (contato óleo-água, por exemplo) como em termos de propriedades de reservatórios, efetivamente (porosidade, permeabilidade). Esta abordagem propicia então uma robusta tomada de decisões em termos de projetos, independente da fase em que os mesmos se encontram.

Assim como no processamento sísmico, de uma forma geral, o caráter de recursividade dos processos de caracterização sísmica da seção evaporítica se mostra como sendo de grande valia. Estes benefícios podem ser observados tanto em termos de melhorias caracterizações da seção evaporítiva em si, quanto em termos de novas migrações sísmica, em especial quando da utilização de técnicas mais avançadas de processamento sísmico, como é o caso de RTM, FWI e LSM.

# 7 CONCLUSÕES

As atividades de exploração, desenvolvimento e produção em regiões onde existem seções evaporítica salinas, devem considerar as heterogeneidades de sal e não apenas a predominância da Halita, mesmo considerando-se que esta muitas vezes apresenta mais de 80% do total de ocorrência.

A utilização de informações de poços, mesmo que apenas as descrições litológicas (amostras de calha), são imprescindíveis para a quantificação destes percentuais de ocorrências que, por si só, já servem de um guia muito razoável para se pensar em termos de modificação de velocidades, em especial para os processos relacionados ao método sísmico. Esta utilização também permite a geração de melhores insumos para os estudos de incertezas volumétricas de reservatórios.

Os agrupamentos mineralógicos propostos, *Low Velocity S*alts - LVS, Halita e *High Velocity Salts* - HVS, em geral resolvem os principais problemas ao se trabalhar com a seção evaporítica salina. Este conceito de agrupamento, relacionado com uma inspecção visual dos domínios de estratificação (*Without Stratification Domain - WSD; Evident Stratification Domain - ESD; Random Stratification Domain - RSD; e Hidden Stratification Domain - HSD)*, é um excelente ponto de partida para os estudos de estratificação da seção evaporítica salina.

Inferências relativas ao comportamento em termos de velocidades intervalares médias inversamente correlacionadas com a espessura da seção evaporítica são também possíveis de serem estabelecidas ou ao menos discutidas. Neste projeto, assim como em outros consultados, de forma geral, ao se observar grandes variações de espessuras do sal, nas maiores espessuras predomina os sais de menores velocidades (LVS e Halita) e nas regiões de menores espessuras há um aumento no percentual de ocorrência dos HVS. E, consequentemente, é de se esperar que seções mais delgadas de sal apresentem velocidades intervalares maiores, quando comparadas com seções mais espessas, que apresentam velocidades intervalares menores.

A construção de modelos de velocidades a partir de estudos de inversão sísmica, de preferência utilizando os dados de poços (perfis quando existentes), inclusive aqueles que foram complementados pelas descrições litológicas, se apresenta como um dos melhores caminhos no sentido de se construir estes modelos para a seção evaporítica salina com grande conteúdo geológico.

Ao método de inversão sísmica (*model-based*) não considerando apenas o topo e a base do sal, mas também a inclusão de horizontes internos ao sal, na tentativa de contemplar possíveis ciclos de deposição salinas, similares aos ciclos de 4ª ordem da estratigrafia de sequências, faz com que os modelos de velocidades apresentem, ainda mais, características geológicas, com resultados comprovadamente mais precisos e robustos. A recursividade nos estudos de inversão, ou seja, um resultado de inversão servindo como entrada para um novo estudo de inversão também se apresentou como de grande valia para a geração dos modelos de velocidades detalhados da seção evaporítica salina.

Em termos de estudos de iluminação, a inserção das estratificações garante uma melhor aproximação do meio geológico por onde a onda sísmica, a partir da fonte, deverá percorrer para atingir o seu alvo de interesse e retornar para o receptor. Desta forma, a construção do modelo de amplitude simulada, ao se utilizar o meio estratificado (inserções de estratificações na seção evaporítica salina), é mais fiel ao que se obterá quando da aquisição sísmica em si, permitindo, assim, melhores decisões em termos de parâmetros de aquisição sísmica (Maul *et al.*, 2015; Maul *et al.,* 2018b - Anexo A1). Questões relacionadas à complexidade dos corpos de sal (Zambrini 2020; Zambrini *et al.*, 2020) e aspectos anisotrópicos também não podem ser descartados no contexto destes estudos.

Durante o processamento sísmico (migração sísmica), o modelo de sal estratificado, propicia um fluxo de atualização por inversão tomográfica, do modelo de velocidades, mais eficiente e com resultados mais geológicos, em especial quando não estão disponíveis tomografias que lidem com a incorporação de informação geológica a partir de regularizadores. O modelo de sal estratificado possibilita, além de imagens sísmicas mais bem construídas em termos de focalização, maior confiabilidade na continuidade, ou não dos eventos, melhores definições de planos de falhas, redução dos efeitos, incorretos de *pull-up* ou *push-down*, e assim por diante. Além disso, os resultados podem ser utilizados para diversas outras aplicações, tais como posicionamento em profundidade (Meneguim *et al.*, 2015; Paes *et al.*, 2019;

Maul *et al.*, 2020a - submetido - A6), variáveis secundárias para a distribuição de propriedades de reservatórios (Maul *et al.*, 2015), incertezas volumétricas (Meneguim *et al.*, 2015; Paes *et al.*, 2019; Maul *et al.*, 2020a - submetido - A6), estudos de simulação geomecânica Teixeira *et al.*, 2018) e segurança operacional na contrução dos poços (Teixeira *et al.*, 2017).

A técnica de *Reverse Time-Migration* (RTM), ao contrário da técnica Kirchhoff, pode usar modelos de velocidades mais detalhados. A construção e/ou atualização dos modelos de velocidades pela técnica *Full- Waveform Inversion* (FWI) também logra maior sucesso quando parte de um modelo inicial de velocidades mais detalhado. O modelo de sal estratificado a partir de estudos de inversão sísmica é atualmente o tipo de modelo mais detalhado possível de ser construído. Até mesmo no processo de atualização dos modelos através dos processos de inversão tomográfica as estratificações propiciam uma melhor e mais rápida convergência do método, não caindo em mínimos locais, gerando ganhos em termos de tempo (e financeiro) e em termos de qualidades das imagens.

A associação desta técnica de inserção de estratifições na seção evaporítica salina com a técnica de *Least-Squares Migration* (LSM), de acordo com este estudo, se apresenta com um efetivo caminho a ser percorrido em termos de processamento sísmico. Os resultados confirmam a melhoria de imageamentos sísmicos em regiões de complexidade geológica, o aumento da resolução dos eventos (aumento do conteúdo de frequências recuperadas), a acurácia em termos de previsão de posição dos eventos, tanto verticais quanto laterais, e a confiança dos valores de amplitude gerados pela focalização dos eventos.

Todas as conclusões demostram a importância de um estudo de caracterização das estratificações da seção evaporítica salina, visando o seu melhor detalhamento, em especial para a construção de modelos de velocidades intervalares para as mais diversas aplicações do método sísmico para os projetos de exploração, desenvolvimentos e produção de hidrocarbonetos. Isto reduz as incertezas associadas ao método, gera informações mais confiáveis e propicia melhores tomadas de decisões, tanto em termos operacionais como econômicos para estes projetos.

## 8 SUGESTÕES PARA ESTUDOS FUTUROS

Para trabalhos futuros sugere-se maior aprofundamento (testes) relacionados à combinação dos modelos de sal com inserção de estratificaçoes conforme apresentado nesta tese com a técnica de *Least-Squares Migration* (LSM), com migrações do tipo *Reverse Time-Migration* (RTM), assumindo outras complicações geológicas sub-sal (Pré-Sal).

A atualização de modelos de velocidades pela técnica *Full-Waveform Inversion* (FWI), já testada em alguns dos artigos listados no Anexo E também se apresenta como um excelente campo de investigação.

Nos flancos dos corpos de sal com grande mergulho onde possivelmente está presente o *Hidden Stratification Domain* (HSD) necessita de melhores entendimentos em termos de respostas de velocidades intervalares, mesmo quando utilizados os modelos gerados a partir da inversão sísmica, inclusive com maior detalhamento (horizontes internos - ciclos), pois os resultados apresentados nesta tese ilustram ainda um comprometimento da resposta nestas porções do dado.

Aspectos relacionados à anisotropia devem também ser testados e melhores compreendidos. Entendimentos das respostas em zonas de seção evaporítica com grande mergulho, regiões com estratificações deformadas, e assim por diante.

A geração de fluxos de estudos de modelagens geológicas de reservatórios, que contemplem incertezas volumétricas, a partir das variações dos topos dos reservatórios ao se utilizar diferentes modelos para a seção evaporítica salina se apresenta, também, como um campo a ser mais profundamente investigado.

Além da qualidade do dado sísmico em si, a resolução sísmica é um fator determinante para a efetiva caracterização dos evaporitos da seção salina. Muitos evaporitos têm espessuras métricas, por vezes centimétricas, mas com grande extensão espacial. Alguns evaporitos, em especial os inseridos no contexto dos LVS´s, são causadores dos mais importantes incidentes nas etapas de perfuração, dentre eles o aprisionamento de brocas, dissolução quando em contato com fluidos específicos e, consequência, perda de fluidos de perfuração, desabamento de coluna de perfuração e assim por diante. Desta forma, o desenvolvimento de metodologias que permitam a melhor caracterização ou, ao menos, a detecção destes evaporitos de baxia espessura se apresenta como um grande campo de pesquisa para estudos futuros.

Ainda no contexto das incertezas, uma vez que os produtos oriundos das inversões sísmicas são os dados de impedância, formulação de equações empíricas propiciando a dedução desta propriedade para outras de interesse (em nosso caso a velocidade intervalar) necessitam ser melhor estabelecidas e testadas, e suas incertezas consideradas, suscitando assim mais um campo de pesquisa a ser investigado.

Análises de simulações geomecânicas foram, de forma muito genérica, abordadas em alguns dos artigos em anexo (Anexo E), carecendo de melhores investigações, principalmente em termos de quantidade de estudos criando assim uma base de dados e resultados, e estabelecendo eventuais métricas, ou mesmo descartando esta possibilidade de adequação da metodologia para esta abordagem.

A possibilidade de utilização de algoritmos de *Machine Learning* é um grande campo a ser investigado, tanto pela automatização dos processos e, consequentemente, menor influência humana, quanto no que diz respeito às baixas espessuras (LVS).

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# ANEXOS

Anexo A1:

***Few Considerations, Warnings and Benefits for the E&P Industry when Incorporating Stratifications inside the Salt Section***

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# FEW CONSIDERATIONS, WARNINGS AND BENEFITS FOR THE E&P INDUSTRY WHEN INCORPORATING STRATIFICATIONS INSIDE SALT SECTIONS

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**ABSTRACT.** This article presents a review of procedures and techniques describing the importance of considering the stratification within the evaporitic section, combining seismic attributes and well information during the processes of seismic migration, in order to build seismic images closer to the geological realities. A new nomenclature is proposed, reflecting the interval velocity and density behavior of different salt strata. The study also reviews the parameters for geomechanical simulations of the reservoir seals, allowing better decisions in terms of production and/or injection rates, among others. The incorporation of intra-salt heterogeneities, or stratifications, allows for a better prediction of operational aspects such as mud weight and penetration rates, which are essential information for drilling safety, and economy. Important considerations about the lithotypes were carried, especially concerning the accumulated frequency of occurrence, the evaporites cyclicity, salt movements, etc. The data resolution, when comparing well models versus seismic models, was another important aspect considered in this review, with emphasis on the uncertainty analysis.

**Keywords:** evaporites, seismic attributes, resolution, uncertainty, model.

**RESUMO.** Este artigo apresenta uma revisão sobre os procedimentos e as técnicas que descrevem a importância de considerar estratificações existentes dentro da seção evaporítica, combinando atributos sísmicos e informações de poços para construir imagens sísmicas o mais próximo possível da realidade geológica, através de processos mais robustos de migrações sísmicas. Uma nova nomenclatura é proposta refletindo o comportamento da velocidade intervalar e densidade de cada estrato. Adicionalmente, são abordados os parâmetros para simulação geomecânica das rochas capeadoras dos reservatórios, permitindo melhores decisões sobre taxas de produção e injeção dos campos, entre outras. A incorporação das heterogeneidades, ou estratificações, nas seções evaporíticas também auxilia na definição de aspectos operacionais, tais como peso de fluido e taxas de penetração, informações essenciais para a segurança e economicidade da perfuração. Importantes considerações sobre a frequência de ocorrência dos litotipos, a ciclicidade dos evaporitos, movimentações do sal, etc., são também abordadas. A resolução dos dados, quando comparamos os modelos oriundos dos poços com os provenientes da sísmica, foi outro importante aspecto considerado, quando da análise de incertezas.

**Palavras-chave:** evaporitos, atributos sísmicos, resolução, incerteza, modelo.

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## INTRODUCTION

The first drilled well to reach the Santos Basin pre-salt reservoir section, at the Brazilian southeastern continental margin, in September 2005, crossed an evaporitic section of approximately 2,000 m, in order to access deep reservoirs about 5,000 meters below sea floor. Currently more than 200 wells have been drilled in the Santos Basin to access the pre-salt section reservoirs. The production in this section already exceeds 1.5 million barrels of oil equivalent per day, through several fields. One important aspect about this evaporitic section is that it cannot be considered homogeneous, composed only by halite, the most common evaporitic salt. Maul et al. (2015) emphasized the stratification inside that section. Those stratifications and their main aspect are the so-called enigmatic structures mentioned by Jackson et al. (2015). Among discussions in the literature and, even more, in the light of the drilled wells, several types of evaporites are identified on the Santos Basin evaporitic succession, as can be found in similar onshore salt mines around the world (Poiate Jr, 2012). Drilling in evaporitic sections is operationally challenging and subject to several risks since these rocks have completely different physical behavior, resulting in drilling column imprisonment, column collapse or over pressured brines. A direct implication of this misguided approach that considers a homogeneous salt is unrealistic seismic images leading to errors during well locations aimed to achieve the reservoirs below the evaporitic section. Robust depth seismic migration strategies depend on more realistic velocity models in terms of geology, therefore, better-constrained salt models become mandatory (Gobatto et al., 2016; Fonseca et al., 2018; Maul et al., 2018a).

From the combination of seismic images and well data, the development of field exploitation models addresses the geomechanical conditions to efficiently produce and determine the injection rates to pressure maintenance within the reservoir. As the evaporitic section is the pre-salt reservoir "seal", the geomechanical behavior is fundamental for the exploration and exploitation stages (Teixeira et al., 2017, 2018). In the present article, we propose a new nomenclature reflecting mineral groups in terms of interval velocity and density aiming to simplify the construction of seismic velocity models. Important aspects to consider when working with heterogeneities in evaporitic sections are reviewed describing the limitations as well as the direct and indirect applications of better-constrained seismic velocity models, in an attempt to investigate the reservoirs below the evaporitic section. Besides, we review the influence of different salts and salt stratification and its influence in seismic imaging, as well as the advantages to use instantaneous seismic attributes or the inversion results. Several published examples are presented, covering almost the entire extension of Santos and Campos Basins, offshore southeastern Brazil (Fig. 1, where hydrocarbon reservoirs in pre-salt section occur, with greater emphasis for the Santos Basin. Through the examples, we will illustrate the improvements when applying different methodological approaches for different E&P projects, allowing better decisions in many disciplines.

## METHODOLOGY REVIEW

Maul et al. (2015) present a methodology for a qualitative evaluation of seismic amplitude response at the base of salt (equivalent to the top of the pre-salt reservoirs in Santos Basin), using seismic illumination studies. They applied several salt velocity models, including constant velocities, inserting dome geometries, interpreting stratified regions and incorporating stratification using as constrains the amplitude response. The referred approach was re-introduced and tested in many other works (Jardim et al., 2015; Maul et al., 2016; González et al., 2016; Gobatto et al., 2016; Falcão et al., 2016; González et al., 2018; Fonseca et al., 2018).

During this first approach, the authors used only the seismic amplitude response in order to incorporate the existing stratification inside the evaporitic section. Despite promising results, these early works still indicated some classic problems, such as interface X layer response; lack of well calibration information; seismic resolution problems; ambiguities. Therefore, the referred authors developed several approaches aiming to mitigate, at least in part, each of the identified problems during project execution.

To improve seismic resolution some suggested studies to recover the high frequencies, using an iterative seismic deconvolution process, intending to remove part of the wavelet lobe effect. Seismic data integration after deconvolution returned the lithology property information as pseudo-layers, instead as interfaces. This process is equal to a 90º phase rotation over the de-convolved data, assuming it is a zero phase data. This combination, although effective, generates a low frequency enhancing effect. To minimize this effect Seifert et al. (2017) proposed a data derivative process, resulting in little high frequency Increase.

However, since they aimed to change from a property interface to a pseudo-impedance, the derivative process resulted

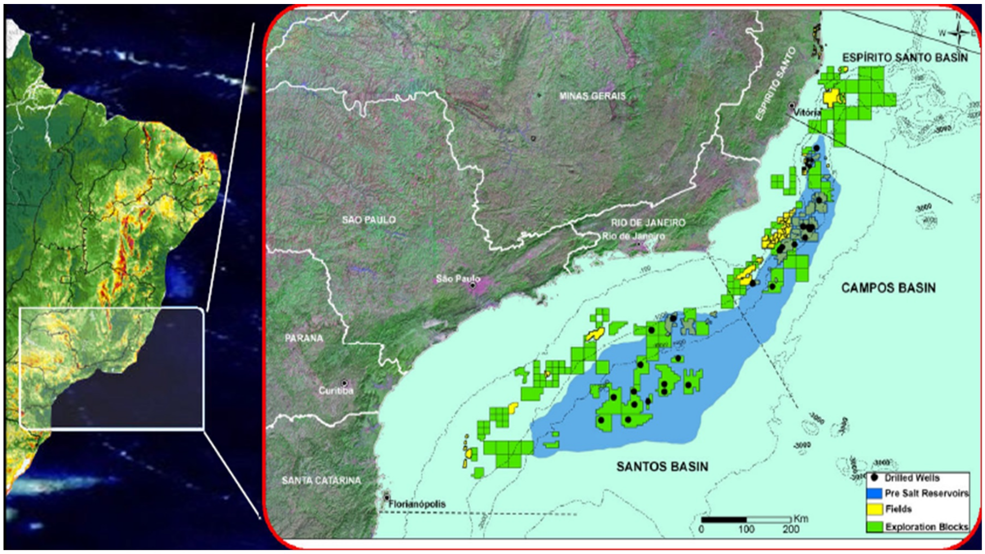


**Figure 1** – Location of Campos and Santos Basins. The blue polygon limits the pre-salt reservoirs totaling an area of approximately 350,000 km$^2$ in water depths between 2,000 and 3,000 m. Green and gray polygons are exploration blocks and yellow polygons the hydrocarbon fields. Black dots locate the drilled wells. Modified from https://diariodopresal.files.wordpress.com/2010/.

in a 90º phase rotation but in the opposite direction when compared with the integrated data. This raised another approach: to run a 180º phase rotation in order to have the same placement of the integration process. The benefits when considering the derivative instead the integration and how any of these approaches enhance the signal resolution is presented in Figure 2.

The thicknesses of evaporitic stratifications are about meters, arising ambiguity issues with respect to the seismic resolution. In addition, many seismic events are often built by the seismic convolutional phenomenon or, as we can simply say, the wavelet lateral lobes, as exemplified by Oliveira et al. (2015). These authors applied a phase rotation (integration/derivation) in search for the layer property, the socalled pseudo-impedance, obtaining better resolution (deconvolution). However, this process does not guarantee proper well and seismic calibration, driving Meneguim et al. (2015) to suggest the use of an absolute inversion process to circumvent this ambiguity response.

Tying well and seismic data properly is of fundamental importance, however, for operational and economic reasons, in the evaporitic section he vast majority of wells have no registered logs. To fill this lack of information, Amaral et al. (2015) propose to use rock-cutting samples to get a better lithological statistical representation. It enabled them to estimate the average interval velocity using average velocities for each lithotype. To establish these values they used the information presented by Justen et al. (2013).

Meneguim et al. (2015), Barros et al. (2017) and Cornelius & Castagna (2018) adopted similar approaches. This approach allows the usage of all the wells for the seismic inversion process even in case the estimated velocity values are not very accurate.

The uncertainty related to this methodology, when calculating average interval velocities, was explored by Meneguim et al. (2015), González et al. (2016), Yamamoto et al. (2016), Gobatto et al. (2016), Falcão (2017) and tested by González et al. (2018).

During the acoustic inversion process, three aspects are of utmost importance. (1) the seismic data quality, regarding phase and noise to signal ratio; (2) the interpreted seismic horizons and faults, which will serve as boundary conditions for the inversion study, as well as for modelling (commonly called trend-model) and, finally (3), the availability of well log information, in particular acoustic sonic and density. After tied to seismic data, the logs serve as inputs for seismic properties distribution, important step when building inversion trend models.

The thickness variation of the evaporitic section, from a few meters to more than 2 kilometers, is another great issue for the seismic inversion. This variation imposes difficulties to establish a single wavelet to represent this range of thickness changes.

As described earlier the seismic acoustic inversion, taking all the described precautions, provides the best response in terms of stratification resolution and positioning, generating the best answers in terms of impedance, density and interval velocity. Additionally, Meneguim et al. (2015) also propose a Bayesian

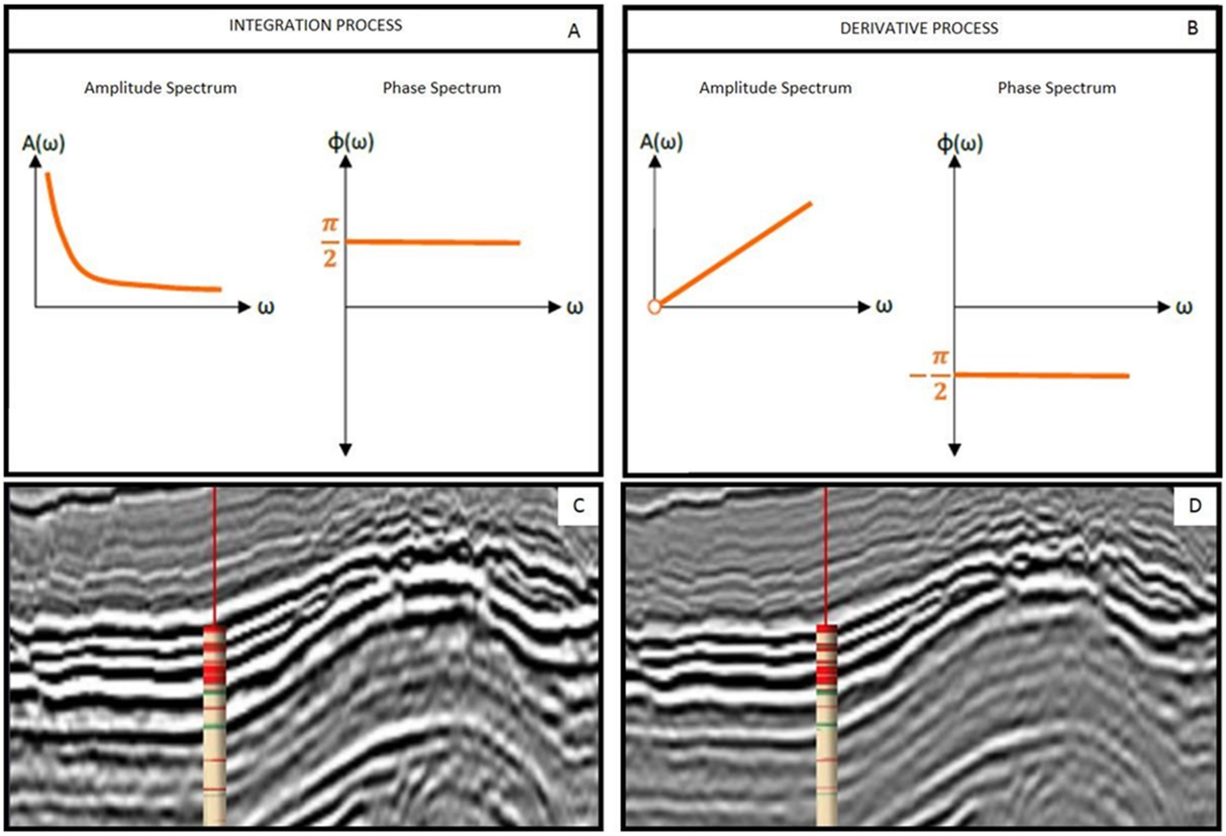


**Figure 2** – Comparison of the integration (A) and derivative (B) processes to enhance the seismic resolution over the amplitude data. A - amplitude and phase spectrum behavior when applying the integration process, note the decrease of the amplitude spectrum and the $\pi/2$ phase rotation; B - amplitude and phase spectrum behavior when applying the derivative process, note the increase of the amplitude spectrum and the - $\pi/2$ phase rotation. In this example, a 180° phase rotation is needed to place the response at the same location as the integration process; C - original amplitude response; D - derivative process + phase rotation response emphasizing the benefits when considering this combined approach. Adapted from Falcão (2017).

classification to complement the acoustic inversion studies. This process brings the possibility to generate probabilistic scenarios for the occurrence of each lithological type inside the evaporitic section, enhancing the resolution. To emphasize the benefits of using the inversion results, Gobatto et al. (2016) present a comparison between the amplitude and the impedance interpretation of the salt heterogeneities (Fig. 3).

## EVAPORITES REVIEW

Evaporites by definition are rocks formed in sedimentary environments with very low terrigenous supply, subjected to high evaporation rates, in arid climate conditions, providing the formation of brines. According to Kendall (1988), a sequential chemical precipitation of carbonates, sulphates and chlorides reflect a vertical succession as well as its lateral positioning, as established by the Walther's Law, with carbonates and sulfates near the entrance to the sea, and more soluble salts in the central and distal areas of the basin. Karner & Gamboa (2007) advocate that evaporites are the final stage of a regional mega-transgressive sequence. However, other researchers argue that the formation of the "salt ponds" were formed as part of the fast break-up during the rift phase causing subsidence and influx of seawater in "restricted lakes".

Characteristically, the total evaporite precipitation occurs in a very short time, even in very large areas, causing few benthic biozones (Schreiber et al., 2007). In the Santos Basin, Dias et al. (1994) and Davison (2007) apud Karner & Gamboa (2007) indicate a maximum age of deposition of about 113Ma. This estimate is in agreement with the pre-salt and post-salt sediments at the proximal portion of the basin, dating somewhere between 120Ma and 110Ma (Freitas, 2006). All authors, however, call the attention for the poor accuracy of the ages. Even with

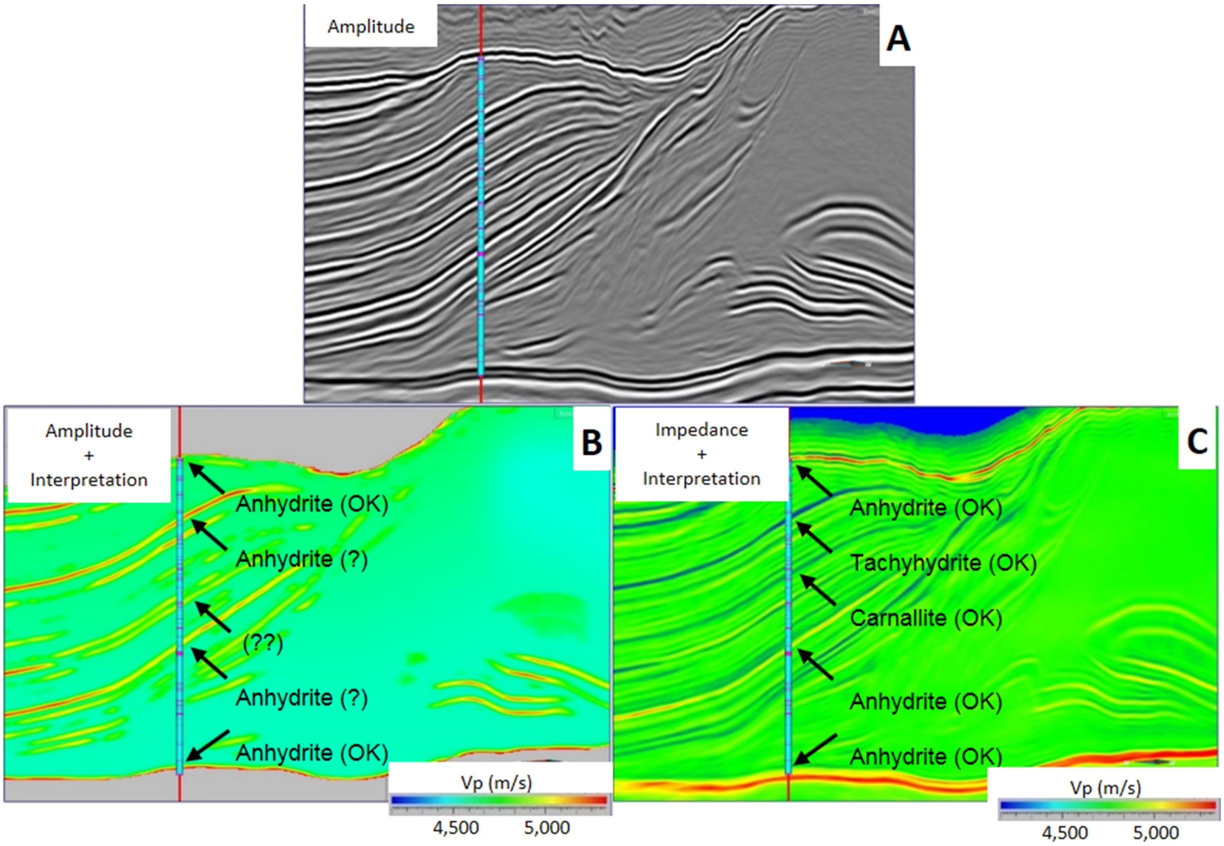


**Figure 3** – Possible interpretations of salt heterogeneities. A - Amplitude response – the main input for the study; B - Salt heterogeneities interpretation based on amplitude response only. Some anhydrite layers are confirmed, but few doubts on the interpretation still remain; C - Salt heterogeneities interpretation based on impedance response. Observe the better interpretation in terms of both, resolution and lithotypes, honoring the well information. Adapted from Gobatto et al. (2016).

this relatively short deposition interval, the evaporitic thickness in the basin depocenter is over 2,000 m, confirming the high depositional rates. The salt movement mechanism, specifically for the halite, results in various structures such as salt pillows, domes, walls, rafts, growth faults, etc. The vertical movement is attributed to the Rayleigh-Taylor (R-T) instability, as described by Lachmann (1910) and Arrhenius (1913) both referenced in Dooley et al. (2015). Ge et al. (1997) discuss the effect of the sedimentary overload over an evaporitic section above an irregular basement. According to these authors, the sediment weight forces the salt to come up on pillows or anticlines. With the overload continuity, these structures were transformed into domes and salt walls. Guerra & Underhill (2012) defend the hypothesis where the gravity force and pressure differences move all the evaporites together from high pressure to lower pressure areas in the Santos Basin.

The seismic interpretation and numerical models provide better understanding of the halokinectic effects present in the Santos Basin. Several authors advocate the division of Santos Basin into “Halokinectic Provinces” (Demercian et al., 1993; Cobbold et al., 1995; Demercian, 1996; Szatmari et al., 1996; Ge et al., 1997; Gemmer et al., 2004; Ings et al., 2004; Mohriak et al., 2008; Guerra & Szatmari, 2009; Davison et al., 2012; Jackson et al., 2014). Gamboa et al. (2009) mention the existing of four major saline cycles within the Aptian Section in Santos Basin: (1) a basal thick package of halite; (2) a composite package of anhydrite at the base followed by halite and other salt compounds; (3) a slender halite package and finally (4) thinner package of the same salts described in (2). Freitas (2006) describes more than a dozen smaller cycles composing the larger cycles previously described. Each individual cycles being composed by a succession of anhydrite, halite, complex salts, halite and finally anhydrite. The complex soluble salts may not be represented in every described cycles.

Jackson et al. (2015) emphasize the existence of enigmatic structures within the evaporitic section in Santos Basin, probably generated by vertical compressive forces (Dooley et al., 2015). The great salt lithotypes variability in the evaporitic section, suggests that each one has different a behavior. Some are classically mobile, other more plastic and other more ruptile. Poiate Jr (2012) consulting several authors mentioned the main evaporites deposits in sedimentary basins according to their chemical composition (Table 1).

**Table 1** – Chemical composition of major evaporitic minerals and their separation in specific groups according to Poiate Jr (2012).

| Group | Mineral | Composition |
|---|---|---|
| **Carbonates** | Calcite | $CaCO_3$ |
| | Magnesite | $MgCO_3$ |
| | Dolomite | $CaMg(CO_3)_2$ |
| | Trona | $Na3H(CO_3)_2 \cdot 2(H_2O)$ |
| **Sulfates** | Gypsum | $CaSO_4 \cdot 2(H_2O)$ |
| | Anhydrite | $CaSO_4$ |
| | Kieserite | $MgSO_4 \cdot H_2O$ |
| | Langbeinite | $K_2Mg_2(SO_4)_3$ |
| | Polyhalite | $K_2Ca_2Mg(SO_4)_4 \cdot 6(H_2O)$ |
| **Chlorides** | Halite | NaCl |
| | Sylvite | KCl |
| | Kainite | $MgSO_4 \cdot KCl \cdot 3(H_2O)$ |
| | Bischofite | $MgCl_2 \cdot 6(H_2O)$ |
| | Carnallite | $KMgCl_3 \cdot 6(H_2O)$ |
| | Tachyhydrite | $CaMg_2Cl_6 \cdot 12(H_2O)$ |

Maul et al. (2018b) based on the methodology proposed by Amaral et al. (2015), compiled the information from more than 200 wells in Santos Basin, showing the halite predominance, over 80% of occurrence. The other 20% are anyhydrite, gypsum, tachyhydrite, carnallite, and sylvite. Other studies considered halite the background mineral in this section representing 75-90% of occurrences (Yamamoto et al., 2016; Gobatto et al., 2016). Based on this work, Maul et al. (2018b) organized the salt types into three specific groups: Low Velocity Salts (LVS), composed by sylvite, carnallite and tachyhydrite, representing something between 5-10% of occurrence; halite (background), representing nearly 80%, and; High Velocity Salts (HVS) represented basically by anhydrite and few gypsum occurrences, corresponding to 10-20% of mineral occurrences.

These percentages are important when considering average interval velocity and density calculations as well as any other derived elastic property for the evaporitic section. These percentages are in accordance to the literature results (Fiduk & Rowan, 2012; Jackson et al., 2014, 2015). Table 2 presents the salt mineral groups, and respective density and interval velocities, comparing the values published by Jones & Davison (2014) with the average values compiled by Maul et al. (2018b) for more than 200 wells in Santos Basin.

Jones & Davison (2014) described the seismic reflectivity response of salt sections and indicated a specific domain nominated "Complex Appearance within Body Salt", in domed regions, where intense salt deformation result in non-reflective evaporites. According to Jackson et al. (2015), it is possible to distinguish four seismic facies inside the salt section as described in Table 3.

**Table 2** – Mineral groups and respective properties. Comparison of density and interval velocity values reported by Jones & Davison (2014), with the average values compiled by Maul et al. (2018b) covering more than 200 well in Santos Basin. Low Velocity Salts (LVS), Halite (Background) and High Velocity Salts (HVS).

| Group | Mineral | Composition | Adapted Jones & Davison (2014) | | Adapted Maul et al. (2018b) | |
|---|---|---|---|---|---|---|
| | | | Density (g/cm$^3$) | Interval velocity (m/s) | Density (g/cm$^3$) | Interval velocity (m/s) |
| **LVS** | Tachyhydrite | $CaMg_2Cl_6 \cdot 12(H_2O)$ | 1.66 | 3500 | 1.57 | 3300 |
| | Carnallite | $KMgCl_3 \cdot 6(H_2O)$ | 1.60 | 3900 | 1.66 | 3910 |
| | Sylvite | KCl | 1.99 | 4110 | 1.86 | 3910 |
| **Background** | Halite | NaCl | 2.20 | 4500 | 2.10 | 4550 |
| **HVS** | Gypsum | $CaSO_4 \cdot 2(H_2O)$ | 2.30 | 5700 | 2.35 | 5810 |
| | Anhydrite | $CaSO_4$ | 2.90 | 6500 | 2.98 | 6100 |

**Table 3** – Seismic facies in relation to the halite content within the salt sections according to Jackson et al. (2015).

| Code | Characteristics | Halite-Percentage |
|---|---|---|
| **A1** | Chaotic to weakly stratified, poorly reflective, halite rich | 77-98 |
| **A2** | Strongly reflective, high amplitude, less halite | 67-86 |
| **A3** | Poorly reflective, more halite | 69-94 |
| **A4** | Strongly reflective, less halite, containing carnallite | 31-94 |

## PROPOSED CLASSIFICATION OF THE STRATIFIED SALT DOMAINS

From the combination of these two approaches (Jones & Davison, 2014; Jackson et al., 2015) it is possible to propose a new classification based on seismic facies and salt composition as follows:

### Without Stratification Domain (WSD)

This domain is characterized by the absence of seismic reflections (which can be understood as absent stratification or a mixture of evaporites). In this domain, the halite predominates with a mixture of small amounts of mobile salts including sylvite, carnallite, tachyhydrite and other less common salts. The halite content exceeds 95%, and the mobile salts account for less than 5%.

### Evident Stratification Domain (ESD)

This domain is represented by the strongest stratification, with presence of all kinds of evaporites. The halite is broadly present, however, other evaporitic groups (HVS and LVS) have important occurrence. In this domain, the salt thickness is the smallest depending on the overload (commonly carbonates on Santos Basin). The overload promotes expulsion of the most mobile salts such as halite, sylvite, carnallite and tachyhydrite, increasing the HVS proportion in these regions, while the halite decreases to about 70%.

### Random Stratification Domain (RSD)

A relatively well identified domain shows erratic stratification originated under deformation mobile salt movements. The salt proportions are erratic. The folded salt layers could even be present many times within the same evaporitic level. However, in wells the halite proportion reaches more than 85%.

### Hidden Stratification Domain (HSD)

In the HSD domain, the seismic response is "hidden", due to seismic resolution, incidence angle and/or mixing of minerals. Salt groups from the "WSD" domain could also be present within the HSD.

Although the WSD, ESD and RSD domains are challenging for any E&P activity, they are relatively simple to identify on seismic images, especially those coming from optimized parametrization of acquisitions followed by appropriate seismic processing techniques. Contrarily the seismic interpretation is unclear and difficult in the HSD domain. Figure 4 illustrates the distribution of the proposed domains on seismic data, considering the presence or absence of stratification within the salt section.

## SALT INFLUENCE OVER SEISMIC MODELS – SHORT REVIEW

The quality of seismic images depends on the acquisition parametrization as well as the processing strategy, especially in terms of the applied migration process (Yilmaz, 2001). This same author has emphasized that considering the structural complexity when building the seismic image has a tremendous influence in reproducing a model faithfully. According to Ritter (2011), the main seismic migration goals are the correct positioning of seismic reflectors (vertical and horizontal) and mainly the correspondence between the reflection amplitudes and the reflection coefficient by themselves. The author also comments that the migration process requires strong knowledge of the velocity field, which is often estimated from seismic data by itself Jones & Davison (2013, 2014) cite various difficulties for imaging over evaporitic bodies such as the flanks, the layer interfaces and the overlying layer. However, they do not mention in an explicit way existing stratifications inherent issues, on which we have our considerations.

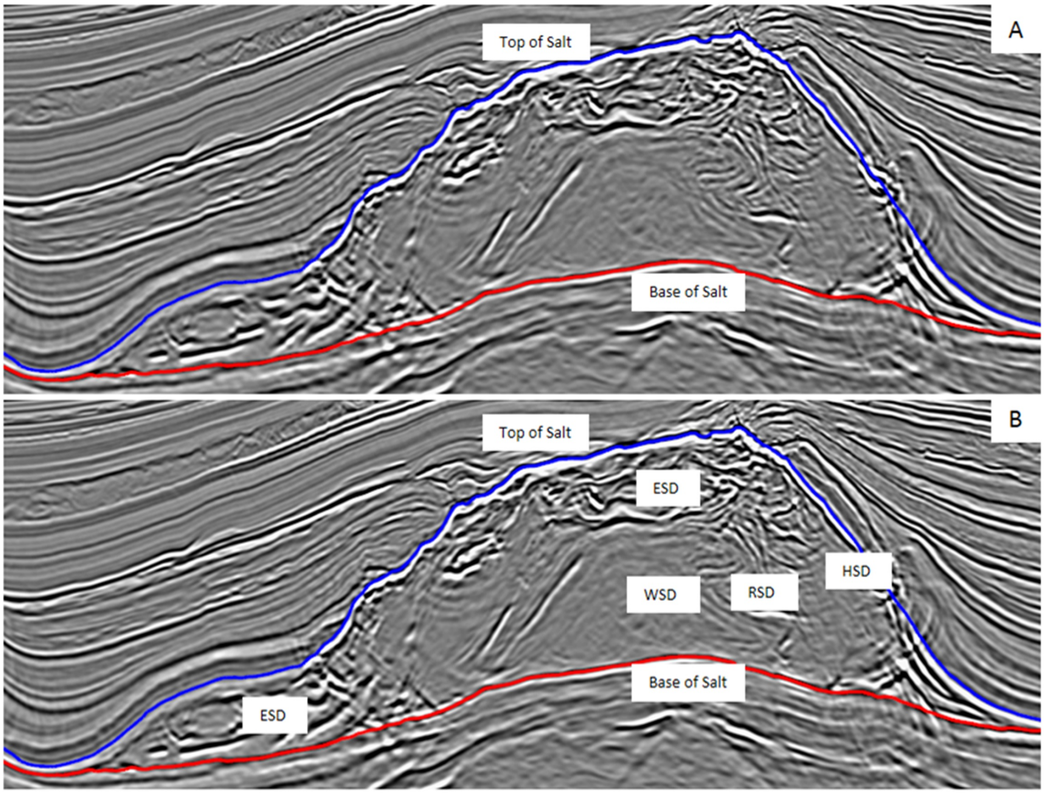


**Figure 4** – Examples of seismic interpretation: "A" without salt domains:"B" including the salt domains; WSD – Without Stratification Domain; ESD – Evident Stratification Domain; RSD – Random Stratification Domain; HSD – "Hidden" Stratification Domain.

Therefore, to improve the seismic image quality over salt layers, sophisticated seismic data processing algorithms are required, especially with regard to the migration method (Fonseca et al., 2018; Maul et al., 2018a). Falcão (2017) illustrates, using a theoretical model, how a plan and horizontal target below the base of the salt is influenced by the salt stratification during the migration process. The results demonstrated that only a stratified salt velocity model, applied during the seismic migration, reproduced the initial target. In areas of complex geology, under the evaporitic section, the application of Reverse Time Migration (RTM) is increasing. This algorithm uses the full wave equation without any asymptotic approximation, therefore not showing limitations due to the structural complexity (dipping layers, lateral velocity variations). Regardless of the correct velocity model applied to the evaporitic section, the contrast between lithology types eventually generates stratifications or similar seismic interfaces due to the convolutional process.

Meneguim et al. (2015) illustrate that robust depth scenarios is also possible when using the stratification information inside the salt section. Gobatto et al. (2016) followed by Fonseca et al. (2018) and Maul et al. (2018a) applied interval velocity models for the evaporitic section, considering the existing stratification, resulting in better gathers alignment during move-out correction. It provides smaller computational efforts when updating velocity models through tomography, as well as assisting Full-Waveform Inversion (FWI) before updating the final velocity model to perform the RTM process.

## STRATIFIED SALT MODEL APPLICATIONS

The obtained results under the stratification insertion methodologies serve as inputs for different disciplines, such as seismic studies as well as geomechanical simulation and operational safety when drilling new wells. We present and discuss some application examples.

### Seismic Illumination

The objective of seismic illumination studies is to illustrate a seismic wave response in a given target. In the exploration and production oil industry regarding seismic studies, several solutions and some examples illustrate the results from ray tracing as well as from simulated amplitude (Laurain et al., 2004a,b). The illumination studies are always models. For that reason, they only generate simplified results. It is an output depending on impedance, interval velocity and density as inputs. The ray tracing has a strong impact on the response, since this technique considers the smoothed interfaces (Pratt et al., 1996). This is not the case for the evaporitic section of Santos Basin, where stratifications are present and some of them are deformed.

As an example for seismic acquisition, we present the instantaneous amplitude map computed over the target of interest to compare with the illumination outputs. After this, taking the available processing velocity model we suggested a ray tracing illumination study. To complement the analysis an amplitude simulation study was performed considering the recovered amplitude energy at any point. In order to evaluate the results a new model (incorporating salt stratification using the amplitude response to generate the stratification inside the salt section) was generated, using the same previous acquisition parameters. Figure 5 presents the results.

We observe in Figure 5 that the amplitude responses observed in ”A” are not present in the simulated amplitude responses in “B”. This happened because the processing velocity model does not reproduce the existing geology above the target (i.e.: the existing salt stratifications). On Figure 5 ”C”, using the stratified velocity model, most of the amplitude features observed in “A” are present. The details observed in ”A” missing in ”C” result from the simplifications required for the ray trace solution.

Maul et al. (2015) suggest a methodology to control the target amplitude response for reservoir properties extrapolation. Knowing the energy at any given point from the migrated seismic data, the authors verified how confident was the amplitude response to use as external drift for well property extrapolation. The authors demonstrate how to generate uncertainty illumination maps (hit-count maps) despite not knowing the real salt velocity model. They also discuss how the overburden model could influence the amplitude responses in a given target. Jardim et al. (2015), Falcão et al. (2016) and González et al. (2018) later supported these results. Figure 6 illustrates the obtained results in a particular project in Santos Basin.

A greater qualitative correlation between the real extracted amplitude’s map on the target of interest “A” with the salt stratified model “D” is observed figure 6. The results are comparable to that presented in figure 5. Subsequently, a quantitative uncertainty analysis regarding the amplitude response, assuming various salt velocity models was performed (Maul et al., 2015). Different models return similar responses in terms of hit-counts where the overburden do not influence the results.

Figure 7 illustrates the combination of each two maps in order to get maps of accumulated variations between them. The energy responses inside the black ellipse in fig 7A have more similarity, in other words, less variation when comparing any two given models. This approach was performed using any two-velocity models and the cumulative difference map is presented (Fig. 7B). The values represent the response confidence degree. The normalized values represent how velocity-model dependent is the response. This information is useful for a property distribution trend variable analysis.

## Seismic Processing

The best seismic images are obtained after a combination of proper acquisition parameters; appropriate seismic processing strategies, particularly regarding migration, and the best possible velocity model for any data. As widely discussed, the evaporitic section should not be considered simple or homogeneous.

Improvements have been observed when considering stratification regardless of the seismic migration method, such as RTM. Even lighter computational methodologies (e.g. Kirchhoff) also get benefits when considering the stratifications applying a prior smooth model velocity (Falcão, 2017). The background velocity, when considering the salt stratification as primary information, has shown to be very efficient when searching for better “gathers alignments” during the Normal Move-Out (NMO) or Dip Move-Out (DMO) processing operations. DMO is commonly applied for environments that are more complex. As a direct consequence, this result in lesser computational effort (Gobatto et al., 2016; Fonseca et al., 2017, 2018; Maul et al., 2018a,b). Figure 8 illustrates the gather alignment using a salt stratified velocity model.

Adequate initial velocity models also provide better tomographic model update assisting in the gathers aligning process and consequently better seismic images (Pombo et al., 2017). On this aspect, the salt stratification serves at least as a boundary condition for tomographic updating providing better convergences and minimizing the computational effort. Guo & Fagin (2002) emphasize the need to incorporate reasonable geological knowledge into any velocity modelling workflow. The method presented by Maul et al. (2015) brings the geological features to velocity model in the evaporitic section, calibrating it using the well information. Figure 9 shows the overlap of the velocity models and seismic image, exemplifying the coincidence

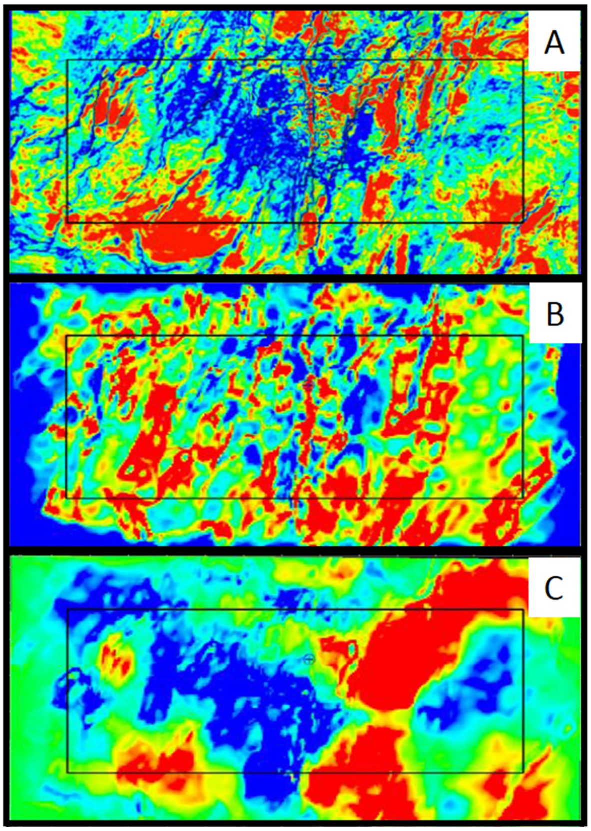


**Figure 5** – Illumination study results based on the ray trace, showing the amplitude response simulation for different salt models. A - Instantaneous amplitude response extracted from the migrated data over the horizon of interest; B - Simulated amplitude response computed after a ray trace illumination study considering the existing processing velocity model as input, over the same horizon of interest; C - Simulated amplitude response computed after a ray trace illumination study considering the stratified velocity model as input over the same horizon of interest. Images kindly provided by the Geophysicists Rejhane Santos, Roberto Dias & Rodrigo Link (2014).

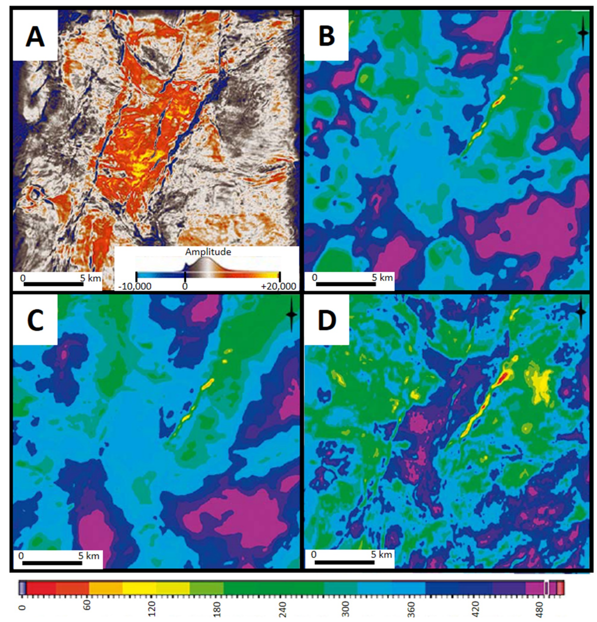


**Figure 6** – Hit-map studies obtained from seismic acquisition simulations considering different velocity models. The more hits at any given point (x,y) the more reliable is the original amplitude response. A - Instantaneous seismic amplitude response extracted on the horizon of interest; B - Point count map (hit-count) in specific targets (x,y) using the seismic processing model as input; C - Point count map (hit-count) in specific targets (x,y) using a constant velocity model for the salt (4,500 m/s) as input; D - Point count map (hit-count) in specific targets (x,y) using the stratified salt velocity model. Adapted from Maul et al. (2015).

of velocity variations guided by the amplitude response in the stratified model (Fig. 9C).

The velocity model update applying the FWI technique has become quite usual even for processing data not containing enough far offset information. One of the major pre-requisites for the FWI application is to provide an almost precise initial velocity model compatible with the final velocity model in terms of geology. Once again, in this case, the generation of geological velocity model considering seismic attributes as guide shows very efficiency results.

The anisotropy consideration when building velocity models in order to generate more realistic seismic images have become increasingly obvious (Cogan et al., 2011; Zdraveva et al., 2011; Cooke et al., 2012). Anisotropic aspects involved in velocity model building depart from well information when comparing expected and observed results. Raymer et al. (1999) and Raymer et al. (2000) indicated that the anisotropy in salt bodies observed in wells could be over than 7% in the preferred direction (parallel to the depositional axis, if there is one). The anisotropic aspect is not predominant in halite and other mobile salts but it exists. The rigidity character of ruptile salts, such as anhydrite, becomes more important, especially following the preferred directions imposed by the stratifications. Thus, the heterogeneous and consistent velocity model presenting salt

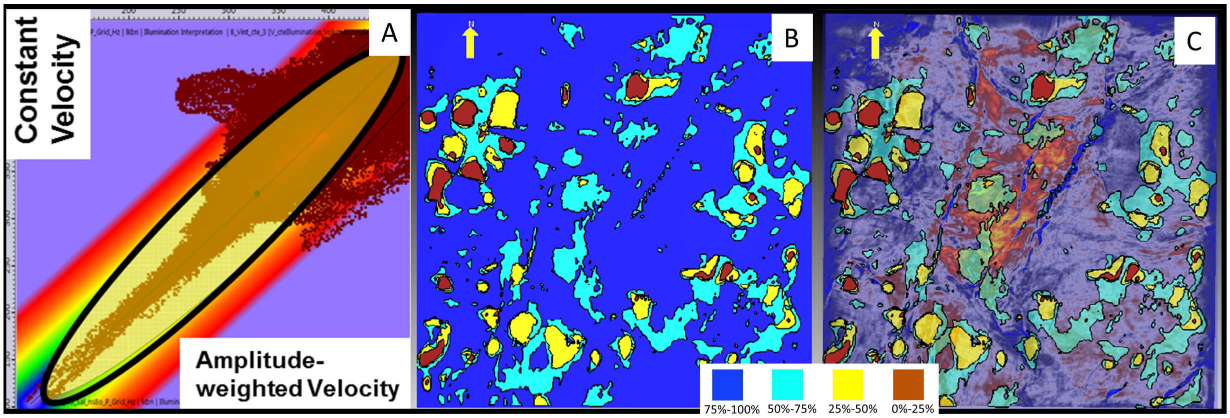


**Figure 7** – Amplitude response uncertainty analysis as a similarity response function considering velocity salt model variation calculated on the horizon of interest. A - Cross-Plot between any two models. The central area (black ellipse) represents greater similarity when comparing two different models; B - Sum of the differences between any two maps. The blue shades represent the greater similarity, independent of the used model; the other colors represent the decreasing similarities and consequently the lower confidence levels; C - The same similarity map "B" overlapping the target extracted amplitude response, filtering out the dark blue where response confidence is higher. Adapted from Maul et al. (2015).

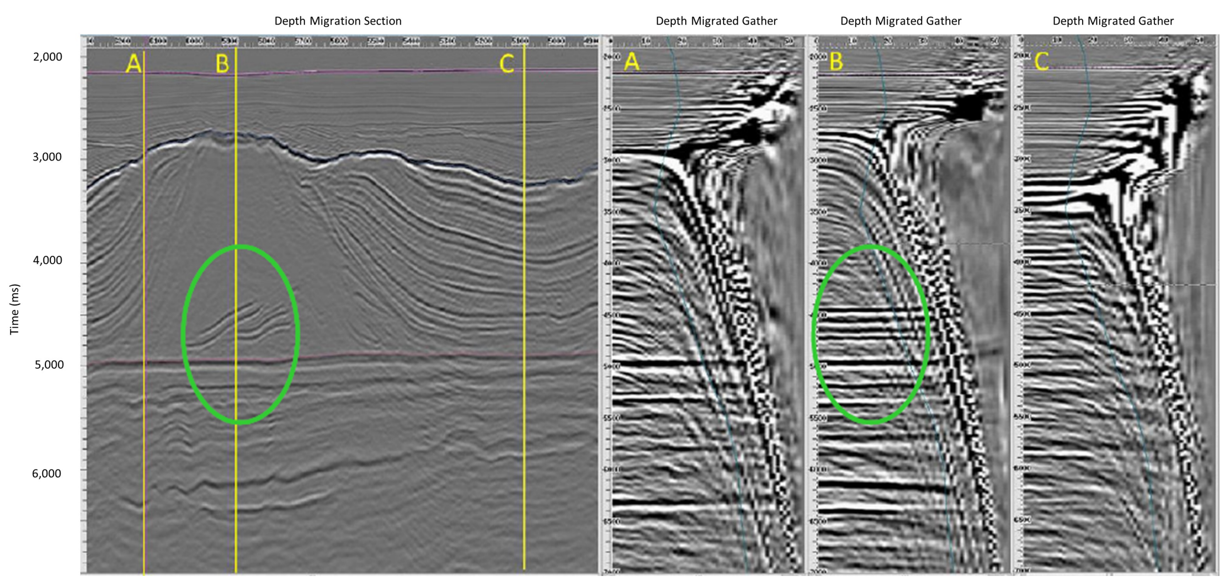


**Figure 8** – Seismic section illustrating the position of gather panels (left). The reflectors in the deformed strata in panel "B" (green ellipse) are perfectly aligned after application of stratified velocity model. Adapted from Gobatto et al. (2016).

stratifications, even without good resolution, is an important input to the anisotropy analysis. At least, the stratifications help controlling the anisotropy extrapolation of information observed in wells.

The previously described aspects (velocity model update by FWI and anisotropy, tomographic update and gathers alignment) aim to the final goal: the seismic migration and its deliverable images. Considering the feasibility and computational effort, the RTM migration is considered the most suitable for complex geology projects, such are the salt bodies, regarding seismic migrations for the pre-salt occurrences. RTM requires a refined velocity model, seeking to reflect the existing media heterogeneities. In this way velocity models incorporating stratification, anisotropy, FWI, tomographic inversion and, RTM with upper frequency bounds (up to 45 Hz), are the best approaches to consider.

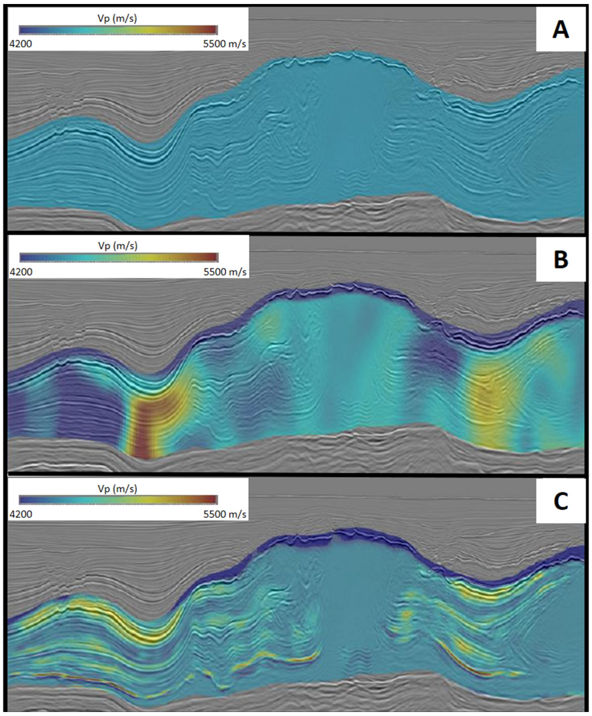


**Figure 9** – Salt interval seismic section with different overlapped velocity models. A - Constant velocity model (4,500 m/s); B - Tomographic velocity model updated over the constant velocity model; C - Stratified velocity model adopting the methodology described in this work. Note the notable coincidence between velocity variations guided by the amplitude response in the model ”C”, while this does not occur in the models “A” and ”B”. The average interval values in both “B” and “C”, for each x and y position, are similar however, only in “C” the velocities follow the geological features. Adapted from Maul et al. (2015).

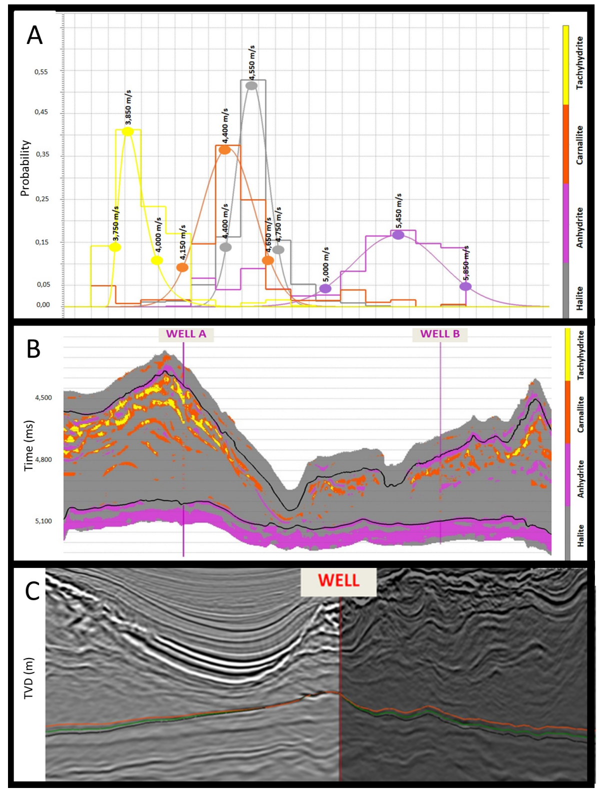


**Figure 10** – Depth positioning uncertainty analysis. A - Velocity variation for each mineral type emphasizing the average values and two standard deviations above and below (TQD–Tachyhydrite; CRN–Carnallite; AND–Anhydrite; HAL–Halite); B - Section illustrating the probability of occurrence of each mineral type at any position (x,y,z), in a time-section; C - Sections illustrating the horizons converted by the velocity models considering the probability velocity cube shown in ”B” and the mineral velocity values as described in ”A”. The green horizon shows the base scenario, the orange represents the lower velocities scenario and the blue represents the highest velocities scenario. Adapted from Meneguim et al. (2015).

## Uncertainty Analysis in Vertical Positioning

An obvious consequence of the stratification modeling is the vertical positioning variation of the target. Even considering simplified velocity models (almost constant) in stratified intervals, tomographic adapted, anisotropic criteria and FWI, always require well information for calibration. To extrapolate the information far from the well position, several works suggest a combination of wells (1D) with spatial information (2D or 3D) from interpreted horizons and velocity analysis, all together (Dubrule, 2003; Robein, 2003; Leron et al., 2003; Sandjivy et al., 2003; Bulhões et al., 2014; Ferreira et al., 2017; Pombo et al., 2017). Meneguim et al. (2015) created a routine, considering the stratification position, classifying the lithological type and assuming the average velocity value for each class. Additionally, the authors applied two standard deviations generating three horizon scenarios for reference (Fig. 10). The base scenario considered the average velocity, the deeper position considers two standard deviations above the average velocity and the shallower position considered two standard deviations below the average velocity. With this approach, the authors reported a 3% displacement gross variation, regarding rock volume, above the oil-water contact, compared to the base case.

## Operational Safety and Geomechanical Simulation Studies

Classically evaporites are low-viscosity, ductile and plastic minerals/rocks. They also present fluidity when subject to high tensions. Because of that, the deposits easily move and may generate large domes and important folds, representing one of the major challenges for drilling. Especially regarding drill imprisonment or even casing collapses, eventually resulting in complete well loss.

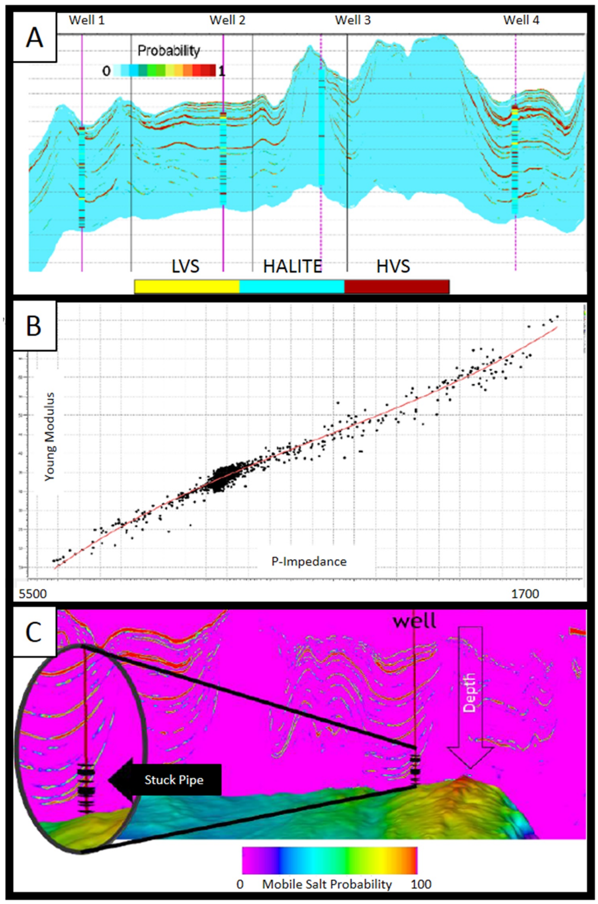


**Figure 11** – Example of property extraction from cross plots applied for the evaluation of operational safety when drilling well. A - Cube of most probable facies generated from Bayesian's classification performed over the salt acoustic impedance cube. LVS – Low Velocity Salts; HALITE – Halite; HVS – High Velocity Salts; B - Cross-plot illustrating how to generate one property from another using well information; C - Example of imprisonments events during drilling and its effective correspondence with the seismic facies predictions. Adapted from Teixeira et al. (2017).

These aspects are more important for halite and mobile salts (sylvite, carnallite, tachyhydrite) and less critical for anhydrite, since it presents greater stability (Costa & Poiate Jr, 2009). For geomechanical simulation studies, the sealing rocks require special attention. In the pre-salt reservoirs, evaporites are the seals. The first geomechanical simulations for these reservoirs considered the evaporitic seal a homogeneous layer, composed by halite. In some cases, the studies also considered a thin layer (around 15 meters) of anhydrite at the base of this "homogeneous" section. In the current methodology, we used the stratified models and, imposed laboratory property values over the established lithotypes: density, elasticity modulus, Poisson ratio, stiffness, friction angle, etc. creating a better geomechanical model in terms of cape rock. Toríbio et al. (2017) confirmed the utility in be considering this methodology in order to generate geomechanical properties. Complementing, cross-plot analysis and the related equations generated compatible property values required to these models. Teixeira et al. (2017) and Teixeira et al. (2018) illustrated how acoustic inversion in salt section plus Bayesian facies classification, combined with properties correlation using well logs, allowed more robust models in terms of elastic properties (Fig. 11).

## CONCLUSION

The results presented in this review indicate that considering the stratification inside evaporitic sections is mandatory for diverse E&P applications. It increases safety during drilling and can enhance geomechanical models of cape rocks, better predicting the production and injection rates.

Using the seismic amplitude or any instantaneous attributes to incorporate stratification inside evaporitic sections is an effective methodology even where the seismic data resolution is not enough or the seismic information has lower quality.

Stratified seismic models based on inversion data help to solve false amplitude interpretations due to the convolutional effect. It helps effective well information calibration. In the absence of inversion data, at least deconvolution, followed by a derivative and phase rotation is recommended.

As expected, these processes combined enhance the frequency, increasing the resolution of layers during the inversion process, even without well calibration.

The seismic facies study complements the acoustic inversion. It offers the possibility to create probabilistic scenarios for the occurrence of each lithotype at any single point, helping to increase the resolution.

In Santos Basin, after compiling information for more than 200 wells, we conclude that around 80% of lithotypes are, basically, halite, 10-20% high velocity salts-HVS (anhydrite and gypsum) and 5-10% low velocity salts-LVS (sylvite, carnallite and tachyhydrite). The seismic response of the "mineral groups" halite, LVS and HVS is effective and adequate, considering the seismic frequencies in Santos and Campos Basins, giving a thickness resolution about 30-50 m. The thickest salt regions have greater prevalence of halite and low velocity salts. In thinner salt regions, the presence of high velocity salts is predominant. The overload above the salt drives the expulsion of the more mobile material (halite, sylvite, carnallite and tachyhydrite) increasing the proportion of high velocity salts (anhydrite and gypsum).

The proposed classification in terms of stratification pattern (WSD, ESD, RSD and HSD) is also another approach to minimize the risk when trying to solve seismic image problems. Stratified velocity models provide better illumination studies for both: seismic acquisition design and to evaluate amplitude quality response. During seismic processing, they provide the means to greatly improve tomographic studies, FWI updating, and gather alignments resulting in better seismic images. The methodology can also be used to evaluate depth-positioning uncertainties.

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Anexo A2:

***Salt Velocity Modeling Uncertainties and Variabilities: Implication for Pre-Salt Projects in the Santos Basin, Brazil***

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# EVAPORITIC VELOCITY MODELING UNCERTAINTIES AND VARIABILITIES: IMPLICATIONS FOR PRE-SALT PROJECTS IN THE SANTOS BASIN, BRAZIL

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**ABSTRACT.** Correct representation of the spatial distribution of physical and chemical properties of the evaporitic section is of great importance for development of pre-salt section reservoirs. In the offshore Santos Basin, SE Brazil, an increasing amount of high quality seismic, well-logs, and production data are available. The initial conceptual model of the evaporitic section, assuming inhomogeneous behaviors in terms of mineral composition, acoustic and elastic properties, had not been well documented yet. Therefore, this interval remains considered as mainly composed by halite, being slightly modified to include a few heterogeneities when needed. A simple way to represent those heterogeneities is by combining seismic attributes and well-log information, which are usually not available for the whole evaporitic section. To mitigate this problem, drill cuttings description can be used. In this paper, we describe some of the uncertainties related to the analysis of 1D information from wells, as well as a possible alternative to represent the data variability where information is missing. The proposed methodology includes generating a detailed evaporitic section model (3D), including properties and their related uncertainties. This model can be used to improve seismic imaging, depth positioning forecast and reservoir property values distribution.

**Keywords:** evaporitic section, data analysis, heterogeneities, property value, uncertainties.

**RESUMO.** Representar corretamente a distribuição espacial das propriedades físicas e químicas da seção evaporítica é muito importante no desenvolvimento dos reservatórios do pré-sal. Na Bacia *offshore* de Santos, região SE do Brasil, grande quantidade de dados sísmicos de alta qualidade, perfis de poço, dados de produção estão disponíveis. O modelo conceitual desta seção, assumindo o mesmo como não homogêneo, em termos de mineralogia e propriedades acústicas e elásticas, ainda não é bem documentado. Assim, este intervalo permanece sendo considerado como, principalmente, composto por halita e, localmente, modificado para incluir algumas heterogeneidades, quando necessário. Um caminho simples para representar estas heterogeneidades é combinar atributos sísmicos e informações dos perfis de poços que, usualmente, não estão disponíveis para toda a seção. Para mitigar este problema, descrição de amostras de calhas pode ser utilizada. Neste artigo, nós descreveremos algumas das incertezas relacionadas a esta análise 1D, oriundas das informações dos poços, assim como uma possível alternativa para representar as variabilidades destes dados inexistentes. A metodologia proposta inclui a geração de um modelo (3D) detalhado da seção evaporítica, incluindo suas propriedades e as incertezas relacionadas. Este modelo pode ser utilizado para melhorar as imagens sísmicas, com previsões de profundidade mais acuradas, e a distribuição de valores de propriedades de reservatórios.

**Palavras-chave:** seção evaporítica, análise de dados, heterogeneidades, valores de propriedades, incertezas.

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## INTRODUCTION

Successful implementation of pre-salt projects in Brazilian ultra-deep waters, where huge capital investments are required, is highly dependent on the robustness and confidence of the available reservoir models. The first discovery of these large hydrocarbon reserves along the southeastern coast of Brazil happened in 2006, and represented a new chapter in global petroleum history. Since then, Petrobras has been facing major multidisciplinary technological challenges, sponsoring massive investments in research and development, working in collaboration with partners, suppliers, universities, and research centers, to economically explore these reserves in a sustainable way.

The construction of reliable velocity models, according to the known geology, enables the generation of seismic images that better represent the subsurface, both in terms of structural positioning and accurate seismic response. Jones & Davison (2014) report the challenge of seismic imaging close to (or inside) salt bodies, due to the high velocity contrasts observed in those areas. Operational safety and drilling hazards are other issues widely discussed in the literature of field development when salt bodies are present.

Most halokinetic models used to reconstruct the basin's structural styles consider the salt section as almost homogeneous, with predominance of halite (Demercian et al., 1993; Ings et al., 2004; Guerra & Szatmari, 2009; Guerra & Underhill, 2012). The concept of salt flooding is a common approach in seismic processing, and involves the assignment of a constant velocity to the evaporitic section prior to the tomographic inversion process to update it (Guo & Fagin, 2002; Zdraveva et al., 2011). Ji et al. (2011) defend the idea that heterogeneous salt velocity models improve the seismic imaging. Cornelius & Castagna (2018), using well-logs and drill cuttings, confirm that velocity variations exist, and that they must be incorporated into the models. The same concept for the evaporitic section has been widely mentioned in several salt stratifications studies (Maul et al., 2015; Amaral et al., 2015; Meneguim et al., 2015; Maul et al., 2018b, 2019; Teixeira & Lupinacci, 2019).

Regarding these heterogeneities, Schreiber et al. (2007) emphasize that evaporites precipitate due to brine evaporation, forming layers according to their solubility rates, with varying mineral compositions. These authors also mention that comprehension of the water supply to the brines, which breaks the expected salt precipitation order, represents the main difficulty when modeling this sort of mineral deposit. The mobility of most evaporites also imposes difficulties to quantify the original mineral occurrence from present day information, either using wells or outcrop descriptions. Based on well data, Freitas (2006) identified more than a dozen evaporitic cycles in the Santos Basin, whereas Gamboa et al. (2009) mentioned the presence of 3 or 4 major evaporitic cycles when inspecting seismic data response.

The enigmatic structures presented in Jackson et al. (2015), which are nothing more than observations of folded strata within the evaporitic section, are clear evidences of a heterogeneous behavior. Costa & Poiate Jr (2009), inspecting outcrops and salt mines, confirmed that there are many different minerals inside the evaporitic sections: halite, anhydrite, gypsum, carnallite, tachyhydrite, and sylvite, just to name a few. Aiming at preventing drilling hazards, these authors recommended a detailed identification of the sequence, their mineral compositions, and their behavior under drilling. It is therefore reasonable to assume that the evaporitic section must be considered as heterogeneous instead of being represented by the halite behavior only.

Based on well information, the studies compilation presented by Maul et al. (2018b) proposed clustering the evaporitic minerals into three main groups, observing their compressional velocity. These groups are: (i) the Low Velocity Salts/Evaporites group (LVS), mainly composed by carnallite, tachyhydrite, sylvite and other mobile salts; which present compressional velocities lower than the represented by the halite mineral (4,500 m/s); (ii) the Halite group, usually abundant and considered as the background group; represented by the compressional velocity of about 4,500 m/s; and (iii) the High Velocity Salts/Evaporites group (HVS), basically composed by anhydrite and gypsum, having compressional velocities higher than 4,500 m/s. Intrusive rocks, when found, due to the same velocity behavior as HVS minerals, were also considered inside this group – an approach that has been adopted in many case studies (Meneguim et al., 2015; González et al., 2016; Gobatto et al., 2016; Falcão et al., 2016; Barros et al., 2017; Fonseca et al., 2017, 2018; Teixeira et al., 2018; Maul et al., 2018a,b, 2019; Dias et al., 2019). Fonseca et al. (2017) also observed carbonate and siliciclastic occurrences within the salt section, and suggested to group them within the Halite group, as their velocity behaviors are more similar to this background's group. These rocks, however, lack representativeness.

The workflow proposed by Maul et al. (2016) and presented in González et al. (2016) uses drill cuttings descriptions to fill in gaps observed in the well-logs in the evaporitic section, and also to constrain the salt velocity modeling, as shown in Figure 1. Even in regions where well data are available, well-logs within the salt section are almost always incomplete, since evaporites are not the main target, and acquiring data in these sections is operationally challenging. To overcome this problem, Amaral et al. (2015) proposed to complete the well information with the described lithology from drill cuttings, a methodology that has been widely reproduced since then (Gobatto et al., 2016; Barros et al., 2017; González et al., 2018; Cornelius & Castagna, 2018; Fonseca et al., 2018; Teixeira et al., 2018; Maul et al., 2018a,b, 2019; Dias et al., 2019).

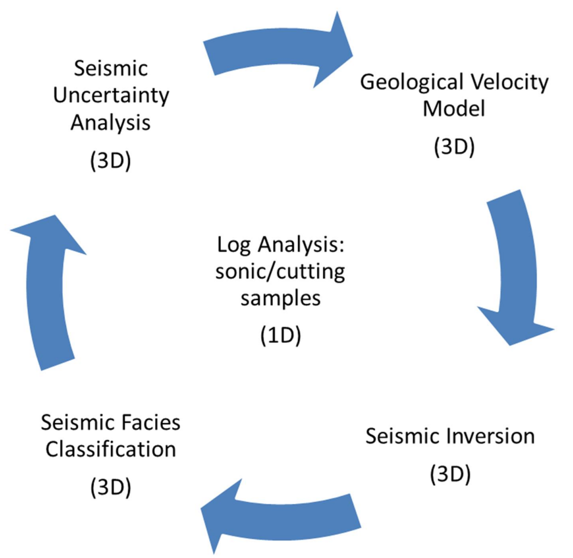


**Figure 1** – Proposed workflow to generate a more realistic geological seismic velocity model (adapted from Maul et al., 2016 in González et al., 2016).

This methodology, albeit effective, should be considered as a semi-quantitative approach, mainly due to inexact sample positioning, potential rock collapse during drilling, and inaccuracies in sample descriptions. These factors impose ambiguities in the estimations of rock properties. The distinction between lack of data, inaccuracy in their measurements, uncertainty associated with interpretation, and data variability are in complete agreement with the classic article presented by Begg et al. (2014).

Maul et al. (2018b) demonstrated the wide applications of a reliable geological evaporitic section model, when simultaneously combining seismic attributes and well-logs, such as better seismic imaging, uncertainty analysis, seismic illumination for acquisition design, etc. The authors demonstrated, using several projects, that stratifications insertion inside the evaporitic section is a key aspect to consider for any seismic purpose. Gobatto et al. (2016), Falcão (2017), Fonseca et al. (2018), Maul et al. (2018a), Dias et al. (2019) and Maul et al. (2019) compared the results obtained by using the proposed methodology for evaporitic velocity model building, in opposed to the ones from conventional velocity models, confirming the benefits of the stratification insertion for seismic imaging in several development and production pre-salt projects.

## STUDY AREA AND AVAILABLE DATA

The study area is inserted in the pre-salt province in the Santos and Campos Basins (Fig. 2). A pre-stack depth-migrated (PSDM) volume covering an area of approximately 200 km$^2$ is available, together with 14 wells with a broad suite of logs. The Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) has provided the data we used in this research. In this study, the wells were labeled with capital letters from A to N, and the official names can be found in Table 1. Maul et al. (2018a,c) showed, using almost 182 wells through 9 projects/fields in the Santos Basin, that the evaporitic section of these studied fields has many features in common, such as mineral percentages, mineral percentages x thickness, velocity ranges per mineral groups, etc.

**Table 1** – Correspondence between the well designation used in this study and the official names from ANP.

| This Study | ANP |
|---|---|
| A | 3-BRSA-788-SPS |
| B | 9-BRSA-1037-SPS |
| C | 8-SPH-23-SPS |
| D | 8-SPH-13-SPS |
| E | 7-SPH-14D-SPS |
| F | 7-SPH-8-SPS |
| G | 7-SPH-4D-SPS |
| H | 9-BRSA-928-SPS |
| I | 7-SPH-5-SPS |
| J | 9-BRSA-1043-SPS |
| K | 1-BRSA-594-SPS |
| L | 7-SPH-1-SPS |
| M | 7-SPH-2D-SPS |
| N | 3-BRSA-923A-SPS |

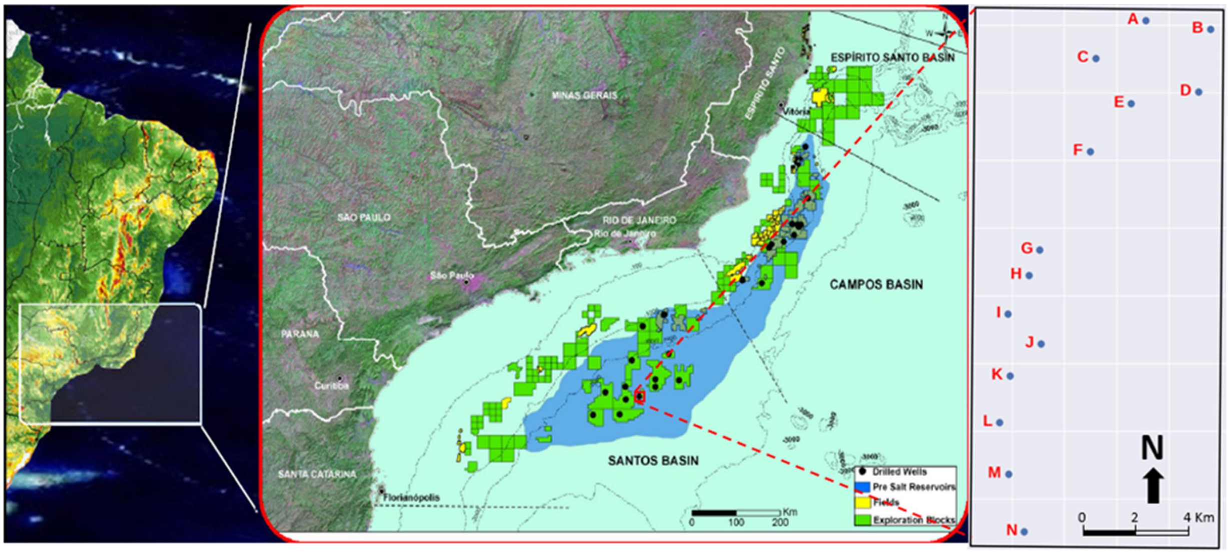


**Figure 2** – Location of study area (regional) and details of the available data. Blue shading is the area with hydrocarbon occurrences in the pre-salt province in the Santos and Campos Basins, totaling an area of approximately 350,000 km$^2$. Water column ranges 2,000 to 3,000 m. Adapted from: https://diariodopresal.files.wordpress.com/2010.

## PROPOSED METHODOLOGY

The main goals of this work are twofold: (1) identifying and characterizing the inherent uncertainties when dealing with the evaporitic section; and (2) assessing the property values from acquired logs, in order to build a 3D velocity model for the evaporitic interval.

Drill cuttings and well-logs were used to classify the entire evaporitic section into the three proposed groups: LVS, Halite and HVS. Almost every well which cross the evaporitic section presents a lack in the log-data. Each percentage per well is shown in Table 2.

Instead of using a simple standard velocity values, such as the halite velocity where the data were not acquired, the missing information (the rock/mineral/group) was stablished using the described lithologies from drilling cuttings, and a single velocity was imposed for each salt group, obtained from the variability/dispersion for each class and the velocity x salt thickness correlation. Therefore, the calculated velocity considering all of these assumptions seems to be more reliable.

## RESULTS, ANALYSIS AND DISCUSSIONS

After combining well-logs and drill cuttings, we obtain a complete lithology log for the evaporitic section, for all 14 wells (Fig. 3, for wells I to N). Figure 4 and Table 3 show the percentage distribution for each mineral.

**Table 2** – Percentage of registered log in the evaporitic section per well (14). Only a single well (K) has the entire evaporitic section logged.

| WELL NAME | REGISTERED LOG (%) | MISSING LOG (%) |
|---|---|---|
| A | 91.90 | 8.10 |
| B | 87.60 | 12.40 |
| C | 91.10 | 8.90 |
| D | 87.30 | 12.70 |
| E | 77.90 | 22.10 |
| F | 87.20 | 12.80 |
| G | 92.00 | 8.00 |
| H | 91.80 | 8.20 |
| I | 91.40 | 8.60 |
| J | 96.00 | 4.00 |
| K | 100.00 | 0.00 |
| L | 95.60 | 4.40 |
| M | 94.30 | 5.70 |
| N | 94.00 | 6.00 |
| **AVG** | **91.30** | **8.70** |

AVG = Average

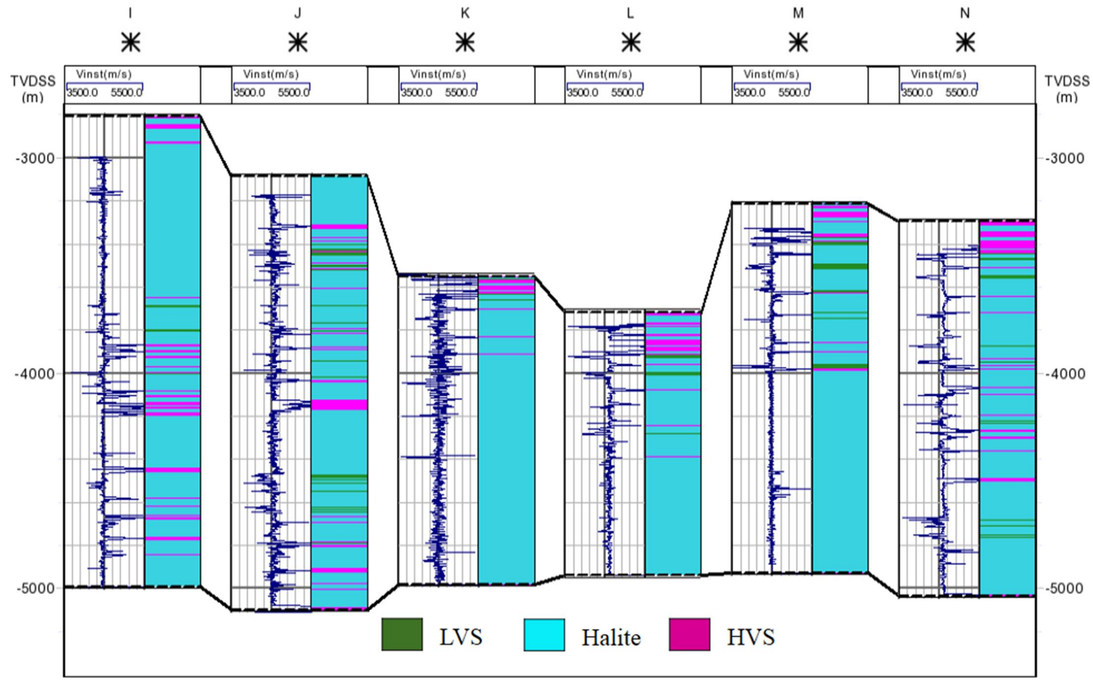


**Figure 3** – A piece of a "N-S" stratigraphic cross-section crossing wells from I to N, showing sonic logs (blue lines – left tracks) and lithology group interpretation (right tracks) for the evaporitic section.

**Table 3** – Fraction of mineral groups in the evaporitic section, considering registered logs and gap-filling from drill cuttings.

| WELL NAME | LVS LOG LITHOTYPE (%) | HALITE LOG LITHOTYPE (%) | HVS LOG LITHOTYPE (%) |
|---|---|---|---|
| A | 5.45 | 86.20 | 8.35 |
| B | 0.50 | 98.90 | 0.60 |
| C | 6.90 | 82.70 | 10.40 |
| D | 0.00 | 91.60 | 8.40 |
| E | 0.30 | 95.40 | 4.30 |
| F | 1.45 | 95.40 | 3.15 |
| G | 4.80 | 92.90 | 2.30 |
| H | 1.20 | 98.10 | 0.70 |
| I | 1.10 | 88.80 | 10.10 |
| J | 5.10 | 83.80 | 11.10 |
| K | 2.12 | 93.10 | 4.78 |
| L | 3.60 | 87.20 | 9.20 |
| M | 4.10 | 89.80 | 6.10 |
| N | 4.60 | 83.20 | 12.20 |
| **AVG** | **2.94** | **90.51** | **6.55** |

AVG = Average

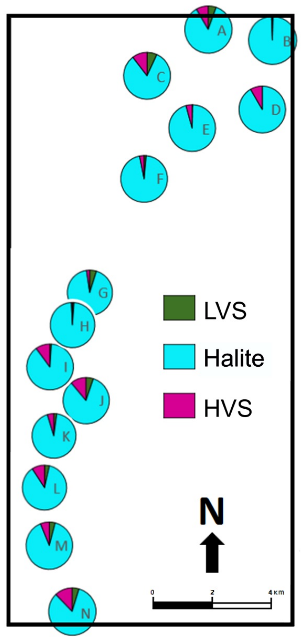


**Figure 4** – Fraction of mineral groups in the evaporitic section, considering registered logs and gap-filling from drill cuttings, considering the mineral grouping suggested by Maul et al. (2018b): LVS, Halite and HVS.

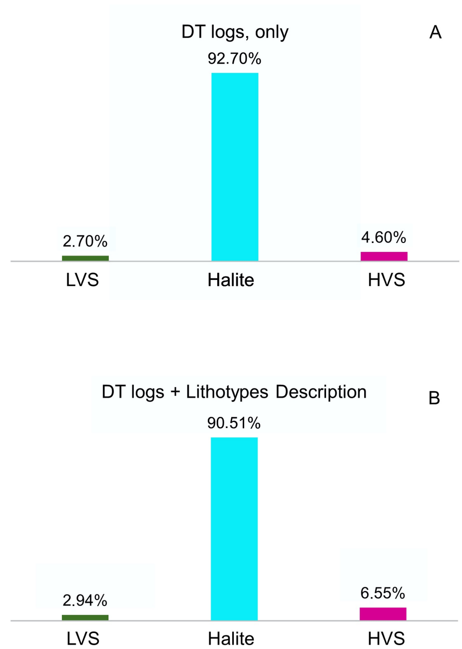


**Figure 5** – Distribution of group mineral occurrences for all wells. 5A: Registered sonic logs only. 5B: After gap-filling with drill cuttings.

As expected, Halite is the dominant group in the evaporitic section, averaging over 90%, whereas HVS and LVS are much less frequent, with a higher content of HVS, as already described in literature (e.g., Jackson et al., 2015). We highlight that the HVS group percentage increases almost 50% when considering the gap-filled lithology (Fig. 5). This is the effect of a sampling bias: for safety reasons, changing of drill stages is preceded by placement of a casing shoe. This is commonly done on top and base of the evaporitic section, and blocks proper well-logging. As the top and base of the evaporitic section are classically characterized by anhydrite, this operational constraint leads to under sampling of anhydrite in the entire evaporitic layer.

Velocity distribution for each evaporitic group was also investigated. Figure 6A illustrates the distribution of velocity values for well L, which is the well in our sample that crosses the thinnest evaporitic section (1,280 m). Figure 6B shows the same, but for well B, which crossed the thickest evaporitic section (2,370 m) containing the three classes of salt grouping (LVS, Halite and HVS – the well D, which would be thickest well in this project, has no the LVS occurrence). Notice that well L presents a small dispersion of values, and Halite can be easily separated from the LVS group. Well B shows a wider range of velocities for halite, which overlaps with the LVS group, rising ambiguous interpretations. The HVS group in well B has a significantly lower interval velocity, also overlapping with halite. Justen et al. (2013) mentioned that thicker evaporitic sections might have resulted from salt mobilization, which promotes mineral mixing. This is particularly stronger for the LVS.

Analysis of all wells together (Fig. 6C) shows a strong velocity overlap for all groups. This is why sometimes a single value is used to represent the whole section - which is clear inaccurate, as it does not capture heterogeneities.

Velocity variability with thickness is usually low for LVS and Halite groups, and higher for HVS (Fig. 7). This is in accordance with the statement presented by Maul et al. (2019). To better understand this variability, the wells are sorted from thinner (left) to thicker (right) evaporitic section. The anhydrite in the HVS group shows a more brittle behavior than Halite and LVS. Therefore, it is reasonable to infer that brittle high velocity evaporites, which are less mobile, better support the compaction effect in the same location, leading to an increase in velocity. The other groups are ductile/plastic and mobile, and

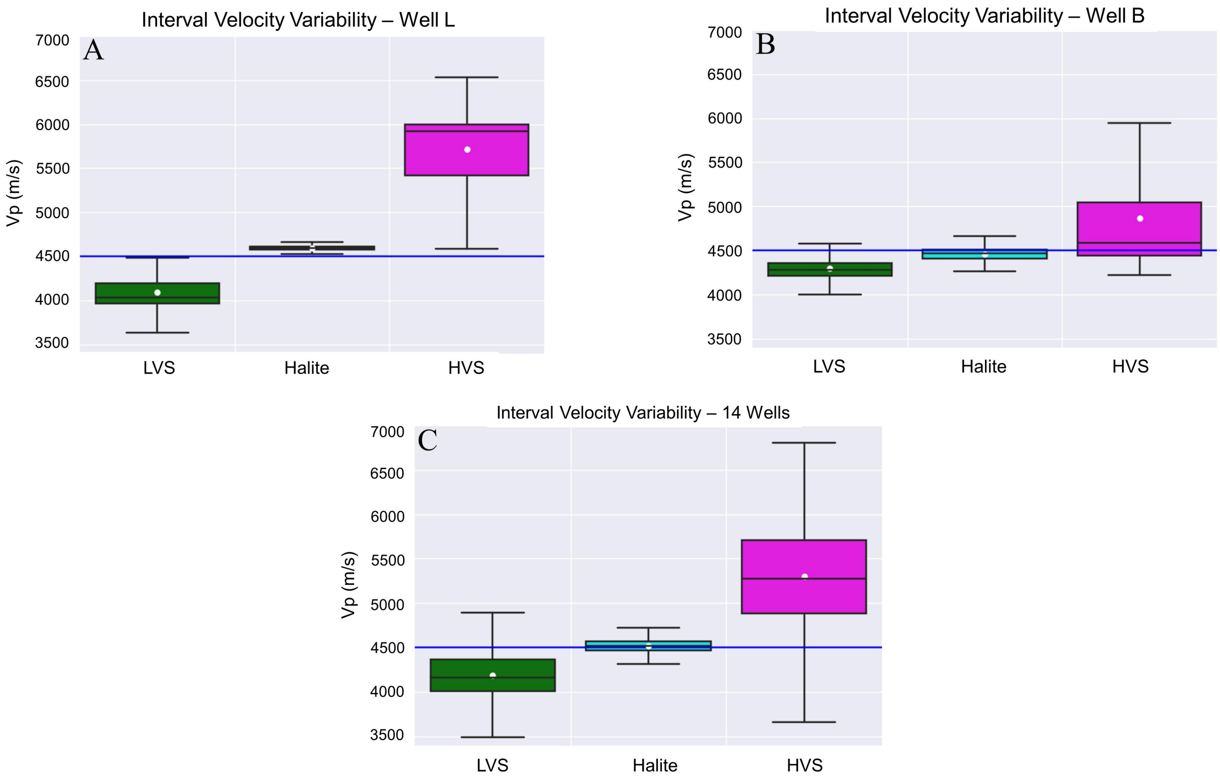


**Figure 6** – Standard statistical box-plot representation of interval velocity variability, obtained from available sonic logs. 6A: Well L, where the evaporitic section thickness is around 1,280 m. 6B: Well B, where the evaporitic section thickness is over 2,370 m. 6C: All 14 wells, with an average evaporitic thickness of 1,900 m. Blue lines are the compressional velocity of reference (4,500 m/s), commonly used in the "salt flooding" for seismic migration purposes. White dots within the box-plots are the average value for the mineral group, and black lines are the median. Black bars spam $\pm$ one standard deviation.

probably move under lithostatic pressure, suggesting that the compaction effect is weaker. The weight of the overburden (water + sediments above evaporites + evaporites) above the "salt" base was also considered but, due to its small variation (from 4,950m to 5,130m), it was assumed as negligible.

In order to avoid spurious values from well-log measurement, the lower and higher 5% values were excluded from the analysis. See Figure 7a, for example: a measurement in well C has Vp over 6,000 m/s, which would correspond to HVS and not to LVS values. The LVS velocity without those anomalous values is almost constant, even considering the evaporitic section thickness variation. This reinforces the hypothesis that this group does not suffer the compaction effect, as observed by the linear regression (thin green line). The Halite group (Fig. 7b) has the same behavior. On the other hand, HVS (Fig. 7c) shows greater variability, and an inverse correlation with evaporitic thickness. An explanation for this inverse correlation would be the compaction effect on anhydrites.

The compaction effects seem to be negligible for LVS and Halite, though noticeable for HVS. Our decision for this work was to consider the average values for gap-filling in each group. This is to be decided on a case-by-case basis, after investigation of a large number of wells and grouping them in representative classes, such as section thickness and burial depth. As shown in Table 2, about 8.70% of the well-logs are missing. Representing these missing values as constant artificially reduces the variability of our dataset, as we are replacing several values by a single one.

The next step is to estimate the velocity variations inside the evaporitic section. Lithology identification by itself is not enough; we need to populate a 3D model, segregated by facies, with the appropriate values. This is done with help of acoustic inversion. Discussions about the most suitable type of inversion for the evaporitic section are not the objective of this article, and the reader may refer to Barros et al. (2017), Fonseca et al. (2018), Teixeira et al. (2018) and Maul et al. (2018b) for further details on this particular subject.

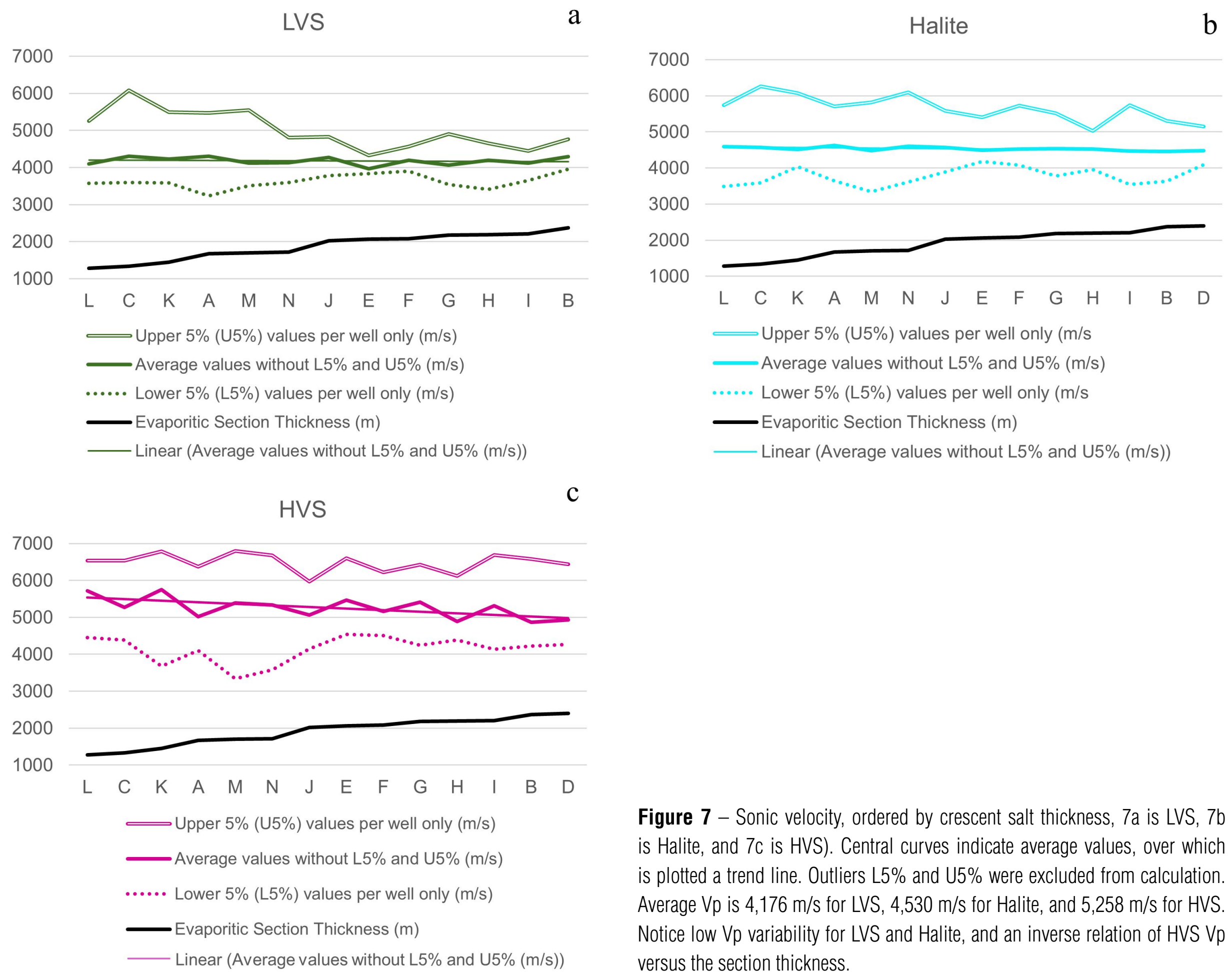


**Figure 7** – Sonic velocity, ordered by crescent salt thickness, 7a is LVS, 7b is Halite, and 7c is HVS). Central curves indicate average values, over which is plotted a trend line. Outliers L5% and U5% were excluded from calculation. Average Vp is 4,176 m/s for LVS, 4,530 m/s for Halite, and 5,258 m/s for HVS. Notice low Vp variability for LVS and Halite, and an inverse relation of HVS Vp versus the section thickness.

The resulting acoustic impedance ($I_p$) from the acoustic inversion process is cross-plotted with the compressional wave velocity ($V_p$) and, from this cross-plot, a best-fit curve is calculated (Eq. 1). The resulting curve fit is applied to the whole 3D volume, generating a 3D velocity volume (Fig. 8). Curve-fitting choice is of course also another source of uncertainties.

$$V_p = ax^3 + bx^2 + cx + d \tag{1}$$

Where:

$V_p$ = Compressional velocity; $[V_p] = m/s$

$x = I_p; [I_p] = \frac{g}{cm^3} * \frac{km}{s}$

$I_p$ = Acoustic Impedance

$a = 1.426; b = -51.59; c = 753.4; d = 847$

A correlation between the evaporitic section thickness and the average $V_p$ is also calculated (Fig. 9). Thinner salt sections show higher velocities, as expected by the Halite displacement mechanism. The displacement is attributed to the vertical movement of halite and other mobile salts (LVS group), which is in accordance with the Rayleigh-Taylor instability: Halite and LVS present a plastic, fluid-like behavior, and do not resist the overburden stresses, being hence displaced and leaving behind thinner sections with a higher proportions of HSV (Lachmann, 1910; Arrhenius, 1913 both referred in Dooley et al., 2015). Evaporitic thickness and its average interval velocity are inversely proportional. This inverse correlation is in agreement with the ideas presented by Oliveira et al. (2015), who mentioned that, in their project, when the evaporitic section increases in thickness, the average velocity for the entire section decreases.

## CONCLUSIONS

Modeling of heterogeneous evaporitic properties is a complex subject, and a clear understanding of the uncertainties and limitations of the available data is crucial to ensure a useful final product.

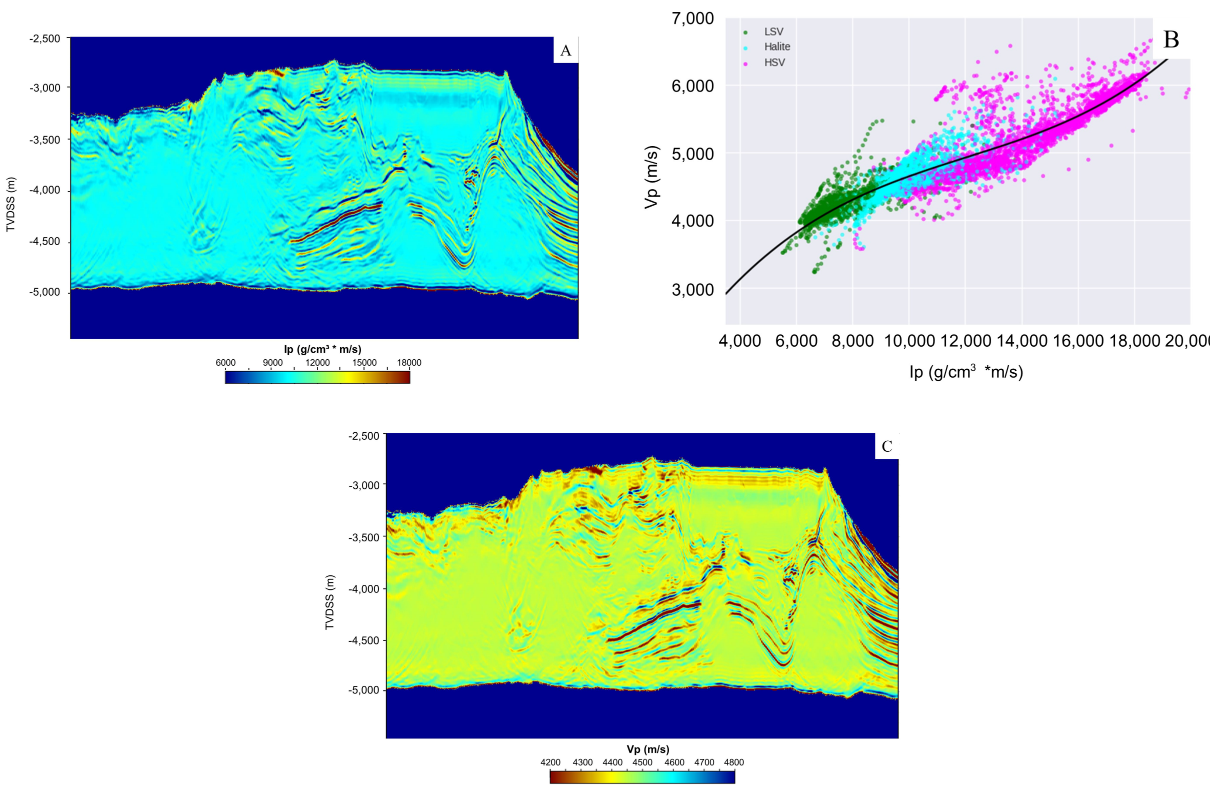


**Figure 8** – Transformation from Acoustic Impedance ($I_P$) to Compressional Wave Velocity ($V_p$). 8A: Result of model-based acoustic inversion. 8B: Well-log cross-plot ($V_P$ versus $I_P$). Colors are mineral groups (Green – LVS; Light Blue – Halite and Purple – HVS), as in Figure 7, and black line is the chosen polynomial fit in this work (Eq. 1). 8C: $V_P$ calculated from impedance (i.e. the chosen polynomial fit (8B) applied on the acoustic inversion result (8A).

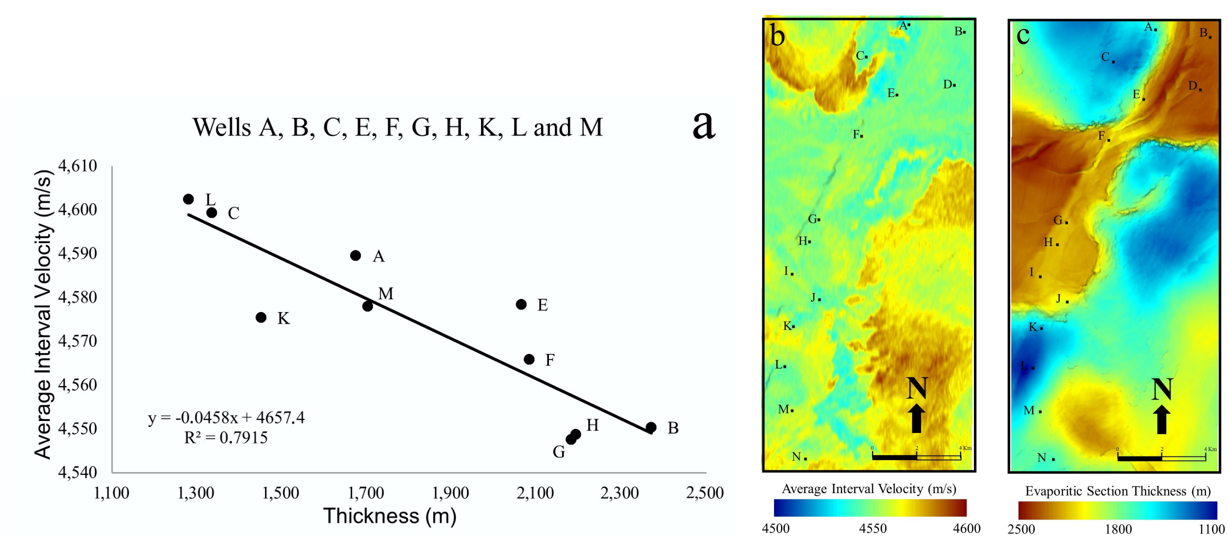


**Figure 9** – Correlation between Vp and evaporitic section thickness. 9a: Inverse correlation between average interval velocity and evaporitic thickness. Each dot represents a well. 9b: Average Vp map for evaporitic section, calculated using Equation 1. 9c: Thickness map for evaporitic section.

In the Santos Basin, the evaporitic section is dominated by halite (about 80% in average – Maul et al. (2018a) – and 90% in the dataset used here). This can lead one to assume a homogeneous compressional velocity ($V_p$) of 4,500 m/s for the entire section – the high occurrence of halite dominates the cross-plot, dwindling the influence of other evaporitic minerals.

Velocity variability is nevertheless observed within the evaporitic section, especially in the HVS group, which could be related to the higher compaction effects in anhydrites. The variability is less pronounced in thicker evaporitic section. This behavior seems to be more related to the mixed mineralogy observed in these thicker sections, and less to the individual mineral variability by itself. We defend the idea that, in these thicker sections, mineral mixing leads us to analyze the halite influence (more stable) over other minerals.

The methodology presented in this work results in an improved initial velocity model for seismic tomography, lowering the computational efforts when compared to the conventional approach ("salt flooding" + inversion tomographic updates), as cited by Gobatto et al. (2016), Falcão (2017), Fonseca et al. (2018), Maul et al. (2018a), Dias et al. (2019) and Maul et al. (2019).

The workflow is easy to implement, and not costly. Besides, the improved velocity can be used to assist other reservoir characterization processes, such as properties distribution studies, depth positioning forecast, uncertainty estimation, geomechanical studies, and drilling in safer conditions.

The inverse relation between salt thicknesses and average interval velocities suggests that mobile salts (LVS and Halite) are expelled by the overburden weight, such as the carbonate rafts, leading to higher HVS fractions in thinner sections.

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Anexo A3:

***Geological Characterization of Evaporitic Sections and its Impacts on Seismic Images: Santos Basin, Offshore Brazil***

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# GEOLOGICAL CHARACTERIZATION OF EVAPORITIC SECTIONS AND ITS IMPACTS ON SEISMIC IMAGES: SANTOS BASIN, OFFSHORE BRAZIL

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**ABSTRACT.** The pre-salt reservoirs in the Santos Basin are known for being overlaid by thick evaporitic layers, which degrade the quality of seismic imaging and, hence, impacts reservoir studies. Better seismic characterization of this section can then improve decision making in E&P (Exploration and Production) projects. Seismic inversion – particularly with adequate low-frequency initial models – is currently the best approach to build good velocity models, leading to increased seismic resolution, more reliable amplitude response, and to attributes that can be quantitatively connected to well data. We discuss here a few considerations about inverting seismic data for the evaporitic section, and address procedures to improve reservoir characterization when using this methodology. The results show that we can obtain more realistic seismic images, better predicting both the reservoir positioning and its amplitude.

**Keywords:** evaporitic section, seismic imaging, seismic inversion, reservoir characterization, seismic resolution.

**RESUMO.** Os reservatórios do pré-sal da Bacia de Santos são conhecidos por estarem abaixo de uma espessa camada de evaporitos, que degradam a qualidade das imagens sísmicas e impactam os estudos de reservatórios. Melhores caracterizações desta seção podem, então, melhorar o processo de tomada de decisão em projetos de E&P (Exploração e Produção). Inversão sísmica –- particularmente com modelos de baixa frequência inicialmente adequados -– é atualmente a melhor abordagem para se construir modelos de velocidades, auxiliando no aumento de resolução sísmica, obtendo-se respostas de amplitude mais coerentes, e tendo seus atributos quantitativamente conectados com as informações de dados de poços. Aqui discutiremos algumas considerações sobre inversões sísmicas para seção evaporítica, e indicaremos procedimentos para melhorar a caracterização de reservatórios quando utilizada esta metodologia. Os resultados mostram que podemos obter imagens sísmicas mais realistas, com melhores predições tanto em termos de posicionamento quanto de amplitude.

**Palavras-chave:** seção evaporítica, imagem sísmica, inversão sísmica, caracterização de reservatórios, resolução sísmica.

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## INTRODUCTION

The proper study of thick evaporitic deposits is quite challenging – they are usually buried, which imposes difficulties to access the intrasalt facies (Stefano et al., 2010). Most of the current knowledge about ancient saline giants[1]/salt giants[2] are built upon outcrop data, seismic reflection surveys, and boreholes that penetrate salt sequences (Rodriguez et al. 2018). According to the last authors, these deposits can easily cover more than 100,000 km$^2$, varying in thickness from a few hundred to thousands of meters, and are usually deposited in restricted marine basins. They present a diverse mineralogical composition, mainly controlled by the solubility of different minerals. A standard depositional sequence will starts with carbonates, followed by gypsum (or anhydrite), then halite, and finally end with the bittern salts, such as potassium- and magnesium-rich minerals (Schreiber et al., 2007).

The evaporitic section in the Santos Basin (offshore Brazil) was regarded as fairly homogeneous in terms of interval velocity – around 4,500 m/s – until early 2000s. This assumption was considered as valid for processing, as the standard workflow included Pre-Stack Time Migration (PSTM). Following the discovery of oil in the pre-salt section in the Santos and Campos Basins, as well as the increase in computational power, Pre-Stack Depth Migration (PSDM) became the industry standard. Inside the PSDM's border-limit, a myriad of methods is available, ranging from Kirchhoff PSDM to Reverse-Time Migration (RTM). Completing the toolbox of state-of-the-art processing techniques are also Full-Waveform Inversion (FWI) (Ben-Hadj-Ali et al. 2008; Barnes & Charara (2009); Operto et al., 2013; Vigh et al., 2014) and Least-Squares Migration (LSM) as per discussed in (Nemeth et al., 1999; Hu et al., 2001; Dias et al., 2017; Wang et al., 2017; Dias et al., 2018).

To get more benefits from these improved processing techniques, models that assume a homogeneous salt layer are not an option, as they fail to reproduce the spatial variability of velocity. It is then mandatory to build more geologically-constrained velocity models. Without a good initial model, not even tomographic inversion is able to correctly update the velocities, due to the complex geological environment (e.g. strong contrasts, steep dips).

Some authors have explored the use of inhomogeneous/heterogeneous evaporitic sections for enhancing migration output (Gobatto et al., 2016; Fonseca et al., 2017; Fonseca et al., 2018; Maul et al., 2018b, 2018c, based on the statements of Maul et al., 2015). Tarantola (1984) and Zhang & 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. Huang et al. (2010) published results for velocity correction using tomographic inversion in the Santos Basin, considering the presence of layered evaporites. For these last authors, intrasalt travel times based on tomography yield good results because layered evaporites create strong reflections, ensuring the correct update. Ji et al. (2011) developed a method to update the salt velocity inserting a random velocity variation (called a *dirty salt velocity*) in a reflectivity-based inversion.

Following these considerations, Meneguim et al. (2015) demonstrated that the inversion study is more likely to deliver good salt velocity models than the simple amplitude approach firstly presented by Maul et al. (2015). Several other authors have explored the adaptive inversion concepts from the reservoir scale to the salt section scale (Gobatto et al., 2016; Toríbio et al., 2017; Teixeira et al., 2018; Fonseca et al., 2018). Barros et al. (2017) introduced the idea of generating pseudo-logs to fill log gaps, using the approach stablished by Amaral et al. (2015), who relied on cutting samples (mud-logs) collected during the well drilling phase. The use of mud-logs was also demonstrated to be useful in the work published by Cornelius & Castagna (2018).

In building the initial velocity model, well-logs are used to provide the missing bandwidth (lower frequencies) of seismic data. Careful pre-conditioning of velocity and density logs plays a crucial role in this step. These data are loaded into a stratigraphic grid (created from any previous seismic interpretation of top and base of the salt body) and interpolated. Seismic-well ties are used to estimate the best local wavelet, and a multi-well wavelet is selected as representative of the whole seismic data. The algorithm employed for inversion is sparse spike algorithm (Simm & Bacon, 2014). Data are then inverted for acoustic impedance, and comparison between the result and the well-logs is the most critical quality control. The inversion outcome is the base to obtain the seismic-derived properties of the salt layer.

In this paper, we propose a comparison among the several approaches for velocity model building in the salt section, such as constant value, tomographic update over constant velocity, insertion of stratification via instantaneous amplitude attributes, and insertion of stratification via acoustic inversion. A tomographic update over the inverted stratified model was

[1]Saline giants (*sensu*): Hsü (1972).
[2]Salt giants (*sensu*): Hübscher et al. (2007).

also performed, and the results were compared. We discuss some pitfalls, warnings and particularities which we consider as paramount when performing seismic inversion for the evaporitic section. All the consulted references regarding seismic inversion for the evaporitic section are summarized in Maul et al. (2018b, 2018c), and the methodology must follows important aspects. One of them is related to data quality to invert to rock property (e.g.: interval velocity, density), mainly because its the low-frequency contents and high noise-to-signal relation. As that matter is also a topic we will not explore in this article we will consider the data with enough quality for our study and tests.

## STUDY AREA AND AVAILABLE DATA

The study area is inserted in the pre-salt province in the Santos and Campos Basins (Fig. 1). A pre-stack depth-migrated volume covering an area of approximately 200 km² is available, together with 14 wells with a broad suite of logs. The Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) has provided the data we used in this research. Wells were labeled with capital letters from A to N, and the original names can be found in Table 1.

**Table 1** – Correspondence between the well symbols for this study and the official names from ANP (National Agency of Petroleum – Brazil).

| This Study | ANP |
|---|---|
| A | 3-BRSA-788-SPS |
| B | 9-BRSA-1037-SPS |
| C | 8-SPH-23-SPS |
| D | 8-SPH-13-SPS |
| E | 7-SPH-14D-SPS |
| F | 7-SPH-8-SPS |
| G | 7-SPH-4D-SPS |
| H | 9-BRSA-928-SPS |
| I | 7-SPH-5-SPS |
| J | 9-BRSA-1043-SPS |
| K | 1-BRSA-594-SPS |
| L | 7-SPH-1-SPS |
| M | 7-SPH-2D-SPS |
| N | 3-BRSA-923A-SPS |

## THE IMPORTANCE OF CHARACTERIZATION OF THE EVAPORITIC SECTION

Evaporites are minerals or rocks formed in a restricted saline environment, submitted to high evaporation rates. The great percentage of halite seems to be the main reason to consider the salt section as almost homogenous, with interval velocity Vp close to the halite's velocity (4,500 m/s), as this is the most frequent mineral within the salt section. However, a look at velocity models obtained by tomographic inversion reveals several inconsistencies, visible in the forms of large spots/marks of different velocities. These marks reflect the necessity to alter the almost constant initial velocity models.

Ji et al. (2011) presented enhanced results of depth positioning in PSDM data when considering seismic amplitudes as the guide for the existing heterogeneity inside the salt section. This improvement alone would be enough to justify the effort of using amplitudes for the velocity modelling. On top of that, it was also noticed that signal quality is improved when using this approach. Gobatto et al. (2016), Fonseca et al. (2018), and Maul et al. (2018a) presented processing results showing that use of salt stratification as input for velocity tomography leads to more realistic seismic images, and to more precise depth positioning and signal quality.

Maul et al. (2015) described how to incorporate salt stratifications using seismic attributes, assigning constant velocity values for those layers. Seismic amplitude is a response of contrasts of elastic properties between rocks. The estimation of layer properties from seismic data is an ill-posed problem (Tarantola, 1984), which bears a set of uncertainties. Seismic inversion is a widely applied technique to combine seismic amplitude, seismic interpretation and well-log information to obtain elastic properties from seismic amplitude (Latimer, 2011). The combination of information from several sources contributes to mitigate the ambiguity of the seismic signal, helping to solve part of the non-uniqueness of the solutions, as observed by Maul et al. (2015).

So far, about 200 wells were drilled to access the pre-salt reservoir in the Santos Basin (Maul et al., 2018b). These wells showed that the evaporites are, in fact, heterogeneous, with halite being the major fraction (between 80 and 90%). A division in three mineral groups was proposed: Low-Velocity Salts (LVS), or the bittern salts, composed basically by sylvite, carnallite and tachyhydrite; Halite (or background); and High-Velocity Salts (HVS), which are basically anhydrite and, in lower proportion, gypsum. The LVS group represents something between 5-10%

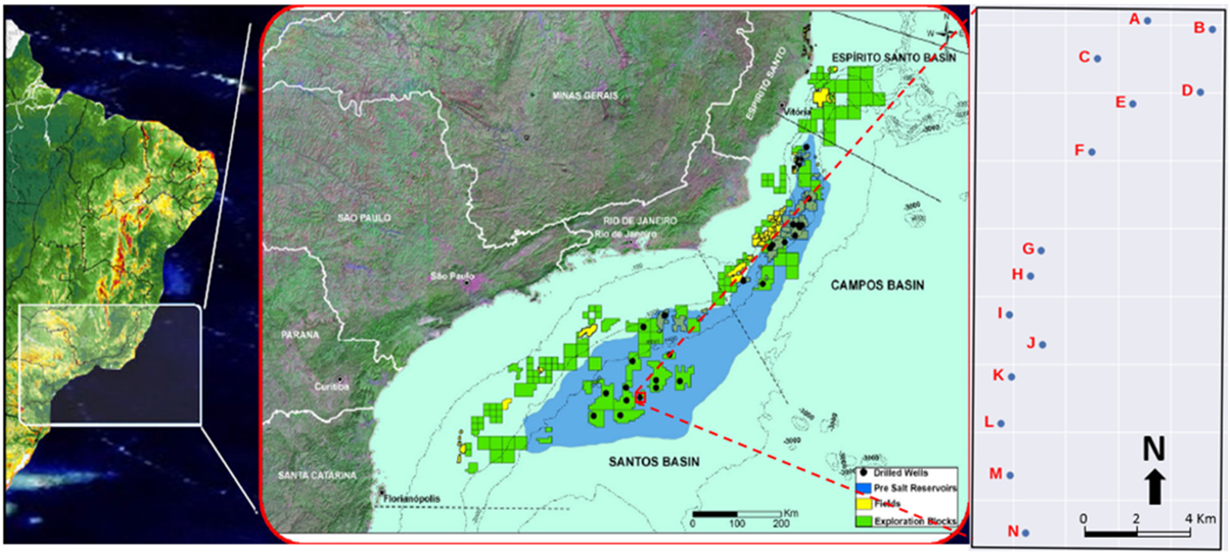


**Figure 1** – Location of study area (regional) and details of available data. Blue polygon delineates the area of the hydrocarbon occurrences identified in the pre-salt province for both Santos and Campos Basins, totaling an area of approximately 350,000 km², and water column varying from 2,000 to 3,000 m. Rightmost panel shows in detail the well locations (A to N) inside the 3D seismic volume zone (rectangle). Adapted from https://diariodopresal.files.wordpress.com/2010/.

of occurrence, and the HVS group, 10-20%. These groups were considered enough to represent the different observed seismic signatures (Maul et al., 2015; Gobatto et al., 2016; Fonseca et al., 2018; Maul et al., 2018a).

Well-log analysis indicates an inverse relationship between thickness and velocity of the salt section. In areas where the evaporite sequence is thicker, velocity is slower. The Rayleigh-Taylor instability, as described by Lachmann (1910), Arrhenius (1913) and Dooley et al. (2015), can be a physical explanation: it states that under the intense overload pressure caused by the upper sediments, the more mobile salts (LVS) move to high-wall portions. The movement of the low-velocity salts towards the high-wall portions implies in a decrease of velocity in the thicker salt sections, caused by an increase in the fraction of low-velocity salts. This observation is consonant with the one made by Oliveira et al. (2015). The overload pressure moving the mobile salt to the "pillowed" portions is also mentioned by other authors, such as Ge et al. (1997) and Guerra & Underhill (2012).

## METHODOLOGY

The proposed methodology in this work consists of:

A. Analysis of the available logs inside the evaporitic section. In this case we observe the presence/absence of data, as well as the property values registered;

B. Precautions regarding the use of samples collected during well drilling, and their associated uncertainties;

C. Interpretation of lithology in the wells, investigating the coupling degree, absence of logs, their description, and their correct positioning;

D. Investigating the property behaviors related to both, their measurement ways as well as considering about anomalous values, their own variability, inferring few commentaries regarding possible compaction effect by each mineral type;

E. Predict properties to insert in log gaps, or where only cuttings description are available. Particularly important for elastic logs;

F. Generation of any other important property for the seismic inversion approach (such as density) using log correlation;

G. Choice of a single and representative wavelet for the whole seismic inversion (in this case, it is important to think about section thickness variation, which could vary from few hundreds of meters to around 3 kilometers);

H. Performing a seismic inversion that reproduces the stratification observed in the well data, for the whole evaporitic section;

I. Obtaining internal stratification for the evaporitic section using other approaches, such as amplitude response, instantaneous seismic attributes, etc.;

J. Comparing the results.

## CONSIDERATIONS, ASSUMPTIONS AND DEVELOPMENTS

A frequent challenge when modelling the salt section is the lack of log data at top and bottom of the evaporitic section, which is caused by operational constraints: these two places are usually selected for changing of casing diameter, making it difficult to acquire data from high-resolution acoustic logging. This argument is presented by Amaral et al. (2015), who argues in favor of using sample cuttings to fill this gap in information.

Figure 2 shows information on logs and cutting samples for the 14 studied wells. Notice that well D, for example, does not contain any LVS interpreted in neither approach.

Barros et al. (2017) proposed to use constant values (average logged values) for each of the mineral groups, in order to fill the gaps in the logs – i.e., assuming generated pseudo-logs as hard information. To do so, we will use the following average values: LVS = 4,188 m/s; Halite = 4,548 m/s; and HVS = 5,281. Those values were obtained from the PDF (probability density function) presented in Figure 3.

On the group of wells available for this study, about 10% of the section is not logged – in some cases, log absence is over 20%. Table 2 illustrates the data inventory for the studied wells, as well as some considerations about filling the log gap with the cutting samples description and the average velocity, following Barros et al. (2017).

After complementing the missing log information with the described cuttings, Barros et al. (2017) calculated the average occurrence per proposed group as following: LVS ~ 3.0%, Halite ~ 90.5%, and HVS ~ 6.5%. These percentages are in good agreement with values presented by Jackson et al. (2015) and Maul et al. (2018b), having the latter provided these percentages based on a database of 182 wells in the Santos Basin (Table 3). It is important to point out that the values obtained from this dataset should not be used as reference for any other study.

To generate the density logs – another input for the seismic inversion, we employed statistical regressions based on the registered logs (density X sonic), as can be seen in Figure 4.

As previously mentioned, the thickness of the evaporitic section in the Santos Basin varies from few hundreds of meters to about 3 kilometers. This variation imposes challenges when deciding the single wavelet to perform the seismic inversion process. In this project, the thickness ranges from 1,200 to 2,400 meters, which is enough to produce too different wavelets to be represented for a single average one (Fig. 5). This can compromise the inversion, delivering results that would perhaps be deemed not suitable for reservoir characterization purposes, but still useful for our goals.

## RESULTS

The results here presented cover two main aspects: the geological model building, by using the inversion methodology to build the evaporitic section (compared to other methods in literature), and how the use of this approach can influence the generation of new seismic images, depth positioning, migration, and focusing of events.

Figure 6A shows a seismic section, illustrating the amplitude responses inside the evaporitic section – the so-called stratifications. Figure 6B shows a velocity model with constant velocity for the evaporitic section (4,500 m/s), which was used as input for tomography, yielding the velocity presented in Figure 6C. If we use the amplitude response (Fig. 6A) to add stratification to the tomography output, we get a more geological look in our model, as can be seen in Figure 6D. Figure 6E shows the velocity obtained with the seismic inversion methodology.

The seismic inversion result is an impedance cube, and we are looking for an interval velocity cube. Following the idea showed in Figure 4, we can compute the correlation between impedance and interval velocity in well data. This was done independently for each of the three salt groups, using linear regressions, and the resulting equations were applied to the acoustic impedance obtained from inversion, yielding the desired 3D interval velocity.

The results show the inverse correlation between average interval velocity and section thickness (Fig. 7), for 10 of the 14 wells. This behavior was not observed in the remaining 4 wells. We believe this can be caused by problems in log data from these wells – the inverse relation is also described by Oliveira et al. (2015) after studying only three wells in another portion of in the Santos Basin, and by Maul et al. (2018b), in a study of 182 wells. It is in fact possible to use the impedance results to verify the same behavior spatially, as in Figure 8. This subject is currently in discussion and will likely be the scope of future work.

In another way, using Table 3 it is also possible to observe different behaviors when analyzing separately each mineral grouping per well. It allows us to infer when staying in thin

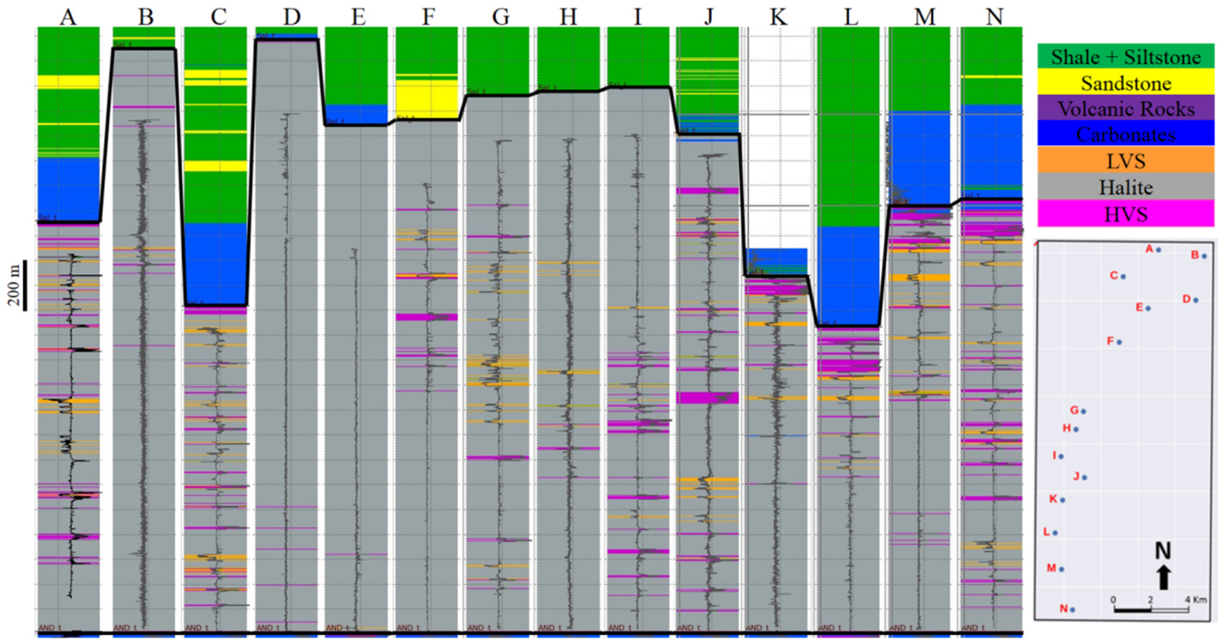


**Figure 2** – Well section illustrating the registered logs and drill cuttings interpretation. Observe the absence of log information in almost all 14 wells.

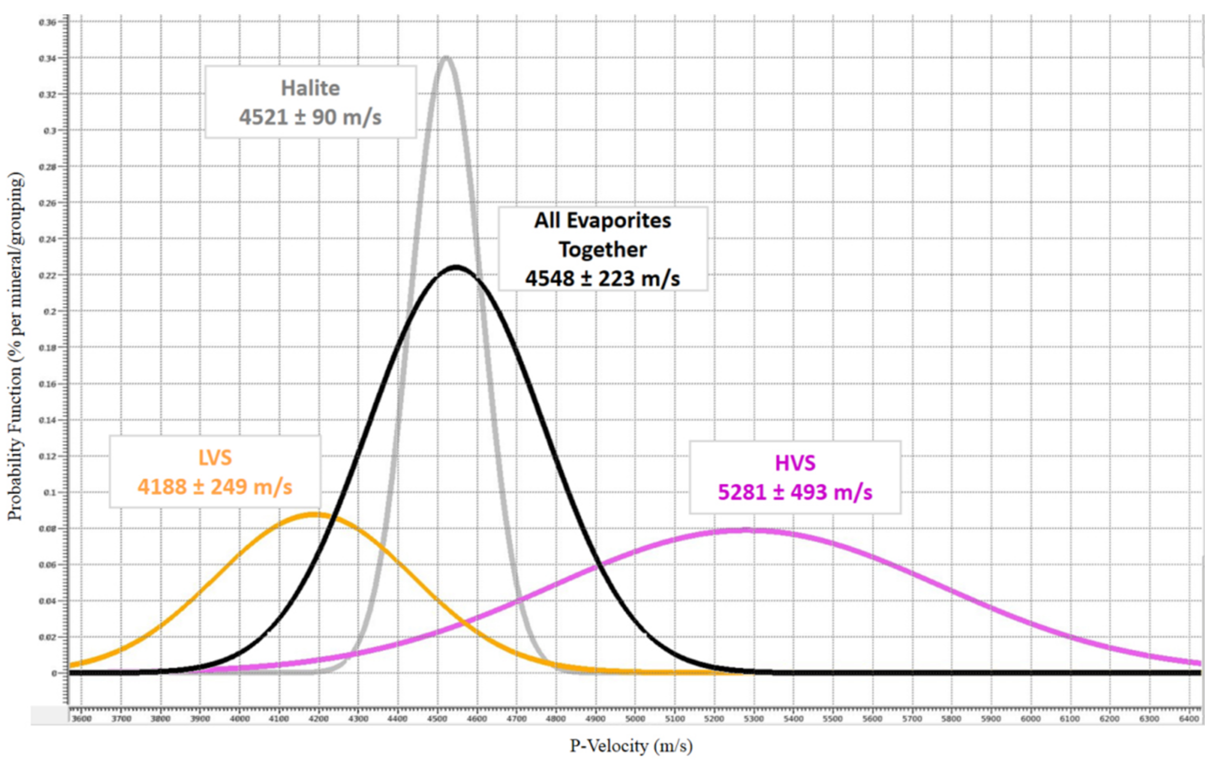


**Figure 3** – Interval velocity behavior for each mineral/group, considering the 14 studied wells.

**Table 2** – Well data inventory.

| Well | EKB (m) | Basal Anhy-drite (m) | Water Column TVDSS (m) | Top of Salt TVDSS (m) | Salt Isopach (m) | Acquired Log ( %) | Log Gap ( %) | LVS Log & C.S. (%) | Halite Log & C.S. (%) | HVS Log & C.S. (%) | AIV Velocity (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 25.00 | 12.90 | -2125.00 | -3264.81 | 1673.49 | 91.90 | 8.10 | 5.45 | 86.20 | 8.35 | 4589.59 |
| B | 24.00 | 13.80 | -2122.00 | -2734.32 | 2369.39 | 87.60 | 12.40 | 0.50 | 98.90 | 0.60 | 4550.39 |
| C | 24.00 | 12.90 | -2146.00 | -3722.50 | 1334.06 | 91.10 | 8.90 | 6.90 | 82.70 | 10.40 | 4599.39 |
| D | 24.00 | 11.50 | -2119.00 | -2717.34 | 2400.94 | 87.30 | 12.70 | 0.00 | 91.60 | 8.40 | 4609.57 |
| E | 24.00 | 11.14 | -2179.00 | -2885.90 | 2063.00 | 77.90 | 22.10 | 0.30 | 95.40 | 4.30 | 4578.44 |
| F | 24.00 | 17.50 | -2182.00 | -2876.91 | 2081.76 | 87.20 | 12.80 | 1.45 | 95.40 | 3.15 | 4565.87 |
| G | 24.00 | 13.57 | -2129.00 | -2804.89 | 2180.45 | 92.00 | 8.00 | 4.80 | 92.90 | 2.30 | 4547.58 |
| H | 24.00 | 11.50 | -2120.00 | -2798.11 | 2191.82 | 91.80 | 8.20 | 1.20 | 98.10 | 0.70 | 4548.81 |
| I | 26.00 | 13.80 | -2126.00 | -2809.53 | 2206.90 | 91.40 | 8.60 | 1.10 | 88.80 | 10.10 | 4618.07 |
| J | 26.00 | 13.40 | -2140.00 | -3088.84 | 2024.65 | 96.00 | 4.00 | 5.10 | 83.80 | 11.10 | 4611.00 |
| K | 32.00 | 11.50 | -2140.00 | -3553.21 | 1450.89 | 98.40 | 1.60 | 2.12 | 93.10 | 4.78 | 4575.41 |
| L | 26.00 | 29.40 | -2143.00 | -3717.59 | 1279.96 | 95.60 | 4.40 | 3.60 | 87.20 | 9.20 | 4602.48 |
| M | 26.00 | 11.65 | -2143.00 | -3256.49 | 1701.27 | 94.30 | 5.70 | 4.10 | 89.80 | 6.10 | 4577.95 |
| N | 26.00 | 13.30 | -2157.00 | -3340.66 | 1717.34 | 94.00 | 6.00 | 4.60 | 83.20 | 12.20 | 4620.87 |
| **AVG** | **25.36** | **14.13** | **-2140.79** | **-3112.22** | **1905.42** | **91.18** | **8.82** | **2.94** | **90.51** | **6.55** | **4585.39** |

EKB: Elevation Kelly-Bushing; TVDSS: True Vertical Depth Sub-Sea; LVS: Low-Velocity Salts; HVS: High-Velocity Salts; C.S.: Cutting Samples; AVG: Average; AIV: Average Interval Velocity.

**Table 3** – Salt proportions and interval velocities (m/s) for nine fields inside Santos Basin.

| Field | # Wells | LVS (%) | LVS AIV | Halite (%) | Halite AIV | HVS (%) | HVS AIV | WIV |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 8 | 4018.56 | 83 | 4480.88 | 8 | 5210.27 | 4462.56 |
| 2 | 29 | 9 | 4218.47 | 82 | 4563.69 | 9 | 4975.84 | 4567.53 |
| 3 | 17 | 12 | 4054.42 | 77 | 4498.25 | 12 | 4989.92 | 4505.66 |
| 4 | 3 | 13 | 3971.00 | 71 | 4507.09 | 16 | 4927.59 | 4505.04 |
| 5 | 5 | 3 | 4167.00 | 84 | 4538.00 | 13 | 5123.33 | 4576.00 |
| 6 | 7 | 3 | 4264.19 | 80 | 4509.87 | 17 | 5061.36 | 4596.05 |
| 7 | 72 | 8 | 4122.33 | 81 | 4526.47 | 11 | 5105.84 | 4560.03 |
| 8 | 25 | 4 | 4182.53 | 88 | 4533.59 | 8 | 5003.35 | 4547.16 |
| 9 | 4 | 6 | 4055.63 | 81 | 4486.58 | 13 | 5077.49 | 4535.67 |
| TNW | 182 | | | | | | | |
| **AVG** | | **7** | **4117.13** | **81** | **4516.05** | **12** | **5052.78** | **4539.52** |

LVS: Low-Velocity Salts; HVS: High-Velocity Salts; AIV: Average Interval Velocity; WIV: Weighted Interval Velocity; TNW: Total Number of Wells; Interval Velocity (m/s); AVG: Average. Modified from Maul et al. (2018b).

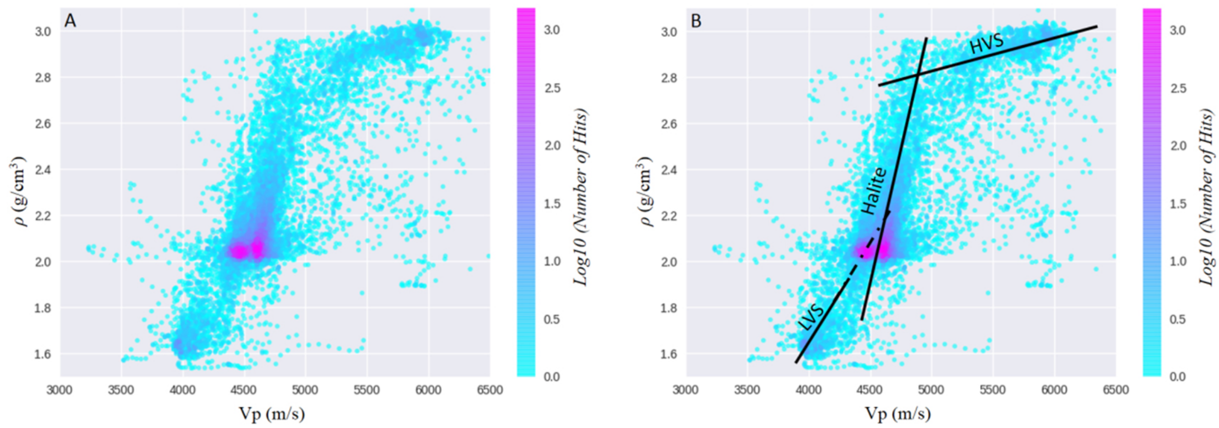


**Figure 4** – Relation between density and instantaneous velocity (Vp). (A) Density X Interval Velocity; (B) Trend line for each proposed group (LVS, Halite and HVS). Notice that the Halite trend is more stable than the others. This is not surprising, since the other groups are in fact a mixing of minerals, while Halite – despite any mixing – has a monomineralic behavior.

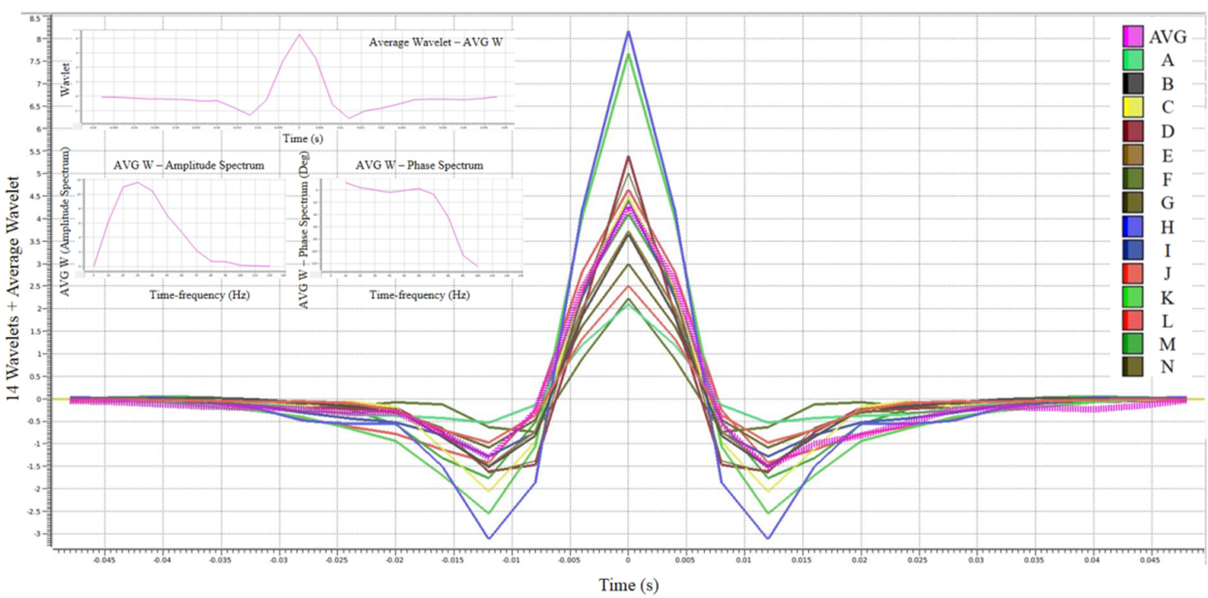


**Figure 5** – Best wavelets for each of the 14 wells, and the average among them (purple). Observe the low representation of the average wavelet compared with the individual ones.

section we preferably have an increase in the HVS content or proportions which is reflected in the interval velocity increasing in these portions (Fig. 9). A feasible explanation is the fact during the period of more mobility observed for the Halite and the LVS, these salts under any overpressure condition tend to move to a any low-pressure portion such as the walls, pillows increasing their amounts in those places which consequently decreasing their velocity content. Another important aspect is the mineral mixing promotion during this moving which as per Justen et al. (2013) statement helps to explain why the halite velocity is commonly measured below the value of 4,500 m/s, once the measurement reflects also the LVS content.

With the velocity models in hands, we can compare the output of processing workflows under different inputs. In this project, tomography and Kirchhoff PSDM were tested, using both the constant velocity model (Fig. 6B) and the impedance-derived one (Fig. 6E) as initial models. Results can be checked in Figure 10.

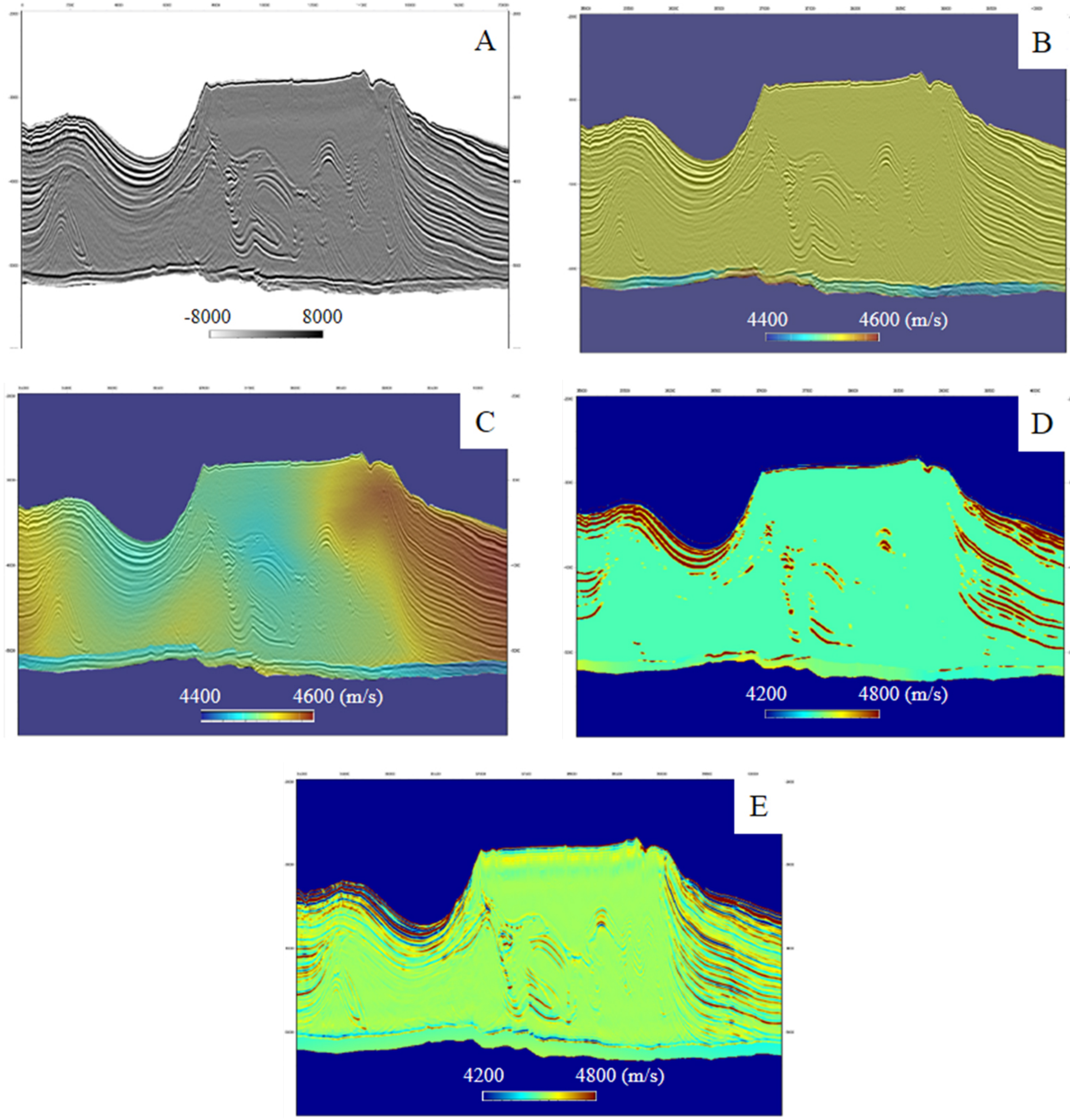


**Figure 6** – The evaporitic section and the velocity behaviors in terms of geological features. (A) amplitude response; (B) constant interval velocity; (C) tomographic update in terms of velocity applied over "4B", which generated "4A"; (D) stratification insertion using the amplitude "4A" as the guide for this insertion; (E) stratification insertion using the seismic inversion methodology.

## DISCUSSION

One hypothesis investigated during this research was that evaporitic sections show higher velocities in thin sections than in thicker sections. Results obtained from seismic inversion – even with a challenging wavelet estimation – are in agreement with this. This assumption could also be inferred by observing the local geology, particularly the mini-basins under carbonate rafts: the heavy sediments in those mini-basins force the LVS to move to other positions, forming domes and walls. Therefore, the thin sections are left with a higher fraction of HVS, explaining their higher velocity.

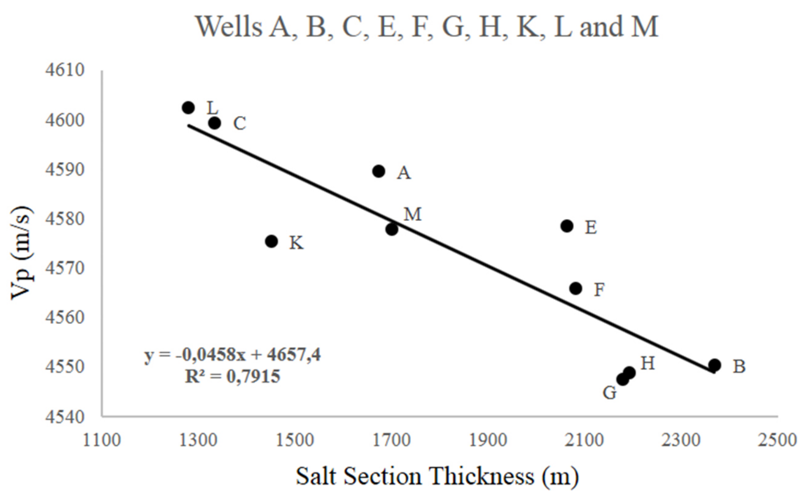


**Figure 7** – Correlation between average interval velocity and salt thickness for the evaporitic section (10 of 14 wells displayed).

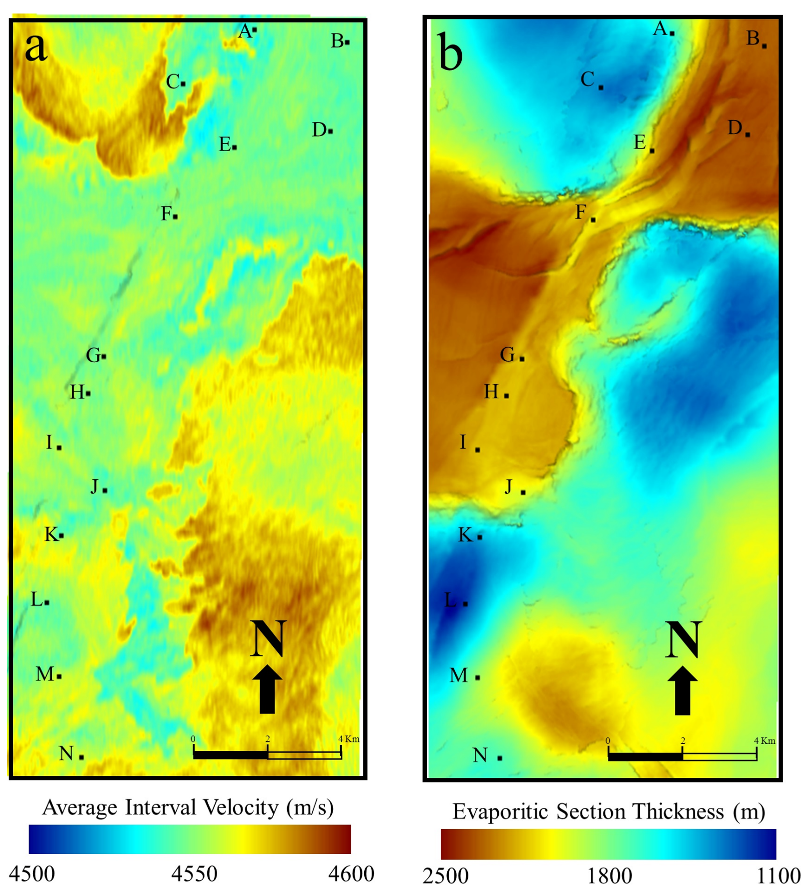


**Figure 8** – Comparison between average interval velocity and thickness for the evaporitic section. (a) map of average interval velocity for the evaporitic section, with location of available wells (velocities were calculated from impedance volume); (b) map of thickness. Notice the same trend found in the cross-plot in Figure 7: thicker layers have slower interval velocity.

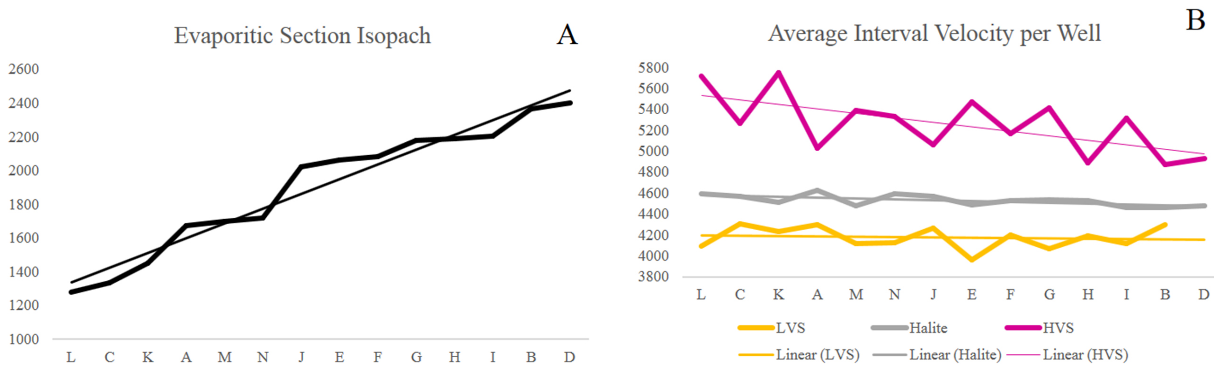


**Figure 9** – Thickness section variation and the impact it may cause for each mineral/grouping. (A) thickness variation from the thinner section to the thicker; (B) average interval velocity per mineral/grouping per well. Note the influence the thickness appears to have of the HVS.

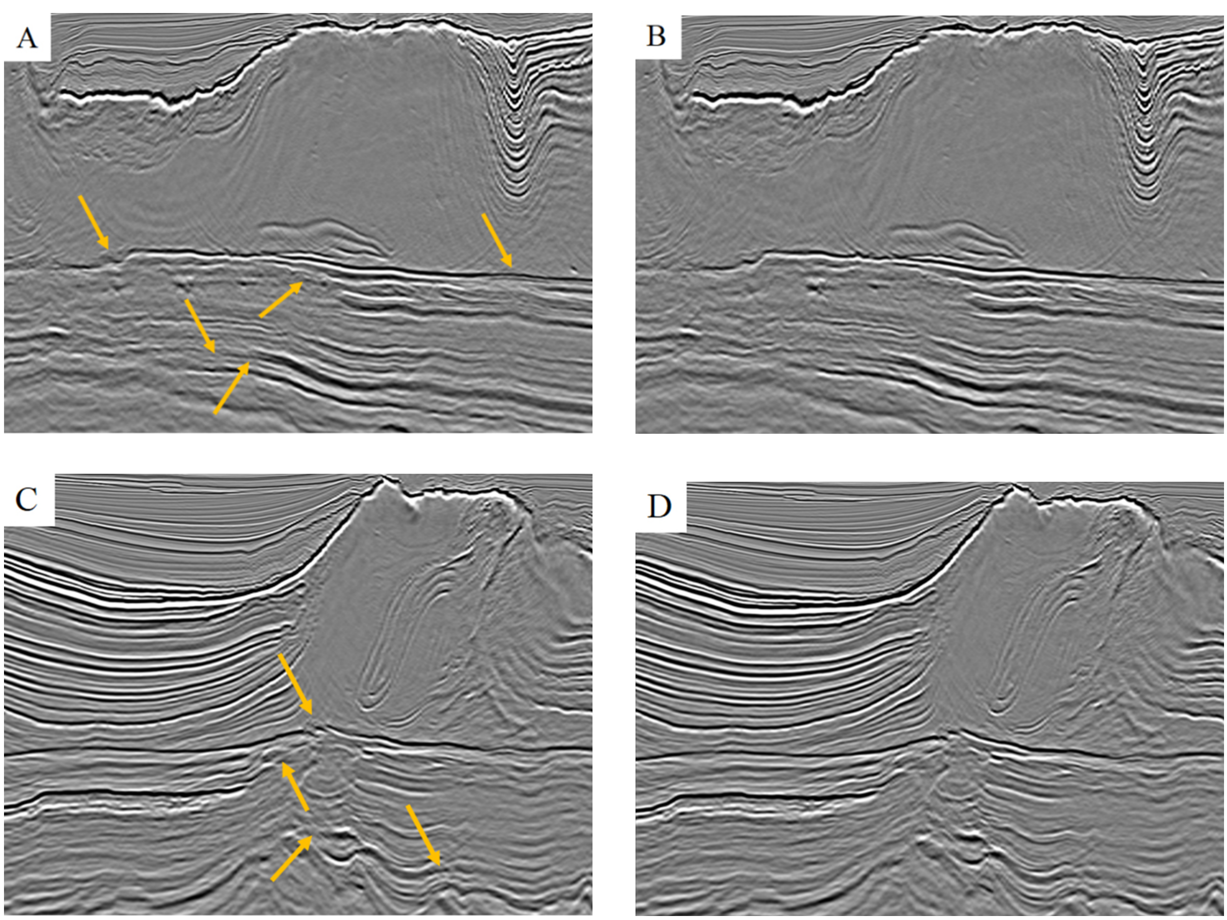


**Figure 10** – Comparison between Kirchhoff migration with the tomographic updated for a constant initial model (Vp = 4,500 m/s) and for model with stratification. (A) migrated Kirchhoff crossline using the traditional tomographic updating for the velocity model (starting model Vp = 4,500 m/s); (B) the same crossline migrated using the Kirchhoff algorithm, now using the tomographic updating over the stratified model; (C) migrated Kirchhoff inline using the traditional tomographic updating for the velocity model (starting model Vp = 4,500 m/s); (D) the same inline migrated using the Kirchhoff algorithm, now using the tomographic updating over the stratified model. Orange arrows indicate positions where we observed imaging enhancement. Adapted from Maul et al. (2018a).

This is a point of attention for imaging and depth positioning under thick salt layers. Looking at the Figure 6, it is possible to notice many differences among the presented models. Although the tomographic update adds a flavor of geology even for constant-velocity starting models (Fig. 6C), the result is noticeably different from the one obtained from inversion results (Fig. 6E). Hence, tomographic update models with distinct initial conditions can lead to significant differences in depth positioning. Previous work regarding this theme (Meneguim et al., 2015) shows variations of +/- 3% in terms of gross rock volume above the oil-water contact.

Imaging enhancement has been reported in recent literature when accounting for stratification prior to tomography (Gobatto et al., 2016; Fonseca et al., 2017; Fonseca et al., 2018; Maul et al. 2018b). Besides better depth positioning and uncertainty reduction, event focusing is also improved. On this particular subject, there is plenty of room for development – the use of Least-Squares Migration (LSM), for example. These are the next steps in our research.

## CONCLUSION

Seismic inversion for the evaporitic section is a suitable approach to start building reliable velocity models, even when the inversion output is not up to the standards of reservoir characterization. Using a stratified velocity as initial model for tomography update delivers clear benefits for the processing workflow, by reducing the computational time necessary for this intensive step. This is mostly due to incorporation of geology into the model, which brings it closer to the optimal solution and trims the number of necessary iterations.

The inverse relation between the evaporitic section thickness and its average interval velocities reinforces the mobile salts (LVS and Halite) expulsion hypothesis. Therefore, the HVS proportion is higher in thin sections. This is sometimes observed in thinner salt sections from tomographic updates of constant initial models, even without any geological input.

Both imaging and depth positioning are improved by using the stratified velocity model for tomography. These improvements can be carried even further by the use of migration algorithms that make better use of detailed velocity models, like Least-Squares Migration. Also, several other tasks can take advantage of better salt characterization, such as illumination studies, geomechanical simulations, and HSE during drilling operations.

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Anexo A4:

***Improving Pre-Salt Reservoirs Seismic Images when Considering the Stratified Evaporites Insertion in the Initial Model for the Velocity Updating Processes prior to the Seismic Migration***

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# IMPROVING PRE-SALT RESERVOIRS SEISMIC IMAGES WHEN CONSIDERING THE STRATIFIED EVAPORITES INSERTION IN THE INITIAL MODEL FOR THE VELOCITY UPDATING PROCESSES PRIOR TO THE SEISMIC MIGRATION

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**ABSTRACT.** Structurally complex areas, such as the pre-salt section in the offshore Santos Basin, SE Brazil, are challenging to represent geologically using seismic images. One of the main causes of the observed imaging problems is the evaporitic section and its considerations about velocities used for seismic migration purposes. Some authors consider set to this section an almost constant value (close to 4,500 m/s) which approximately represents the halite velocity, the most abundant mineral in this salt formation. Others, over these models, apply the tomographic inversion or FWI schemes giving to the velocity model the mathematical support to build confident seismic images. We believe in the importance of building starting velocity models reflecting the existing geological features prior to applying the tomographic/FWI updating. In this sense, we propose the insertion of the so-called stratifications within the evaporitic section using an adaptation of the model-based seismic inversion technique. Following this new velocity model including the stratification, we suggest tomographic iterations update or FWI, to add to the geological constrains of the model the needed mathematical convergence. Finally, in this work, we performed the seismic migration with and without inserting these geological features in the initial velocity model and compared the results.

**Keywords:** evaporitic section, stratifications, velocity model, seismic migration, seismic image.

**RESUMO.** Em áreas estruturalmente complexas, como na seção pré-sal da Bacia *offshore* de Santos, região SE do Brasil, é um desafio representar a geologia utilizando imagens sísmicas. Uma das principais causas dos problemas observados está nas considerações sobre a seção evaporítica e suas velocidades com propósito de migração sísmica. Alguns autores consideram esta seção como tendo velocidades geralmente constantes (próximas de 4.500 m/s), o que representa aproximadamente o comportamento da halita, o mineral mais abundante nesta seção. Outros, sobre este modelo, aplicam a atualização por inversão tomográfica ou FWI para dar ao modelo de velocidades o suporte matemático necessário para construir imagens sísmicas confiáveis. Nós acreditamos na importância de construir modelos iniciais de velocidades que reflitam as características geológicas existentes antes de aplicar esta atualização tomográfica/FWI mencionada. Neste sentido, propomos a inserção das denominadas estratificações dentro da seção evaporítica, utilizando uma adaptação da técnica de inversão sísmica *model-based*. Seguindo este novo modelo incluindo as estratificações, sugerimos a atualização por iterações tomográficas ou FWI, para adicionar ao controle geológico do modelo a convergência matemática necessária. Finalmente, neste trabalho, nós realizamos a migração com e sem a inserção destas características geológicas no modelo inicial de velocidades e comparamos os resultados.

**Palavras-chave:** seção evaporítica, estratificações, modelo de velocidade, migração sísmica, imagem sísmica.

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## INTRODUCTION

Drilling in the Brazilian offshore pre-salt reservoirs, in the Santos Basin, always requires crossing an evaporitic section that ranges from dozens of meters to a few kilometers of salt thickness. Besides, the presence of different types of evaporitic minerals, with diverse mechanical behaviors, imposes the creation of structural complex scenarios. Therefore, understanding and properly characterizing the rocks inside this section are essential for diverse activities as safety during the well drilling operations, geomechanical hazard evaluations, and geological velocity modeling for seismic processing, among many others processes.

Ji et al. (2011) defend the idea that homogenous velocity for the evaporitic section affects the images quality under the salt section. They cite the weakness and discontinuity in seismic reflection, diffractions-like events and misinterpretation as the main problems when choosing those homogeneous compressional velocity models over more heterogeneous ones. They propose the insertion of heterogeneities inside the evaporitic section, to better represent the compressional velocity variations.

Huang et al. (2010), evaluating seismic images in the Santos Basin, consider that good images for the pre-salt reservoir do not ensure a reliable depth position for the base of salt, which is the reference for the top of pre-salt reservoir. They associate this phenomenon with the usage of simple velocity models in the evaporitic section. These models disregard the velocity inhomogeneity as they are noticed by the stratifications inside the evaporitic section. They also confirm the necessity to adopt a complete "salt model" to correctly position the reservoir structures.

Jones & Davison (2014) mention many difficulties for the seismic imaging around or inside the salt bodies and use a dataset of the Santos Basin as the main example to emphasize those difficulties. They cite the inaccuracies in the compressional velocity assumptions or representations for the evaporitic section velocity model as the probable cause of this issue. They also observe some features such as interbedded layers (stratifications), overlying layers (a superior anhydrite and/or the Albian rafts presence) and salt flanks (encompassed within the HSD – Hidden Stratified Domain as proposed by Maul et al., 2018b).

Jackson et al. (2015) emphasize the presence of "enigmatic structures" within the evaporitic section in the Santos Basin. In Mohriak et al. (2008), we found the first statement of the term "enigmatic reflectors" which we believe have same meaning of the "enigmatic structures" as mentioned by Jackson et al. (2015). These features probably are the part of the seismic response of interbedded layers as mentioned by Jones & Davison (2014).

Since 2015, several results related to the evaporitic stratification modeling intending to enhance the pre-salt projects have been presented (Maul et al., 2015; Jardim et al., 2015; Meneguim et al., 2015). Maul et al. (2018b) summarize and state these features as the evaporitic stratifications caused by the mineral variation.

During the methodology development, several applications have taken advantage of using this strategy of modeling evaporitic stratifications. The more promising applications are related to uncertainties (Maul et al., 2015; Jardim et al., 2015), geomechanics (Toríbio et al., 2017; Teixeira et al., 2018), Kirchhoff migration and Reverse Time Migration – RTM (Gobatto et al., 2016; Fonseca et al., 2018; Maul et al., 2018a) and the initial model for Least-Square Migration (Dias et al., 2019).

In seismic migration tasks, until the early 2000's, the evaporitic section in the Santos Basin was usually considered as almost constant (compressional velocity around 4,500 m/s), with some tomography approach in order to update the compressional velocity, observing the gather alignment behaviors. Falcão (2017) proves that a reasonable depth migration in complex areas such as the pre-salt reservoirs in the Santos Basin depends on the accuracy of the geological velocity models.

Although the tomographic inversion supports the entire migration process, it is not a perfect solution for the velocity models updating (Guo & Fagin, 2002). These authors emphasize the necessity of incorporating a reasonable geological knowledge into velocity modeling workflow. Potentially, the FWI (Full-Waveform Inversion) methodology can generate high-resolution velocity models (Vigh & Starr, 2008), which are currently appropriate for the RTM (Reverse Time Migration) technique. However, according to Vigh et al. (2009), one of the main challenges for the FWI techniques is to produce (or to reproduce) a good initial velocity model to generate the seismic images with geological confidence regarding the subsurface geology.

Currently, the state-of-the-art regarding processing techniques are FWI for velocity model building (Ben-Hadj-Ali et al., 2008; Barnes & Charara, 2009; Operto et al., 2013; Vigh et al., 2014) and Least-Square Migration (LSM) for imaging as per discussed in Nemeth et al. (1999); Hu et al. (2001); Dias et al. (2017); Wang et al. (2017); Dias et al. (2018). These techniques are becoming the standard for the pre-salt projects in the Santos Basin, offshore Brazil.

Even though laboratory measurements indicate that the anisotropy in core evaporite samples is negligible (Yan et al., 2016), the multilayered rock sequences impose extrinsic anisotropy behavior when the seismic wavelength is significantly larger than the thickness of any individual layers (Backus, 1962).

Raymer et al. (1999, 2000) state that the salt extrinsic anisotropy could be over than 7% in the preferred direction of evaporation. Landrø et al. (2011) analyze salt-mine outcrops and infer a moderate degree of anisotropy in the order of 5% difference between horizontal and vertical velocities. Several authors consider that anisotropy for any geological layer is mandatory in order to generate more realistic seismic images (Cogan et al., 2011; Zdraveva et al., 2011; Cooke et al., 2012).

The importance of the anisotropy for the seismic imaging process is undoubtable. However, this aspect is not within the scope of this work and further discussions about this matter are not presenting in our results.

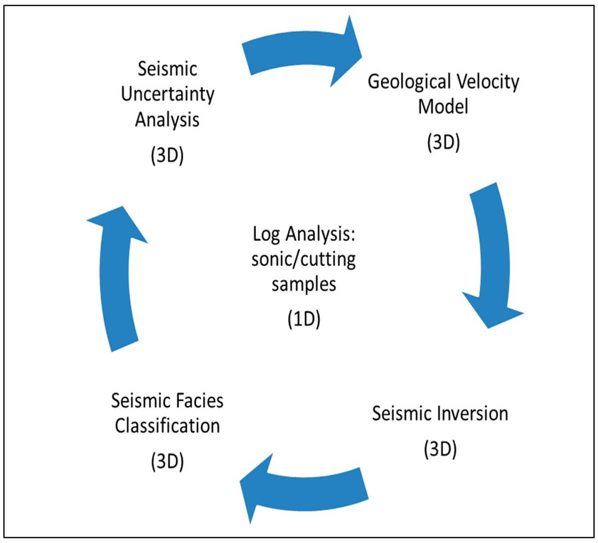


**Figure 1** – Proposed workflow to generate a more realistic geological seismic velocity model (adapted from González et al., 2016).

## METHODOLOGY

The first part of the methodology applied in this project follows the workflow presented in González et al. (2016), see Figure 1. This method allows the insertion of the salt stratifications or the layered sequence using seismic acoustic inversion (as presented by Meneguim et al., 2015), or any other seismic attribute if the inversion output is not available. The 1D analysis is performed with well logs and cutting supporting all stages. The first 3D approach is an initial model with geological constraints, where the stratifications are represented by combining velocities and seismic attributes. Then, a model-based inversion can be done for a better characterization of the rocks in the evaporitic section. Finally, a seismic facies classification, using impedance response in a Bayesian probabilistic approach, is performed to improve the modeling and to include uncertainty analysis to work with several scenarios. This gives to the evaporitic section the needed heterogeneity, especially to generate the initial compressional velocity model for the tomographic/FWI updating process, which precedes the migration as postulated by Fonseca et al. (2018), see Figure 2. The workflow requires previous stratigraphic interpretation, rock-physics analysis, model-based seismic inversion building and conversion from acoustic impedance to compressional velocity. It provides the initial velocity model to velocity updating (Tomography/FWI). After those velocity updating processes, and the gather alignment evaluation, another seismic migration is performed, generating a new and enhanced seismic image.

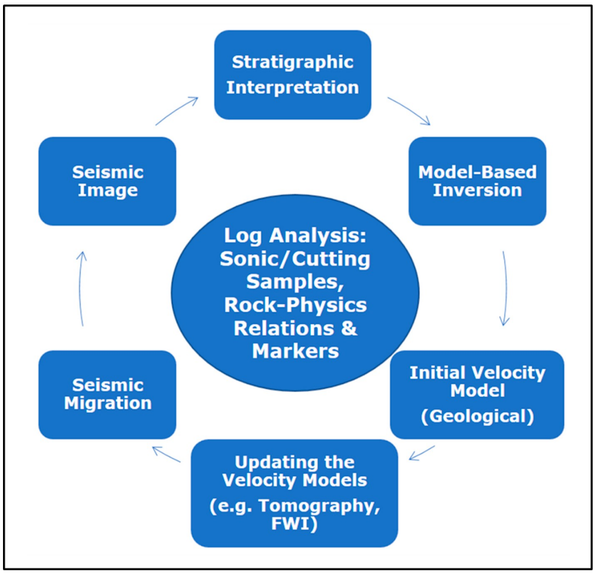


**Figure 2** – Proposed workflow for the seismic image updating (adapted from Fonseca et al., 2018).

To verify the efficiency of the methodology, we performed the tomographic inversion process and analyzed the gather alignment panels over two models. The first model is the standard one, which considers an almost constant compressional velocity model for the evaporitic section; the second is the stratified one, generated by an acoustic seismic inversion, as tested and presented in Gobatto et al. (2016); Fonseca et al. (2017); Fonseca et al. (2018); Maul et al. (2018a).

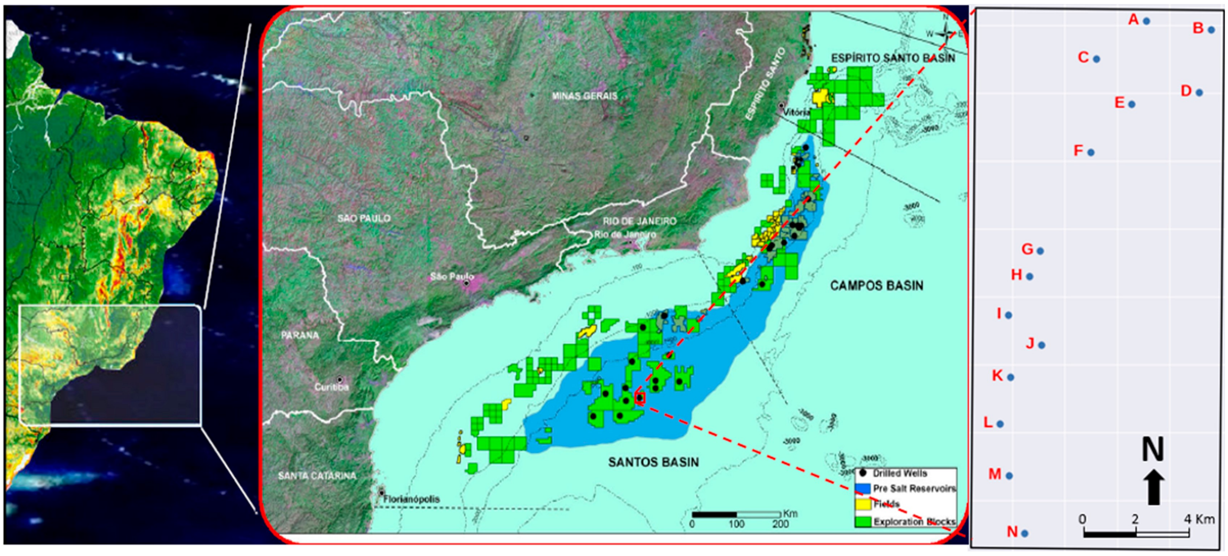


**Figure 3** – Location of study area (regional) and details of the available data. Dark blue shading is the area with hydrocarbon occurrences in the pre-salt province in the Santos and Campos Basins, covering an area of approximately 350,000 km². Water column ranges from 2,000 to 3,000 m.

## STUDY AREA AND AVAILABLE DATA

The study area is located in the pre-salt province in the Santos and Campos Basins. The specific tested dataset for this work is inserted into the project area that the first author has the formal authorization from the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) to develop his doctorate research. This area is a piece of the pre-salt Santos Basin province (Fig. 3) and contains a pre-stack depth migrated (PSDM) covering an area of approximately 200 km² and 14 wells with a broad suite of logs. In this study, the wells were labeled with capital letters from A to N, and the official names can be found in Table 1. Maul et al. (2018a & 2018c) demonstrate, using 182 wells of different 9 projects/fields in the Santos Basin, that the evaporitic section of these studied fields has many features in common, such as mineral percentages of occurrence, mineral percentages x thickness relation and velocity ranges per mineral groups.

## RESULTS, ANALYSIS AND DISCUSSIONS

The type variation of minerals, occurrence frequency and velocity are important considerations addressed when analyzing heterogeneities inside the evaporitic section. Figure 4 shows some wells drilled in the Santos Basin emphasizing the multilayered evaporite sequence. In this sense, Maul et al. (2018c) summarized the study of these 182 wells (Table 2), reflecting the average occurrence for each field, based on the following grouping: Low Velocity Salt (LVS); Halite and High Velocity Salt (HVS). The low velocity salt group (LVS) is mainly composed by carnallite, tachyhydrite, sylvite and other mobile salts; and the high velocity salt group (HVS) is basically composed by anhydrite and gypsum.

**Table 1** – Correspondence between the well designations used in this study and the official names from ANP.

| This Study | ANP |
|---|---|
| A | 3-BRSA-788-SPS |
| B | 9-BRSA-1037-SPS |
| C | 8-SPH-23-SPS |
| D | 8-SPH-13-SPS |
| E | 7-SPH-14D-SPS |
| F | 7-SPH-8-SPS |
| G | 7-SPH-4D-SPS |
| H | 9-BRSA-928-SPS |
| I | 7-SPH-5-SPS |
| J | 9-BRSA-1043-SPS |
| K | 1-BRSA-594-SPS |
| L | 7-SPH-1-SPS |
| M | 7-SPH-2D-SPS |
| N | 3-BRSA-923A-SPS |

Figure 5 illustrates how the compressional velocity varies among the minerals. In this study, we considered the average value per mineral plus the variation (+/-) taking two standard deviations as the reference.

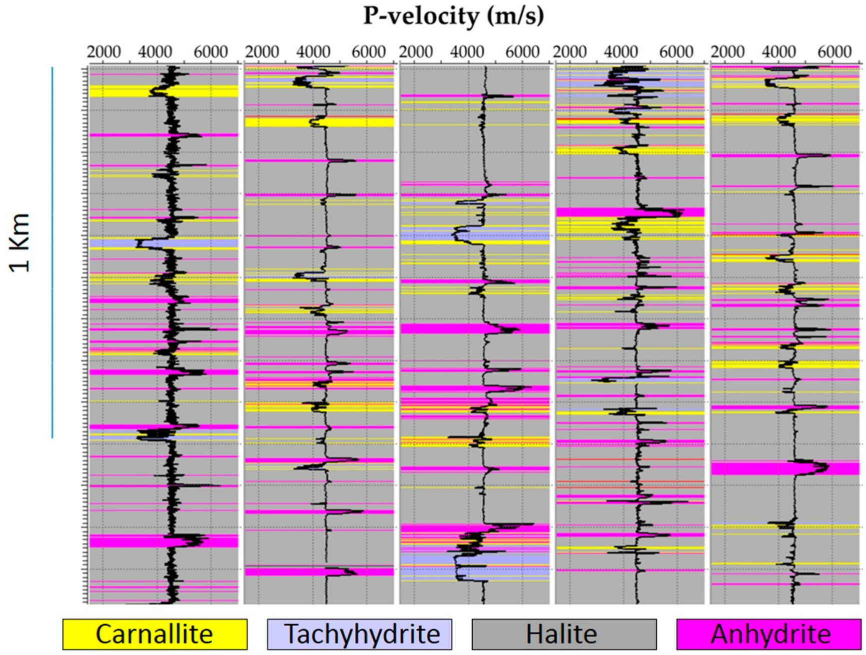


**Figure 4** – Identified stratifications inside the evaporitic section, considering a small piece of wells (5) from the 182 previously mentioned. Adapted from Maul et al. (2018a).

**Table 2** – Salt proportions and interval velocities (m/s) for nine fields inside the Santos Basin.

| Field | # Wells | % LVS | LVS ACV | % Halite | Halite ACV | % HVS | HVS ACV | WCV |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 8 | 4,018.56 | 83 | 4,480.88 | 8 | 5,210.27 | 4,462.56 |
| 2 | 29 | 9 | 4,218.47 | 82 | 4,563.69 | 9 | 4,975.84 | 4,567.53 |
| 3 | 17 | 12 | 4,054.42 | 77 | 4,498.25 | 12 | 4,989.92 | 4,505.66 |
| 4 | 3 | 13 | 3,971.00 | 71 | 4,507.09 | 16 | 4,927.59 | 4,505.04 |
| 5 | 5 | 3 | 4,167.00 | 84 | 4,538.00 | 13 | 5,123.33 | 4,576.00 |
| 6 | 7 | 3 | 4,264.19 | 80 | 4,509.87 | 17 | 5,061.36 | 4,596.05 |
| 7 | 72 | 8 | 4,122.33 | 81 | 4,526.47 | 11 | 5,105.84 | 4,560.03 |
| 8 | 25 | 4 | 4,182.53 | 88 | 4,533.59 | 8 | 5,003.35 | 4,547.16 |
| 9 | 4 | 6 | 4,055.63 | 81 | 4,486.58 | 13 | 5,077.49 | 4,535.67 |
| TNW | 182 | | | | | | | |
| AVG | | 7 | 4,117.13 | 81 | 4,516.05 | 12 | 5,052.78 | 4,539.52 |

LVS: Low Velocity Salt; HVS: High Velocity Salt; ACV: Average Compressional Velocity; WCV: Weighted Compressional Velocity; TNW: Total Number of Wells; AVG: Average; Compressional Velocity (m/s). Modified from Maul et al. (2018c).

In Figure 6, Fonseca et al. (2018), using 2 among the 182 available wells, illustrate how the mineral occurrence can be quantified per well, considering the mineral grouping proposed by Maul et al. (2018b), following the methodology described in Amaral et al. (2015), which intends to fill the well-log gaps using the interpreted drill cutting samples. In the mentioned study, the authors calculated the average compressional velocity for each well location, weighting by each mineral grouping proportion.

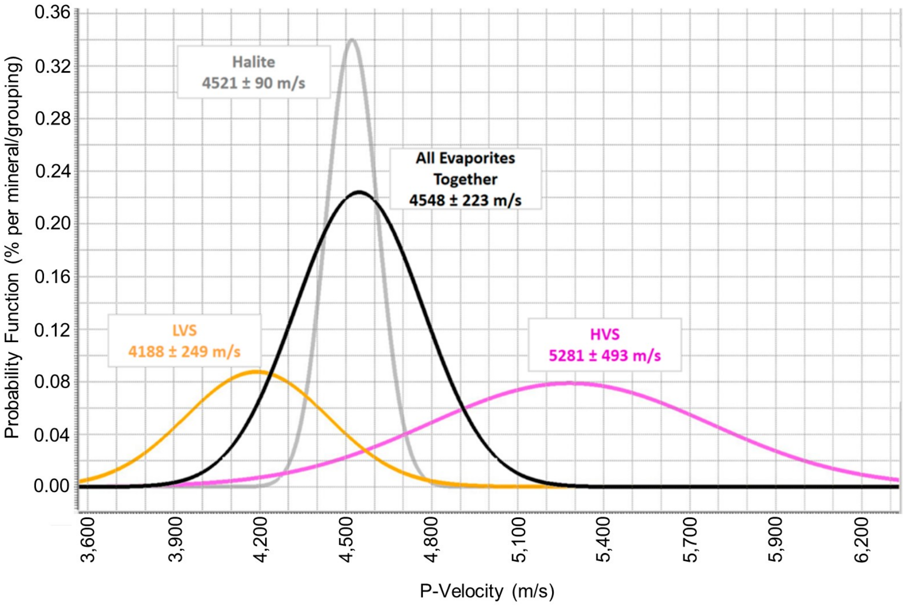


**Figure 5** – Mineral compressional velocity variation obtained from the logs considering a sample of 10 wells, among the 182 ones summarized in Table 2. Adapted from Maul et al. (2018a).

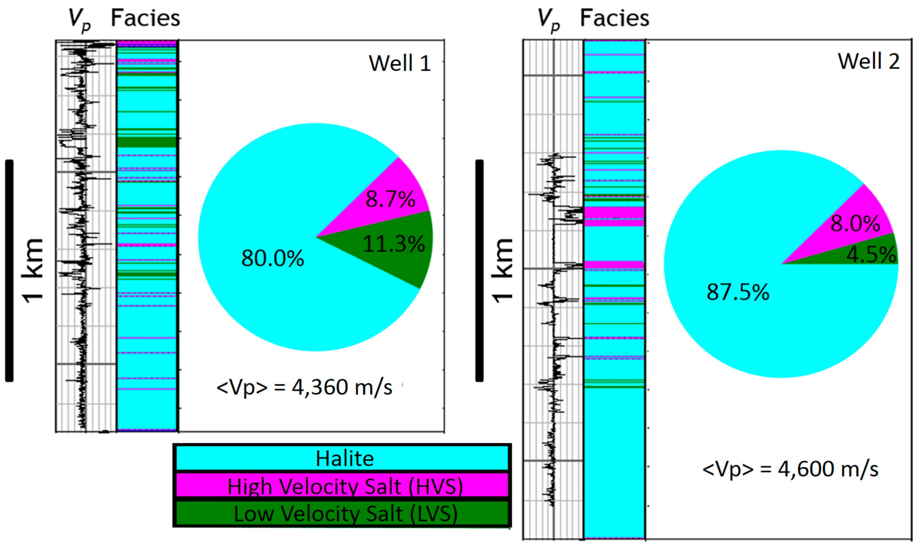


**Figure 6** – Example of the mineral occurrence (grouping) of 2 wells from the 182 wells analyzed for the development of the methodology. Adapted from Fonseca et al. (2018).

Analyzing Figure 6, it is reasonable to infer that the mineral content would be influencing the average compressional velocity at any well location. At well 1, the LVS proportion is higher than the HVS one. This difference affects the average compressional velocity in this well, decreasing its value. On the opposite way, analyzing well 2, the HVS content is higher than the LVS, increasing the average velocity compressional velocity. However, in both cases, the seismic velocity used for the legacy migration at those locations is close to 4,500 m/s, representing only the halite compressional velocity.

Figure 7 depicts the compressional velocity for the evaporitic section considering the stratification insertion by combining rock-physics and seismic inversion. We also compare it with the tomographic compressional velocity provided by

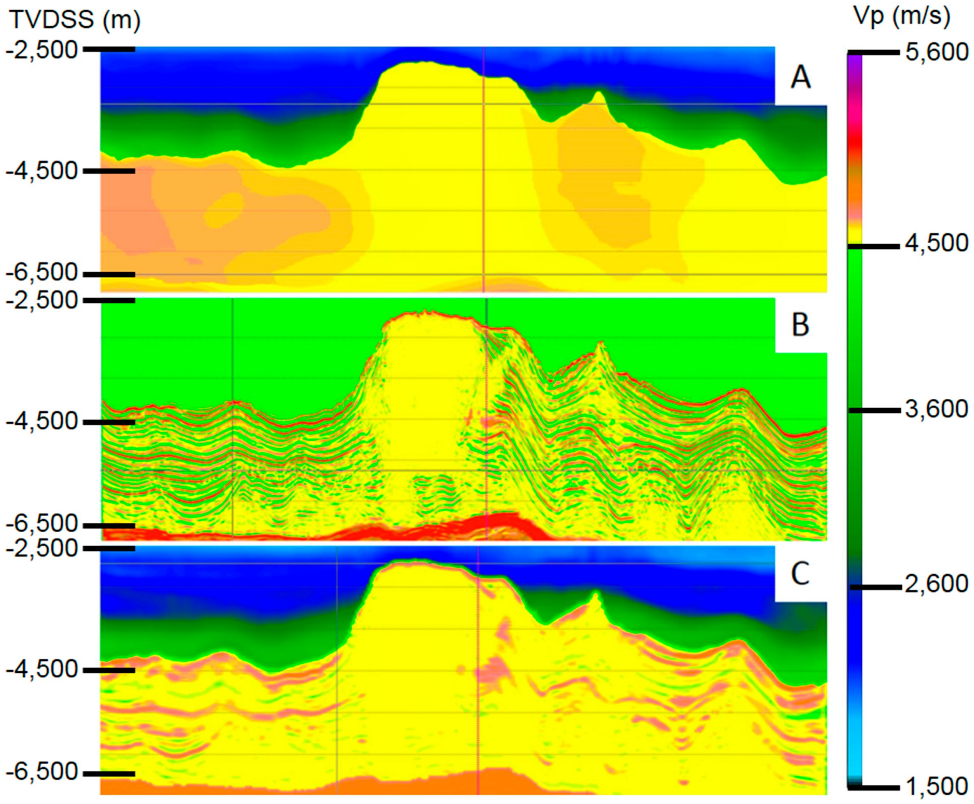


**Figure 7** – Salt heterogeneity representation: A: Compressional velocity obtained from the inversion tomography. This model corrects the almost constant velocity model using gather alignment as criteria; B: Compressional velocity obtained from the acoustic inversion results (model-based approach) applying a polynomial transformation to the impedance guided by the well logs. It illustrates the existing stratification controlled by amplitude response and well information; C: Smoothed compressional velocity model obtained from the inversion results. In this case, after applying a polynomial transformation guided by the well logs, we smoothed the model vertically. Adapted from Maul et al. (2018a).

the seismic processing. It is important to notice that, in order to use the stratified model to migrate the data, a vertical smoothing is necessary (Fig. 7C). The importance of considering the model-based inversion approach to better establish the stratification is well exemplified and documented in several works (Meneguim et al., 2015; Teixeira et al., 2017; Toríbio et al., 2017; Barros et al., 2017, Fonseca et al., 2018; Teixeira et al., 2018; Maul et al., 2019a, 2019b; Teixeira & Lupinacci, 2019).

As mentioned in Figure 7, the acoustic inversion output (Acoustic Impedance - Ip) must be converted to compressional velocity (Vp) to be used in the migration process. In this case, we consider the polynomial fit illustrated in Figure 8. It is important to mention that the curve-fitting choice is a source of uncertainties for the entire study. Thus, considerations about uncertainties are important in the development of similar studies. To emphasize this uncertainty estimation and the alternatives in controlling it, Teixeira & Lupinacci (2019) suggest the confidence level for the estimation as one possibility. In this case the authors regards the 95% of the best-fitting curve and propose that inside this confidence level any alternative fit are defensible. However, the physical implications in the choice of different equations need to be carefully analyzed and constrained by well logs, essentially because they can lead to incorrect depth positioning.

In Figure 9 we present two maps of the average compressional velocity for the evaporitic section. Figure 9A illustrates the average compressional velocity map for the evaporitic section considering the original tomographic velocity model (the standard approach). In that case, the methodology applied a “flooded salt model” (initially almost constant – 4,500 m/s), followed by tomography – three iterations were necessary to achieve a good gather alignment. In the second map (Fig. 9B), we built the compressional velocity model for the evaporitic section

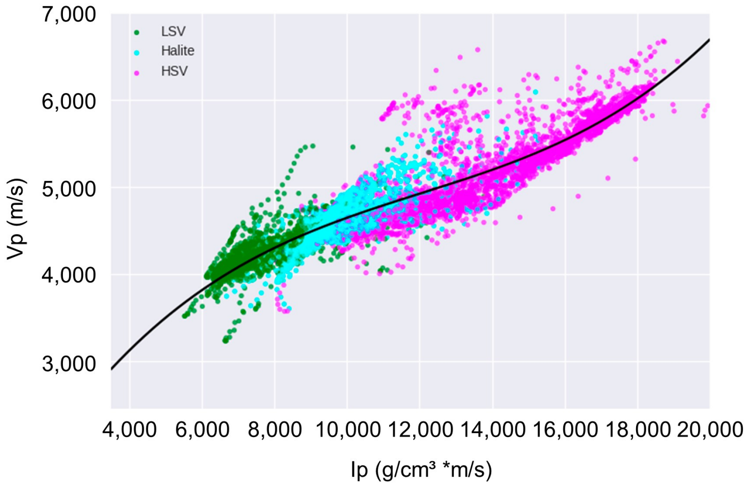


**Figure 8** – Transformation from Acoustic Impedance (Ip) to Compressional Velocity (Vp). Well-log cross-plot (Vp versus Ip). Colors are mineral groups (Green – LVS; Light Blue – Halite and Purple – HVS). Black line is the polynomial fit considered in Maul et al., 2019b.

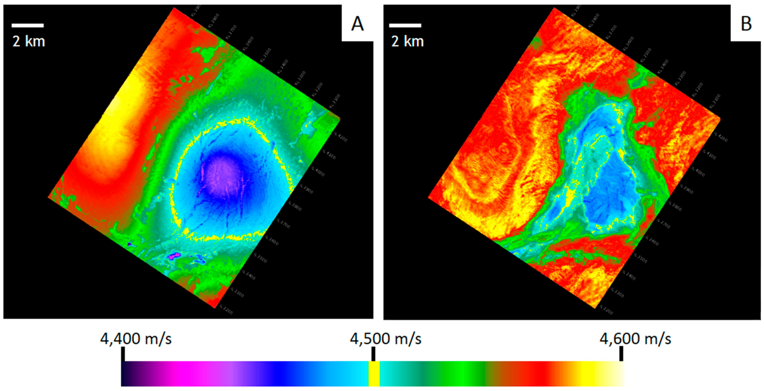


**Figure 9** – Average compressional velocity (Vp) map for the evaporitic section. A: Considering the almost constant Vp (4,500 m/s) as the initial model, plus the three tomographic inversion updates for the evaporitic section; B: Considering the stratified velocity model as the initial model, plus the one tomographic inversion update for the evaporitic section. Adapted from Maul et al. (2018a).

using the combination of rock-physics analysis and model-based acoustic inversion. Remarkably, only one tomographic iteration was necessary to achieve a similar level of gather alignment.

The stratification insertion imposes to the evaporitic compressional velocity model the heterogeneities observed in the seismic response (the reflections inside the evaporitic section), and sampled during the well drilling process. Therefore, the average compressional velocity map must reflect it, which we can observe only on Figure 9B. Figure 9A does not present these heterogeneities, since it considers a smooth compressional velocity model for the evaporitic section.

Figure 10 presents a seismic section and an example of gather alignment. The main difference when adopting the stratified model is the reduction in the number of iterations necessary during the tomographic inversion. The "cost" reduction due to the application of this procedure also ensures a good image quality.

We can see through the analysis of Figures 11, 12 and 13 that, besides the gain related to the reduction of computational cost, the image quality has also improved, with better images focusing, structural representation, and vertical positioning. In these images, the only difference is the velocity model used

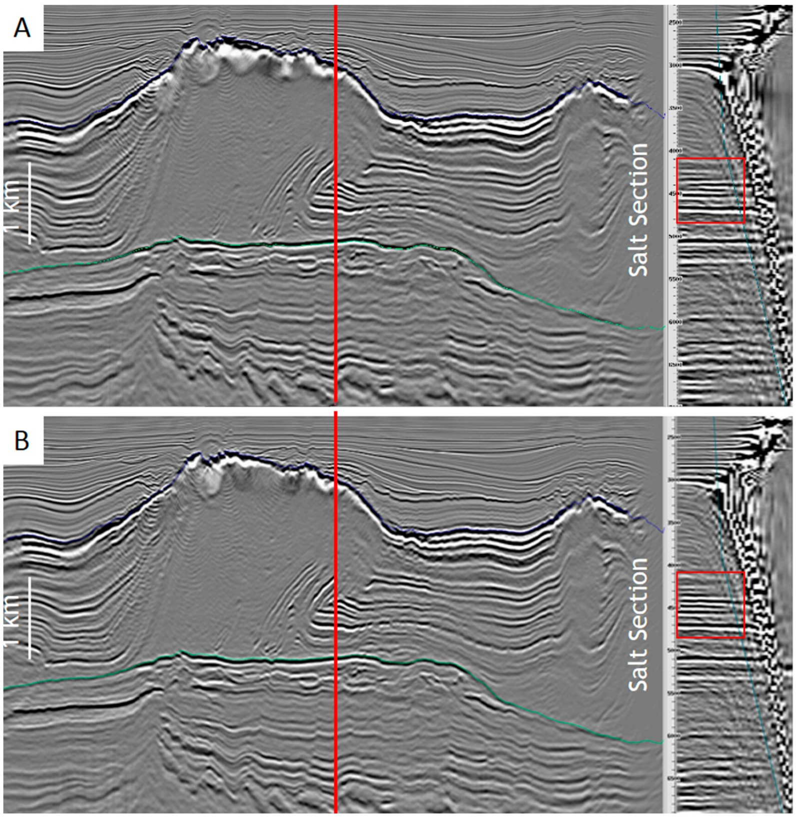


**Figure 10** – Migrated seismic section and a piece of a seismic gather panel illustrating the obtained alignment considering (the vertical red lines in the left part of figures "A" and "B" represent the position where the gathers were analyzed and the boxes in the right part represent the details of the gather alignment in both cases): A: The starting compressional velocity model, almost constant, after the three tomographic inversion iterations to align the analyzed gathers; B: The starting compressional velocity model delivered by the stratification insertion, after the single tomographic inversion iteration to align the analyzed gathers. Observe the same level of gather alignment in both examples, which implies a reduction of computational cost when considering the stratified model. Adapted from Maul et al. (2018a).

for migration. Another point to be considered is the fact that due to computational limitations, the Kirchhoff algorithm was the choice for the seismic migration, although we are aware of better algorithms to be applied in this dataset, like Reverse Time Migration (RTM) and Least Square Migration (LSM). In other words, we believe that the image quality could be even more enhanced when considering more appropriate algorithms.

## CONCLUSIONS

We believe that the way to improve seismic images in structurally complex areas such as the pre-salt reservoirs in the Santos Basin is to choose wisely the correct migration algorithm and to construct more realistic compressional velocity model containing reliable geology features.

The combination of rock-physics and model-based acoustic inversion approach gives to the evaporitic section an important contribution in terms of geology by inserting the existing multilayered stratifications.

The representation of geological features decreases the computational effort as it reduces the numbers of iterations in order to obtain good gather alignments prior to the final migration process (Maul et al., 2018a).

Besides the decrease in computational effort, the most important result when applying this combined approach (to perform the velocity update over the stratified model plus a good migration algorithm) is a more confident seismic image,

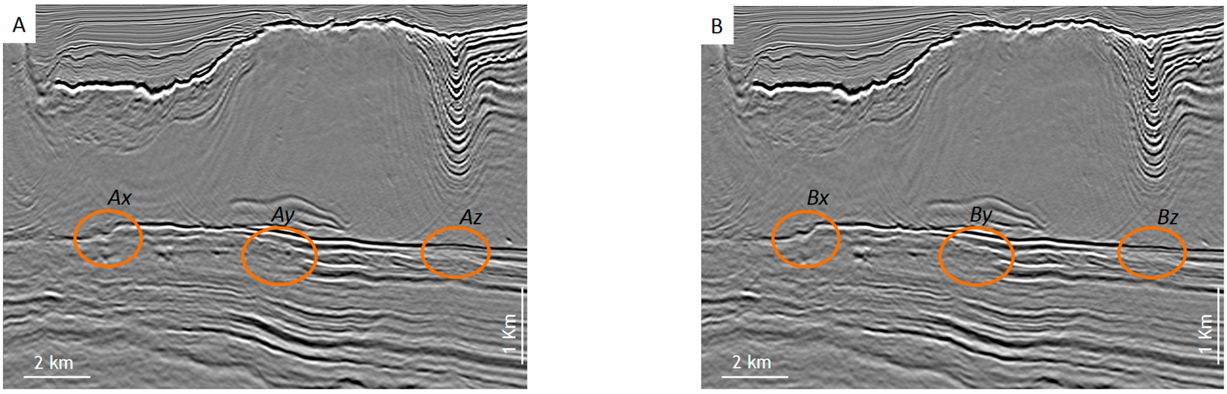


**Figure 11** – Migrated seismic sections using both models: A: The starting compressional velocity model, almost constant, after the three tomographic inversion iterations to align the analyzed gathers; B: The starting compressional velocity model delivered by the stratification insertion, after the one tomographic inversion iteration to align the analyzed gathers. Observe the better imaging when using the model with the stratification insertion: better continuity of the reflector Bx over Ax and By over Ay, and the more coherent positioning in Bz than Az (notice the evaporitic behavior above the analyzed point). Adapted from Maul et al. (2018a).

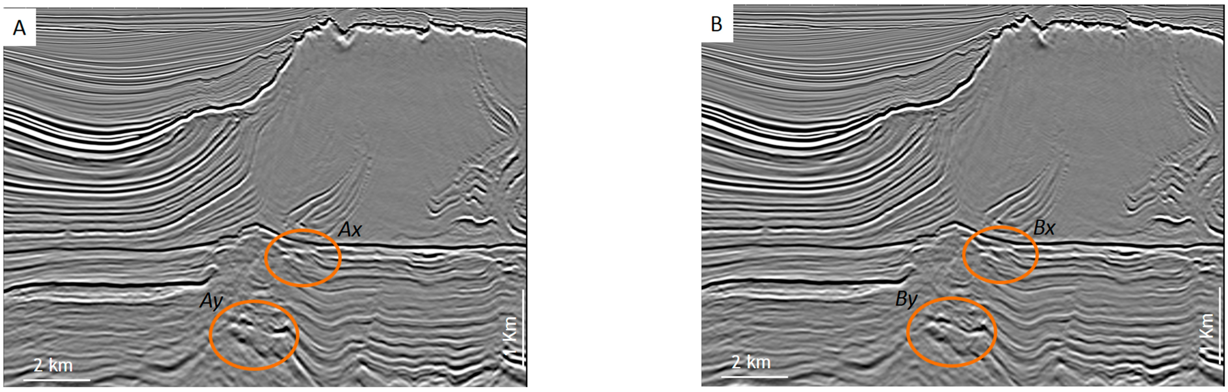


**Figure 12** – Migrated seismic sections using both models: A: The starting compressional velocity model, almost constant, after the three tomographic inversion iterations to align the analyzed gathers; B: The starting compressional velocity model delivered by the stratification insertion, after the one tomographic inversion iteration to align the analyzed gathers. Observe the better focusing of the image when using the model with the stratification insertion: positions Bx over Ax, and better imaging building (continuity in geology) in By than Ay. Adapted from Maul et al. (2018a).

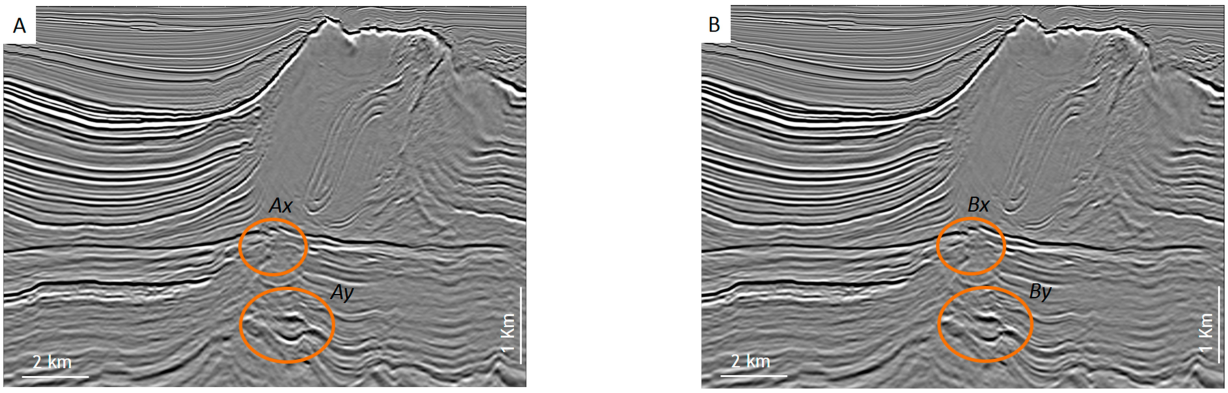


**Figure 13** – Migrated seismic sections using both models: A: The starting compressional velocity model, almost constant, after the three tomographic inversion iterations to align the analyzed gathers; B: The starting compressional velocity model delivered by the stratification insertion, after the one tomographic inversion iteration to align the analyzed gathers. Observe the better imaging (the fault sharping) when using the model with the stratification insertion: positions Bx over Ax, and better event focusing when comparing By over Ay. Adapted from Maul et al. (2018a).

which covers several aspects: better representation of structures, geological event continuity, depth predictions and signal quality, allowing a better rock property distribution based on the seismic quantitative interpretation.

We still believe that the anisotropy of the evaporitic section could also consider the stratified model to guide the distribution of the three-dimension anisotropic parameters.

The methodology was tested in several seismic processing projects. Moreover, we also tested those models for new seismic design studies such as illumination studies (Maul et al., 2015), uncertainty analysis regarding both depth and lateral positioning and accuracy in reservoir property distribution (Meneguim et al., 2015; Paes et al., 2019), security in well drilling (Teixeira et al., 2015), geomechanical flow simulation (Teixeira et al., 2018).

Therefore, despite the seismic ambiguity and seismic resolution, we believe that it is an approach to consider in all projects for the pre-salt section in any basin around the world.

It is also important to take care about other relevant aspects in terms of compressional velocity model building not only for the evaporitic section as described in this paper. The authors are also researching and applying similar methodologies, looking for the incorporation of other important geologic features such as the Albian rafts in the Santos and Campos Basins, Brazilian offshore, structural complexity related to folds and faults, among others.

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Anexo A5:

***Combining of Stratified Salt Velocity and Least-Squares Migration: Effects on Image Quality, Resolution, Depth Positioning and Amplitude Response***

Journal of Applied Geophysics, APPGEO-D-20-00150.

Submetido em 30/10/2020.

Maul, A., Bulcão, A., Dias, R.M., Pereira-Dias, B.,
Teixeira, L., Borges, F., González, M., Guizan, C. & Cetale, M.

**Cover Letter**

Alexandre Maul
Petrobras, Av. Henrique Valadares, 28, Rio de Janeiro, RJ, Brazil;
Universidade Federal Fluminense, Av. Gal. Tavares de Souza, Niterói, RJ, Brazil
.

September 29th, 2020

Dear Editor of Journal of Applied Geophysics,

We wish to submit an original research article entitled "COMBINING OF STRATIFIED SALT VELOCITY AND LEAST-SQUARES MIGRATION: EFFECTS ON IMAGE QUALITY, RESOLUTION, DEPTH POSITIONING AND AMPLITUDE RESPONSE" for consideration by Journal of Applied Geophysics.

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

Several studies describe the importance of building detailed seismic velocity models and the necessity of applying the state-of-the-art migration schemes, such as Reverse-Time Migration (RTM), and Least-Squares Reserve-Time Migration (LSRTM) to generate enhanced seismic images, especially for geologically complex areas. In the Santos Basin, Brazilian offshore, after the discovery of the pre-salt province, the well data information confirmed the complex morphology and heterogeneities of the salt section, which included the internal stratifications. However, we observed none has tested the effect of including the intricate intrasalt velocities on these standard migration algorithms. The evaluation relies on the creation of a geologically complex model under the salt section based on the observed data. We modelled a forward finite-difference seismic amplitude (synthetic seismic) using the velocity model that includes the complexities of the salt heterogeneities (stratified velocity model). After, we used these models to perform LSRTM whose result is our reference seismic image. This reference seismic image (i) is compared with the other possibilities: (ii) tomographic velocity and RTM; (iii) tomographic velocity and LSRTM; (iv) new stratified velocity model and RTM; and (v) new stratified velocity model and LSRTM. We quantitatively compared the observed differences among them. Therefore, we demonstrated how the association of more reliable velocity model for the salt section – considering its internal stratification – and the right combination of migration strategies (LSRTM) delivers the optimal results covering several aspects such as image quality, resolution, depth positioning and amplitude response. We truly believe that the novelty of this applicable research mainly resides in the seismic migration subject, especially where the geological complexity is present, not only in the Santos Basin but also in widespread seismic-dependent hydrocarbon basins.

Thank you for your consideration of this manuscript.

Sincerely,

Alexandre Maul

Journal of Applied Geophysics

# Combining stratified salt velocity model and least-squares migration: effects on image quality, resolution, depth positioning and amplitude response

--Manuscript Draft--

| | |
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| **Manuscript Number:** | APPGEO-D-20-00150 |
| **Article Type:** | Research Paper |
| **Section/Category:** | Exploration seismics, including Theory and Modelling |
| **Keywords:** | Salt stratification; least-squares migration; Detailed velocity model; seismic imaging; Seismic inversion; Reliable models |
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| | Cleverson Guizan, PhD |
| | Marco Cetale, DSc |
| **Abstract:** | Seismic amplitude is a key attribute for reservoir characterization. Its use as a trend to populate reservoir grids with properties and poses some challenges due to the intrinsic uncertainties of the seismic experiment, especially under complex geological environments. The combination of reliable velocity models for the salt section and a suitable algorithm for seismic imaging seems to be the best way to achieve good results for both data quality and depth positioning. However, state-of-the-art depth-migration algorithms still need to be combined with an amplitude-compensation scheme to correct the effects caused by uneven seismic illumination. In this work, we present the benefits of combining a reliable velocity model - with stratification of the evaporitic section - and least-squares migration. We use modeled seismic amplitude in different imaging scenarios and show a quantitative comparison in key horizons. The results suggest that salt stratification has a significant impact on the depth positioning of the seismic events, while least-squares migration plays a more significant role in recovering the seismic amplitude. |
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Highlights

- Pre-salt reservoirs require enhanced seismic images for projects evaluation
- Salt stratification insertion is a way in building detailed seismic velocity models
- Model-based seismic inversion helps to build detailed seismic velocity models
- LSRTM is the most indicated migration method for complex areas

# COMBINING STRATIFIED SALT VELOCITY MODEL AND LEAST-SQUARES MIGRATION: EFFECTS ON IMAGE QUALITY, RESOLUTION, DEPTH POSITIONING AND AMPLITUDE RESPONSE

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## Abstract:

Seismic amplitude is a key attribute for reservoir characterization. Its use as a trend to populate reservoir grids with properties and poses some challenges due to the intrinsic uncertainties of the seismic experiment, especially under complex geological environments. The combination of reliable velocity models for the salt section and a suitable algorithm for seismic imaging seems to be the best way to achieve good results for both data quality and depth positioning. However, state-of-the-art depth-migration algorithms still need to be combined with an amplitude-compensation scheme to correct the effects caused by uneven seismic illumination. In this work, we present the benefits of combining a reliable velocity model - with stratification of the evaporitic section - and least-squares migration. We use modeled seismic amplitude in different imaging scenarios and show a quantitative comparison in key horizons. The results suggest that salt stratification has a significant impact on the depth positioning of the seismic events, while least-squares migration plays a more significant role in recovering the seismic amplitude.

## 1. Introduction:

Seismic imaging in complex geological environments is remarkably challenging (Zhang and Sun, 2009; Huang *et al*., 2010; Jones and Davison, 2014). High-quality seismic images in such conditions play a crucial role in exploration and development of the giant fields in the Santos Basin, offshore Brazil (Cooke *et al*., 2012). For the case of imaging within geological complexity, e.g. near-to-prominent salt bodies, the literature suggests significant improvements when considering full-waveform inversion (FWI) to update the velocity model prior to migration (Tarantola, 1984; Zhang and Wang, 2009; Kang *et al*., 2019). Reverse-time migration (RTM) is currently the most suitable algorithm for this environment, and it requires a velocity model that captures the overburden complexity (Jones and Davison, 2014; Kang *et al*., 2019; Shadrina *et al*., 2020). If no such model is available, RTM images can deliver suboptimal amplitude response (Guo and Fagin, 2002; Zdraveva *et al*., 2011). In this challenging scenario is where FWI has been used successfully in recent years to update the velocity model prior application of imaging algorithms, especially one that are formulated as an optimization problem such as in the least-squares migration (LSM) technique (Vigh *et al*., 2019).

A significant fraction of the seismic data used for reservoir characterization in the Santos Basin was processed using tomography-derived velocity models for the evaporitic section (Johann *et al*., 2013). The initials models for these tomographies was usually salt flood (around 4,500 m/s), mainly reflecting the halite velocity, as this is the more abundant mineral in these formations. However, the use of relative acoustic impedance as a proxy for the existing heterogeneity inside the salt section improves results of depth migration algorithms (Ji *et al*., 2011).

The improvement of salt velocity estimations in the Santos Basin is an active field of research. Maul *et al.* (2015) proposed a method to quantify and incorporate existing stratification in evaporitic sections, obtaining significant improvements in structural positioning below salt bodies. Later, the inclusion of intrasalt velocity proved to be valuable for seismic processing (Gobatto *et al.*, 2016; Falcão, 2017; Maul *et al.*, 2018; Maul *et al.*, 2019a; Maul *et al.*, 2019c). However, since the evaporitic section is not the main target of the companies, the vast majority of the drilling plans do not include sonic or density logging in salt layers – a crucial information to improve our understanding of this formation (Amaral *et al.*, 2015).

Despite playing an important role in seismic imaging of subsalt reservoirs, salt characterization alone is not enough to solve all the imaging issues - it is a common sense that the areal distribution of amplitude below complex salt bodies does not represent the elastic contrasts in subsurface correctly. LSM is a cutting-edge tool that compensates the poorly illuminated seismic amplitude (Schuster, 1993; Nemeth *et al.*, 1999), and remarkably improved the seismic quality below the salt section in the Santos Basin (Pereira-Dias *et al.*, 2017; Pereira-Dias *et al.*, 2018; Shadrina *et al.*, 2020). Nevertheless, it is particularly sensitive to errors in the velocity model, reinforcing the need for accurate and detailed model building schemes in order to capture the wave propagation and its illumination effects (Luo and Hale, 2014, Shadrina *et al.*, 2020).

In this paper, we explore the results of the combination of improved velocity models - including the stratification in the salt section - and least-squares migration. Both qualitative (visual inspection of the images) and quantitative (depth positioning and amplitude in some key horizons) comparison are shown for different imaging scenarios, allowing us to evaluate the benefits of each technique, individually and combined.

## 2. Methodology:

In order to generate the study scenarios, a synthetic geological model was built. This model was derived from field data acquired in the Santos Basin, and made available by the Brazilian National Petroleum Agency (ANP). As this study focuses on the benefits of including the salt velocities into the migration velocity model, we are aware of that isotropic multi-layered formations produce extrinsic anisotropic response in long-wavelength-effective medium (Backus, 1962; Yan *et al.*, 2016). Alternation of salt sequence can generate from 5% to 7% of anisotropy in velocity models (Raymer *et al.*, 1999, 2000; Landrø *et al.*, 2011). Therefore, we opted not to incorporate this information particularly because it would overlap the impact of the salt stratification and anisotropy on the seismic amplitude and depth positioning. Therefore, the difference in the subsalt seismic images of this study is exclusively due to the inclusion of intrasalt velocity. The preparation of the property model for the forward seismic modeling are described in details by Maul *et al.* (2019b) and is not be detailed here. The workflow followed in the current paper was:

a) Selection of a 2D line from the 3D model presented in Maul *et al.* (2019b), containing amplitude and impedance (the impedance was delivered from a model-based seismic inversion using the same amplitude data and all the available wells);
b) Insertion of geological features into the section (item "**a**"), creating contrasts of elastic properties (velocity and density) – which is used as control points for comparison of depth and amplitude in the modeled scenarios;
c) Forward modeling of seismic survey from the item "**b**" – this is the data that will be migrated using all the velocity models built in the sequence;

d) Reverse-time migration (RTM) of modeled data using the reference velocity model (described in step **c**), followed by LSM, resulting in our reference model (Image **I** – LSM (MODEL));

e) Reverse-time migration (RTM) of modeled data using the tomography-derived velocity model from the processing of the field data, obtaining Image **II** – RTM (TOMO);

f) Use of Image **II** as input for a model-based inversion, where the low-frequency model is built from the 5 pseudo-well logs (the pseudo-wells were taken from the 2D section described in "**a**" having only the log information from salt section). The result of the seismic inversion is combined with empirical correlations to transform the acoustic impedance into velocity model (Maul *et al.*, 2019b, Teixeira and Lupinacci, 2019);

g) Reverse-time migration (RTM) of modeled data using the velocity model obtained in step **f**, generating Image **III** – RTM (INV);

h) Least-squares migration of Images **II** and **III**, with their migration velocities, obtaining respectively Images **IV** – LSM (TOMO) and **V** – RTM (INV);

i) Evaluation and quantification of the differences between Images **II**, **III**, **IV** and **V** and the reference scenario (Image **I**).

It is important to mention that all the modeling and migration (RTM and LSM) in this work were done using as a source a Ricker wavelet with a cutoff frequency of 45 Hz, due to computational limitations. Table I summarizes the scenarios in this study. The reference property model (see figure 1), was used to simulate the seismic acquisition through the forward finite-difference modeling program employing the two-way acoustic wave equation, with non-reflecting boundary condition at the top (i.e. does not simulate surface related multiples in the seismic data). This modeling kernel is more realistic than the acoustic first order Born modeling, since it generates internal multiples and it is not the perfect adjoint for the migration operator (Schuster, 2017).

**Table 1**: Summary of the RTM scenarios considered in this study.

| Image | Combination | Migration Velocity | LSM |
|---|---|---|---|
| I | LSM (MODEL) | Same as Forward Finite-Difference Velocity Modeling | YES |
| II | RTM (TOMO) | Velocity from Standard Tomography Data | NO |
| III | RTM (INV) | Salt Inversion of Image II | NO |
| IV | LSM (TOMO) | Velocity from Standard Tomography Data | YES |
| V | LSM (INV) | Salt Inversion of Image II | YES |

LSM (MODEL): RTM + LSM using the forward finite-difference velocity model as input; RTM (TOMO): RTM using the original tomographic velocity model; RTM (INV): RTM using a new inversion of the salt section having the tomographic migration - RTM (TOMO) - as seismic data; LSM (TOMO): application of the LSM over the migration using the original tomographic velocity model - RTM (TOMO); and LSM (INV): application of the LSM over the migration using the new inversion of the salt section.

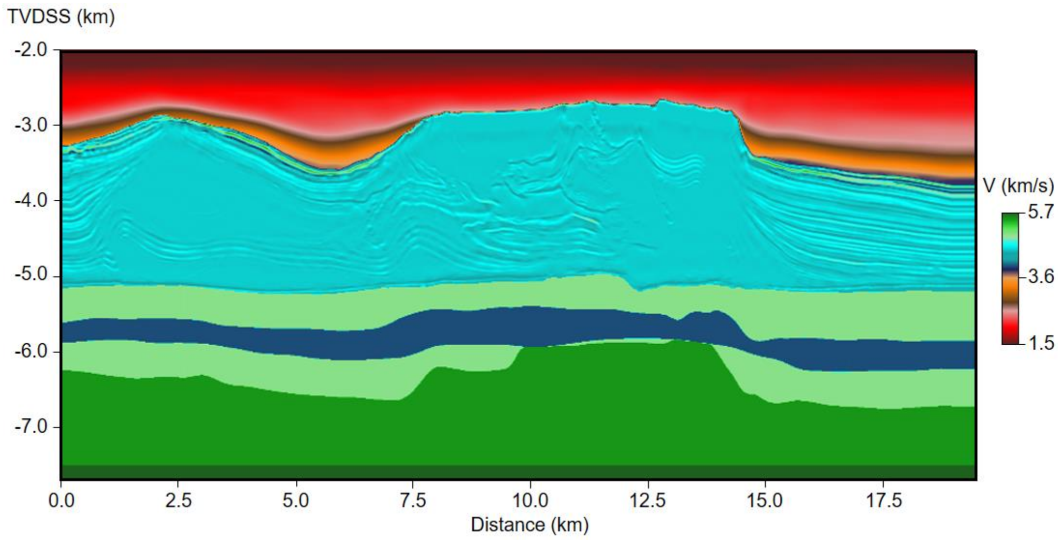



**Figure 1**: Velocity model used for forward-modeling seismic amplitude in all the migration tests. The model, which considers the heterogeneity in salt layer, includes horizons interpreted in the field data, as well as a flat, reference level close to the bottom, where we performed some comparisons. After the simulation of the seismic acquisition, we combined the migration velocity model (the tomographic velocity model X a velocity model from a new model-based seismic inversion), the using or not of the LSM, running RTM migrations.

The main goal of the LSM is to recover, based on an optimization process, the best reflectivity model according to a functional that measure the misfit between the observed and simulated dataset assuming a propagation model based on the Born approximation, mitigating distortions in poorly illuminated areas and extending the data bandwidth and, hence, its resolution (Schuster, 1993; Nemeth *et al.*, 1999). Despite the improvements, the technique has its limitations, mainly regarding the lack information about the subsurface, as the method usually relies on a first-order Born´s approximation to model. the events as we can see in figure 2, and where we can notice that the LSM response is closer to the actual reflectivity, when compared to the RTM response. There is also a significant improvement in resolution (Pereira-Dias *et al.,* 2017; Wang *et al.,* 2017).

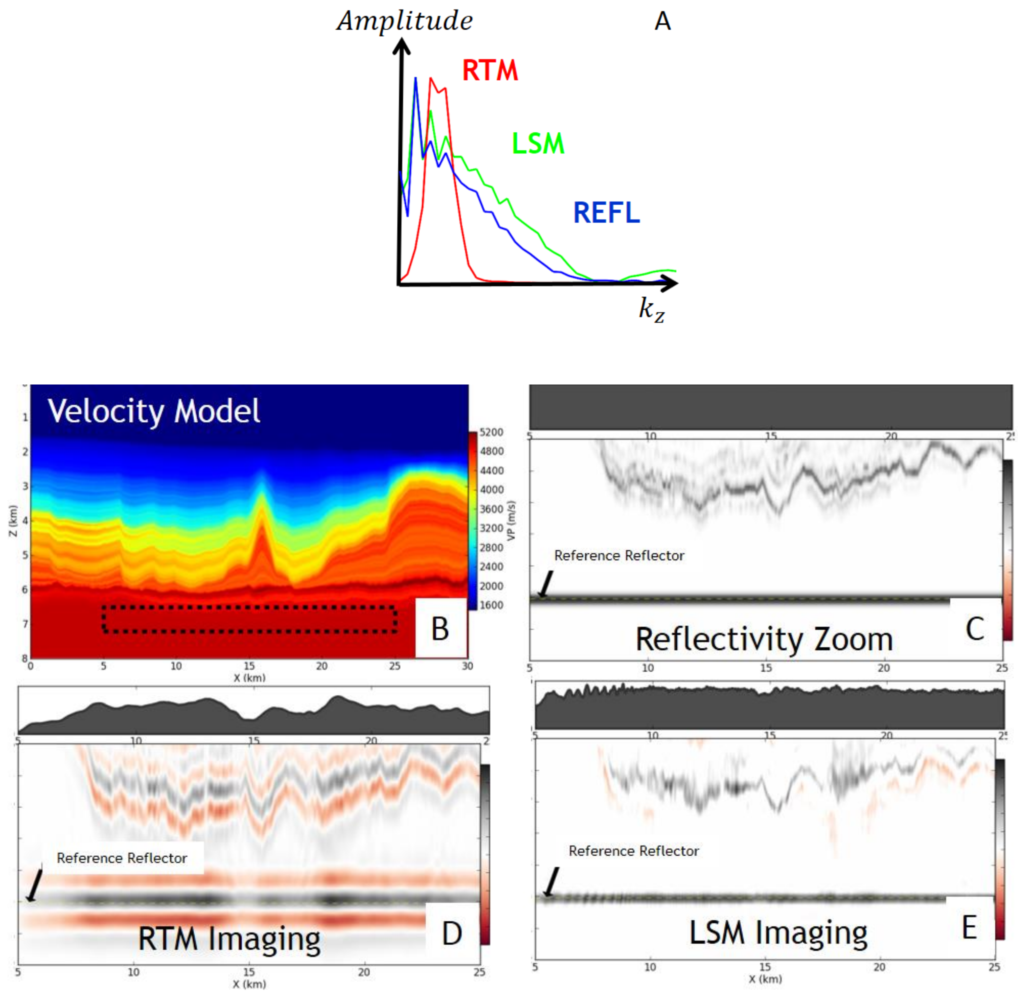



**Figure 2**: Example of the results of least-squares migration.
A: Comparison of LSM (green) and RTM (red) against the reflectivity response (blue). Notice how the LSM curve is much more similar to the reflective curve than the RTM's;
B: A synthetic model used for the experiment, emphasizing the target area to be evaluated (dotted rectangle);
C: Zoom in (dotted rectangle); Reflectivity on the "reference reflector" obtained from the synthetic model in B;
D: Zoom in (dotted rectangle); The amplitude response on the reference reflector, obtained from the synthetic model using standard RTM;
E: Zoom in (dotted rectangle); The reflectivity amplitude response on the reference reflector, obtained from the synthetic model using LSM.
Figure adapted from Pereira-Dias *et al.* (2017).

## 3. Results:

We modeled a narrow seismic acquisition using the velocity model in Figure 1 using the acoustic two-way wave equation with constant density. The synthetic dataset was reverse-time migrated with a slightly smoother velocity model version (a Gaussian filter was used in the slowness to avoid backscattering artifacts (Loewenthal *et al.*, 1987), followed by a least-squares migration, resulting in Image I, which is the best solution in terms of seismic imaging and will be used as the reference model. The result can be seen in Figure 3.

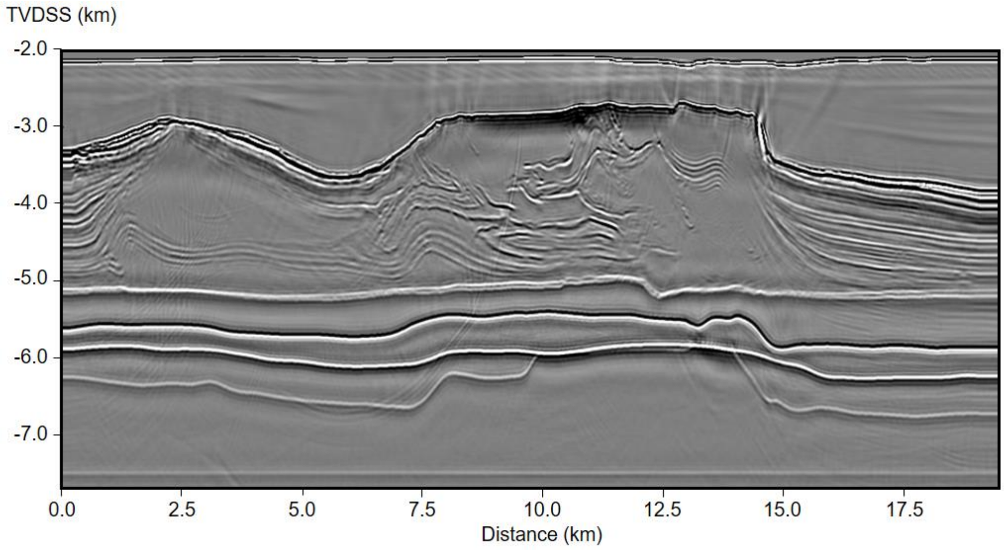



**Figure 3**: Image **I**, obtained from synthetic data modeled and migrated (RTM followed by LSM) using the property model shown in Figure 1.

The synthetic data also underwent reverse-time migration with two other velocity models. The first one is the velocity obtained from pre-stack tomography on the field data, and the second model, which is a new model-based seismic inversion using the migrated data and the pseudo-wells will be described in the sequence. The velocity model, as well as the resulting image (Image **II)** in figure 4, and its details regarding the geological features we are interested in can be seen in Figure 5.

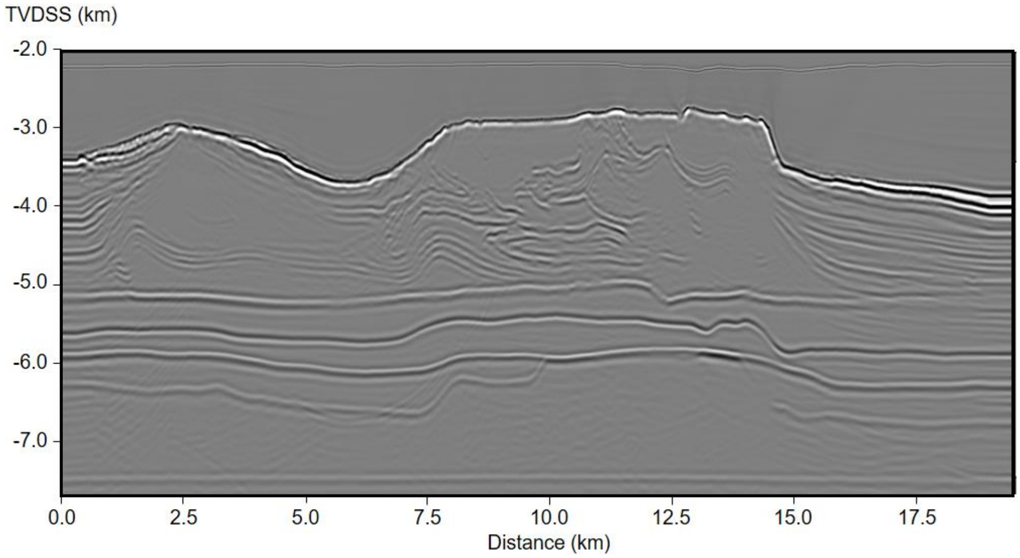



**Figure 4**: Image **II**, obtained from synthetic data modeled and migrated (RTM) using velocity from field data.

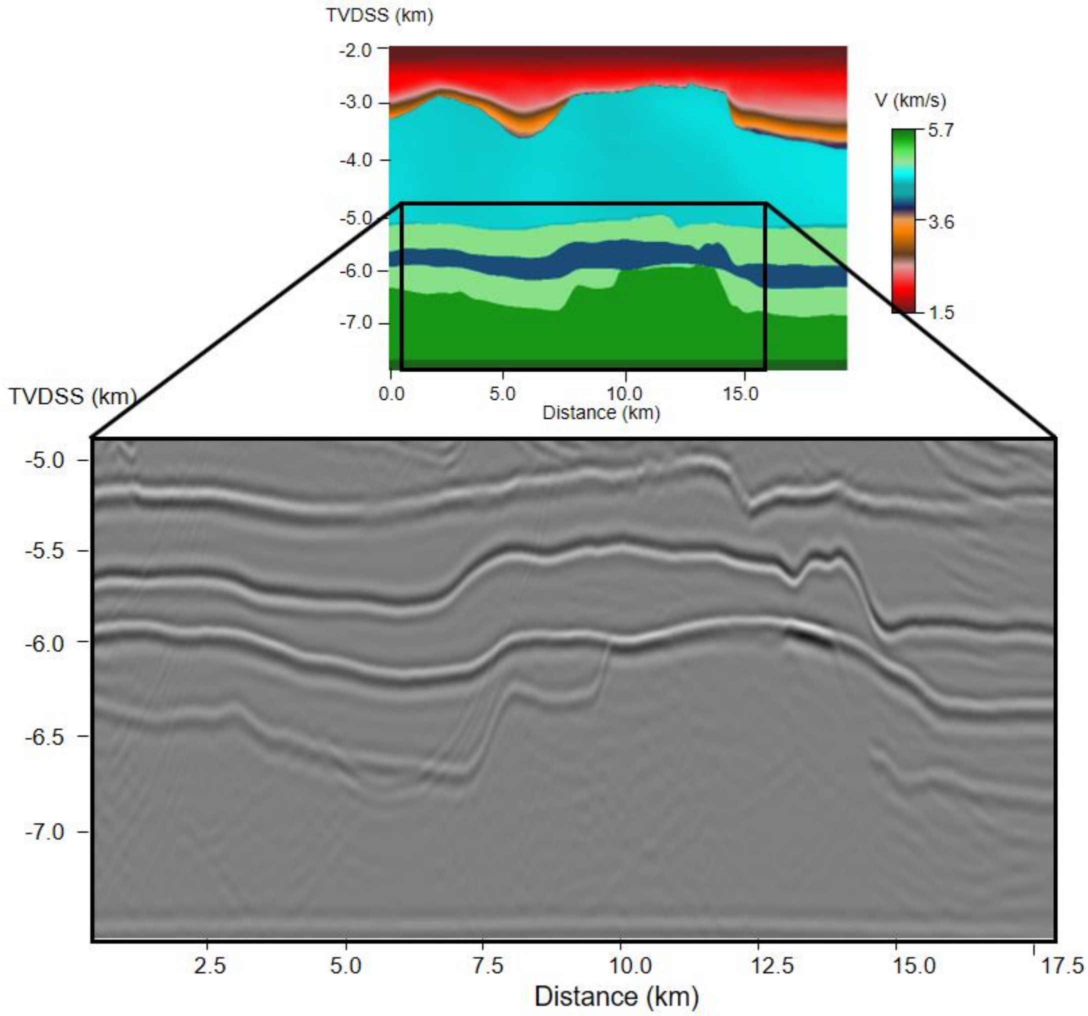



**Figure 5**: Migration details (bottom - Image **II**) using the standard tomographic velocity model (top).

Using Image **II** as input, combined with the log information from the five pseudo-wells containing impedance data, a model-based seismic inversion is performed with the goal of inserting in the intrasalt stratification into the velocity model. This improved velocity model (our second model) was used to migrate the synthetic data, resulting in Image **III**. Figure 6 shows both the improved velocity model and the resulting seismic. To Images **II** and **III**, least-squares migration was applied (with their respective migration velocity models), generating Images **IV** and **V** (Figures 7 and 8, respectively).

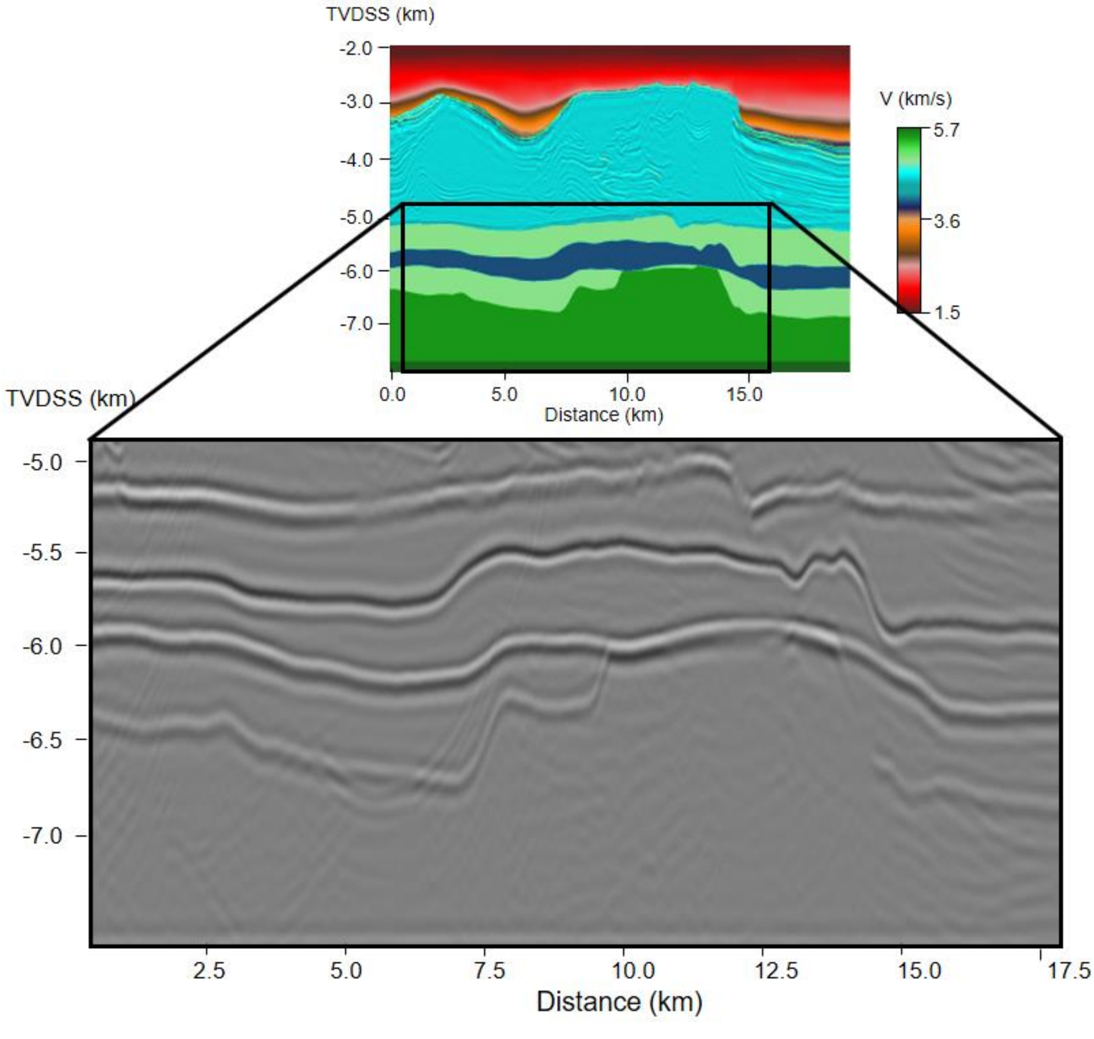



**Figure 6**: Migration details (bottom - Image **III**) using the updated velocity from seismic inversion. (top).

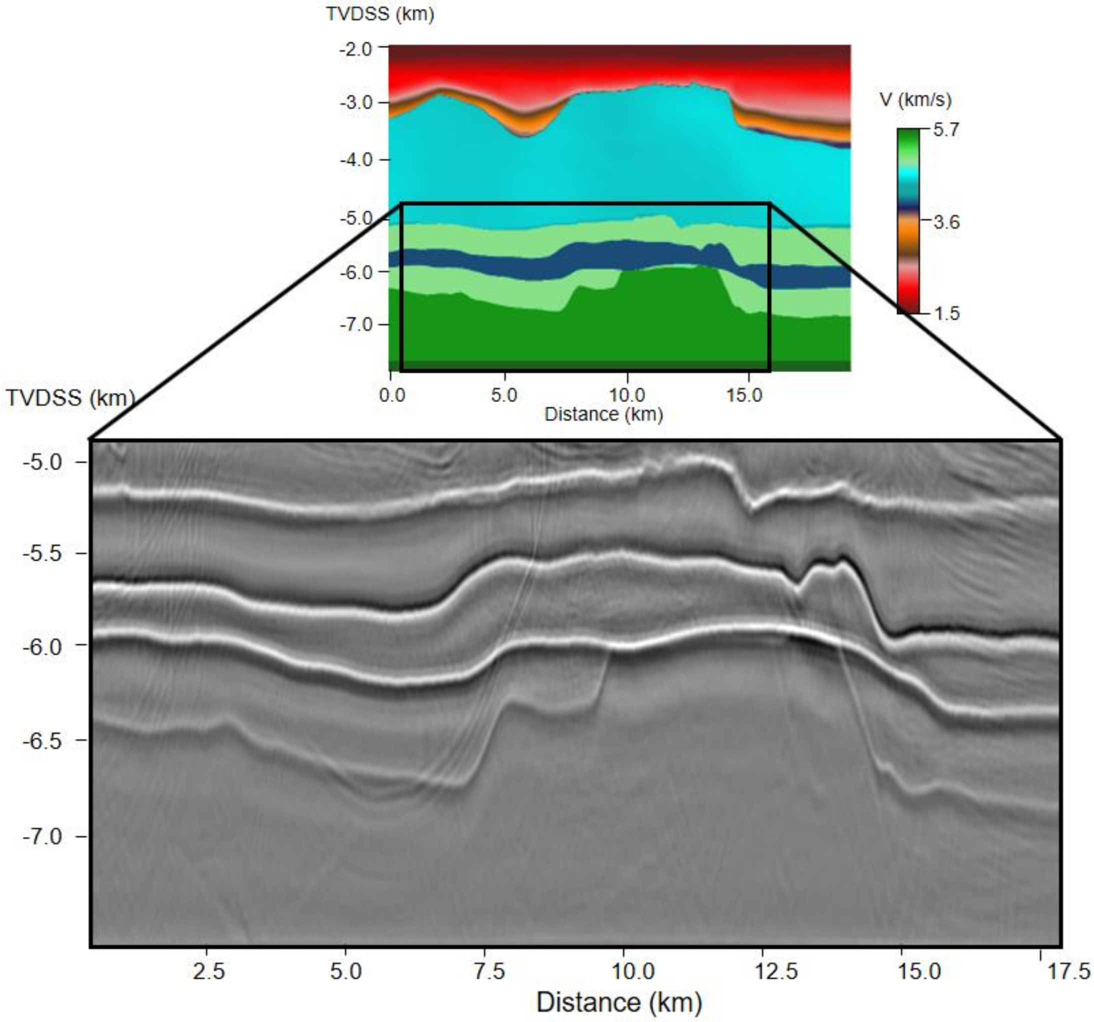



**Figure 7**: Migration details of Image IV, which corresponds to application of the LSM over the Image II.

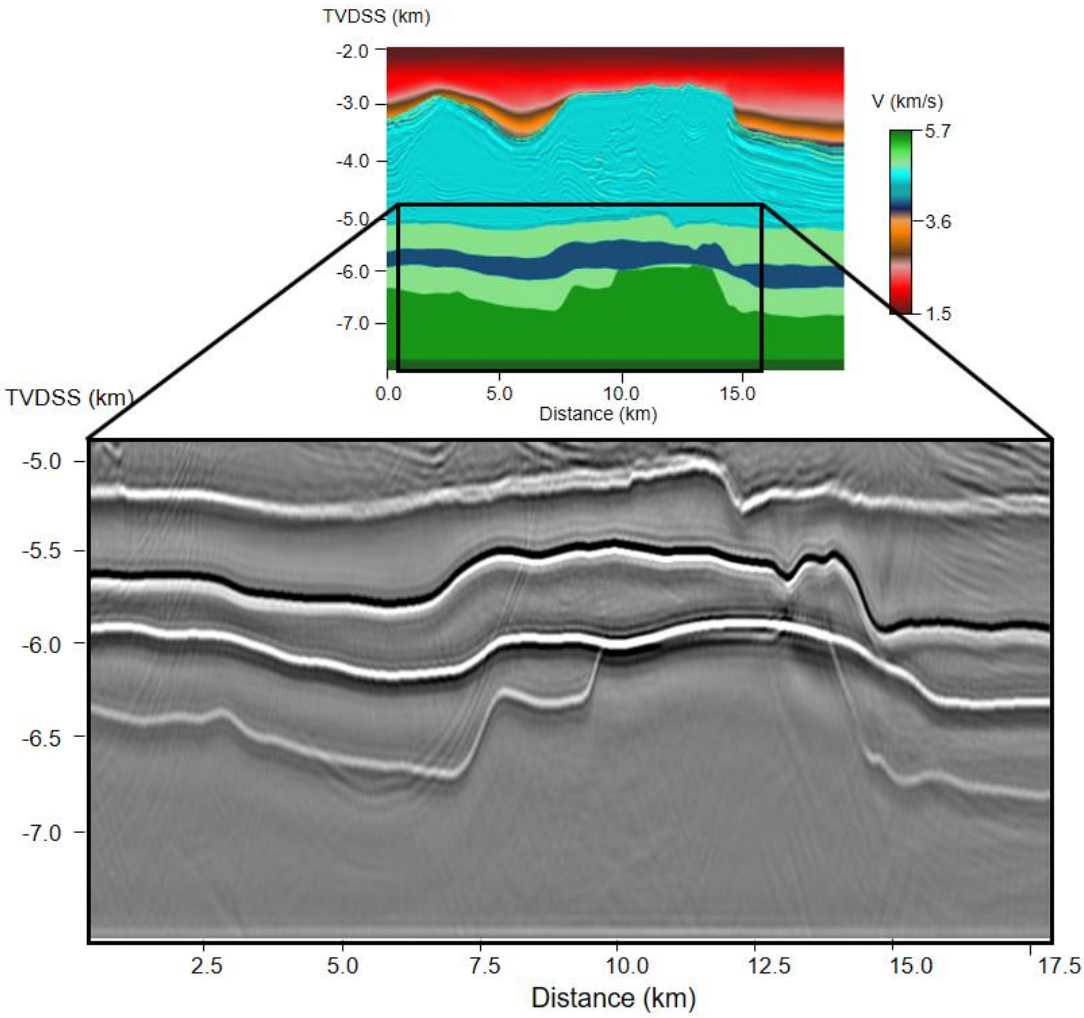



**Figure 8**: Migration details of Image V, which corresponds to application of the LSM over the Image III.

Figure 9 shows the power spectrum of the migrated images. The grey plot corresponds to the reference model (Image **I**).

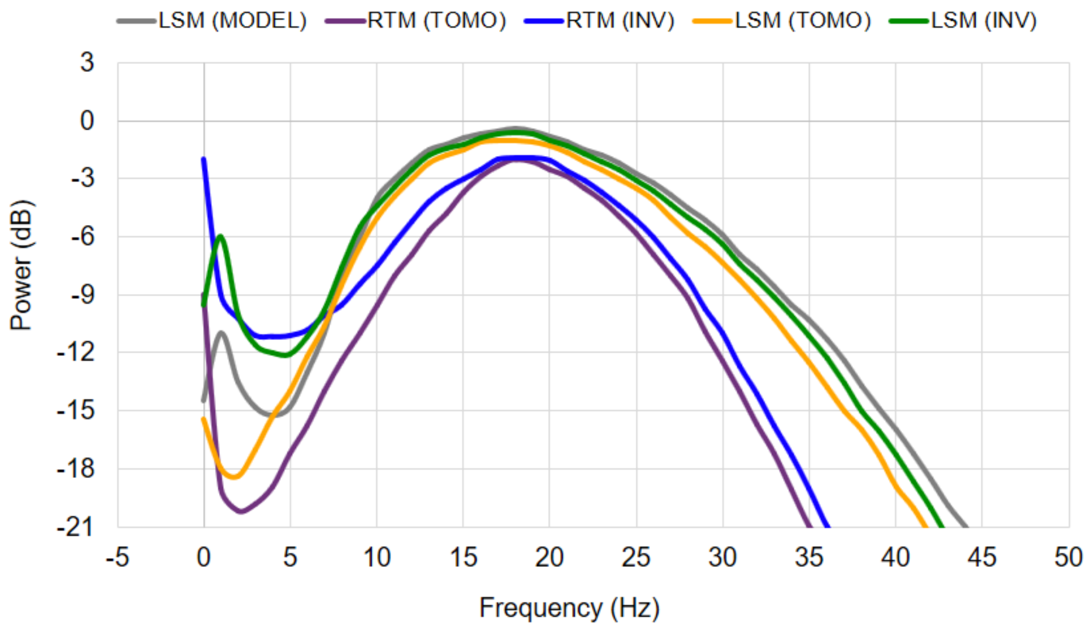



**Figure 9**: Frequency content of the five built images, including our reference result – LSM (MODEL), Image **I**.

Three key horizons are selected for a quantitative comparison between the reference image (Image **I**, in Figure 3) and the four modeled scenarios. Figure 10 represents these horizons. R1, the first level of reference, corresponds to the top of the dark blue layer; R2 represents the reflection at the base of this same layer; and R3 is a flat horizon positioned at the constant depth of -7,500 m, and can be seen in Figure 10 as the top of the deepest dark green layer. Figures 11-16 show quantitative comparisons computed at these three reference levels.

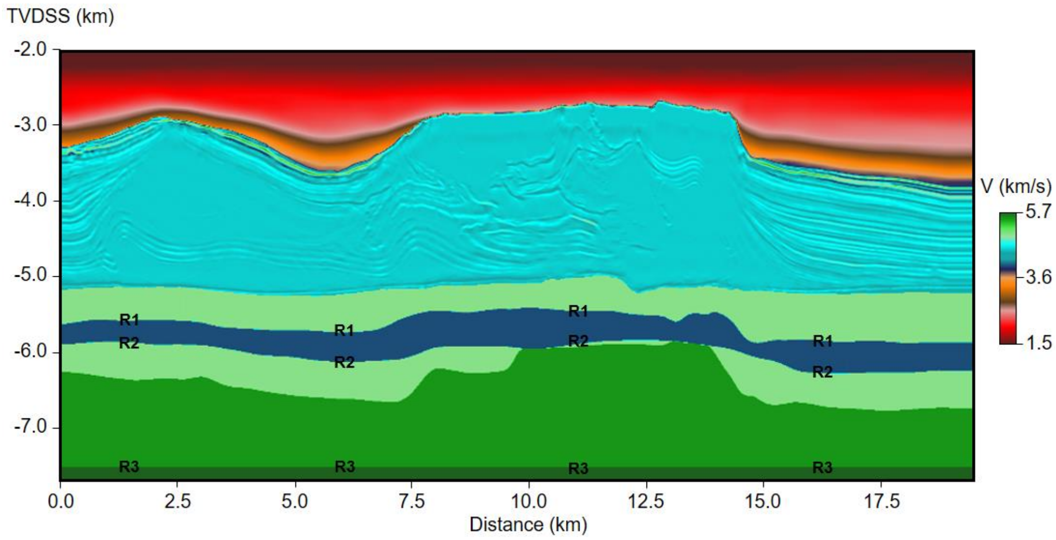



**Figure 10**: Positioning of the three reference horizons used for quantitative analysis.

Figures 11, 12 and 13 show the values of depth positioning of R1, R2 and R3, respectively, when considering the different configurations of migration velocities and algorithms. The top panels show the absolute depth values, and the bottom panels show the vertical difference between the modeled scenario and the reference image (Image **I**). Figures 14, 15 and 16 present a similar comparison for amplitude at the horizons.

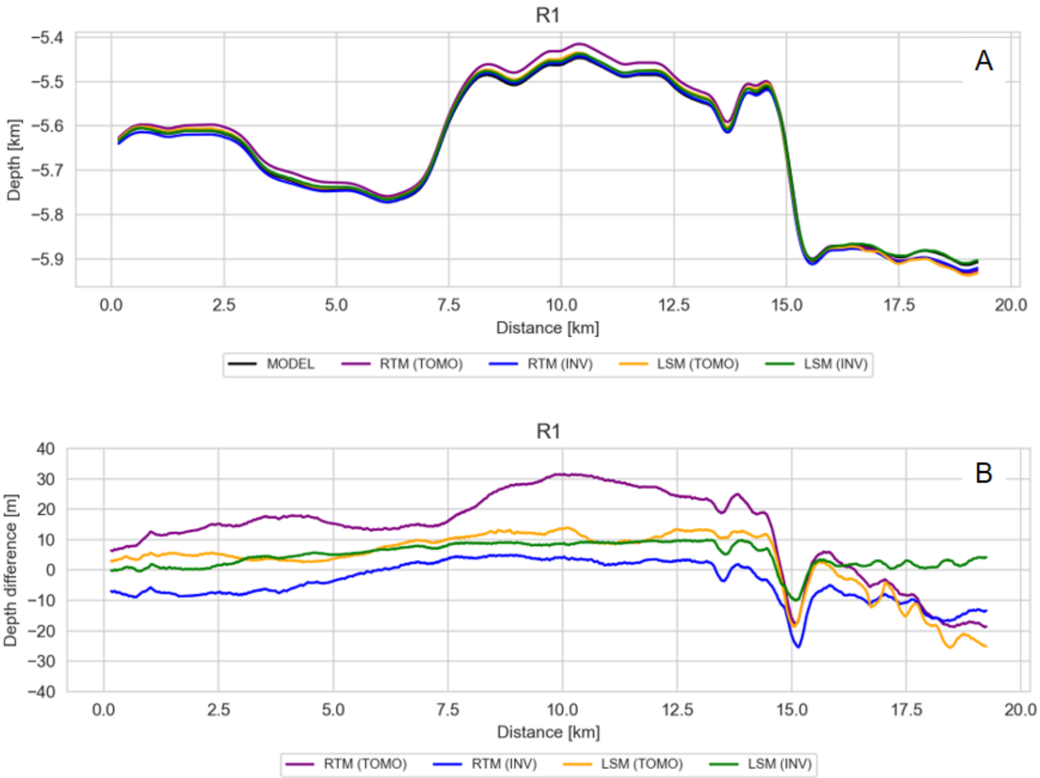
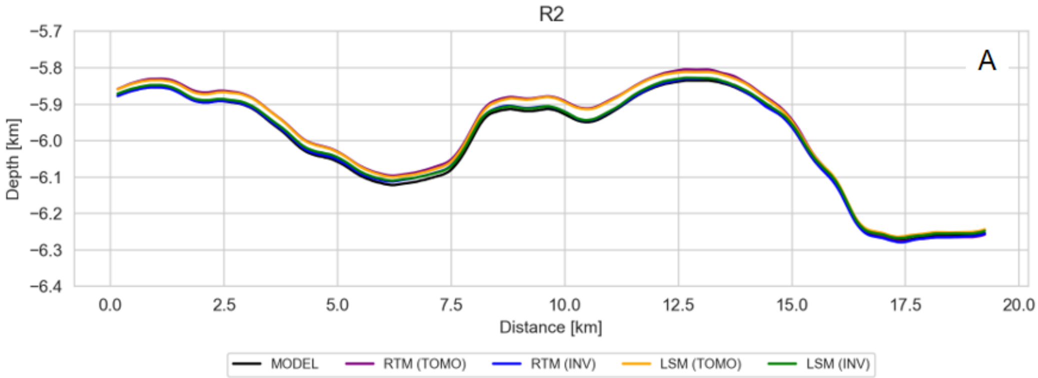



**Figure 11**: Depth positioning obtained from each of the four combination for R1 (A) and the differences having in consideration the reference model (B).
MODEL: positioning of R1 in the original model as described in figure 10 – Image **I**;
RTM (TOMO): results of the RTM application over the tomographic velocity model – Image **II**;
RTM (INV): results of the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **III**;
LSM (TOMO): results of the LSM compensation after the RTM application over the tomographic velocity model – Image **IV**;
LSM (INV): results of LSM compensation after the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **V**.



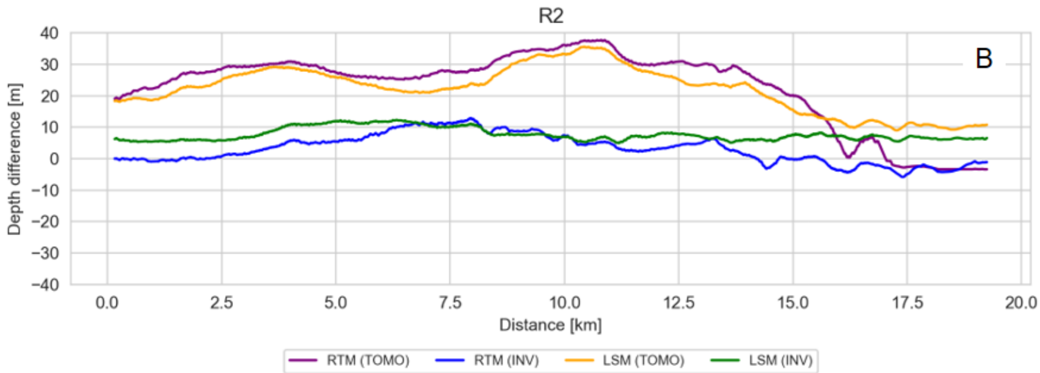




**Figure 12**: Depth positioning obtained from each of the four combination for R2 (A) and the differences having in consideration the reference model (B).
MODEL: positioning of R2 in the original model as described in figure 10 – Image **I**;
RTM (TOMO): results of the RTM application over the tomographic velocity model – Image **II**;
RTM (INV): results of the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **III**;
LSM (TOMO): results of the LSM compensation after the RTM application over the tomographic velocity model – Image **IV**;
LSM (INV): results of LSM compensation after the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **V**.

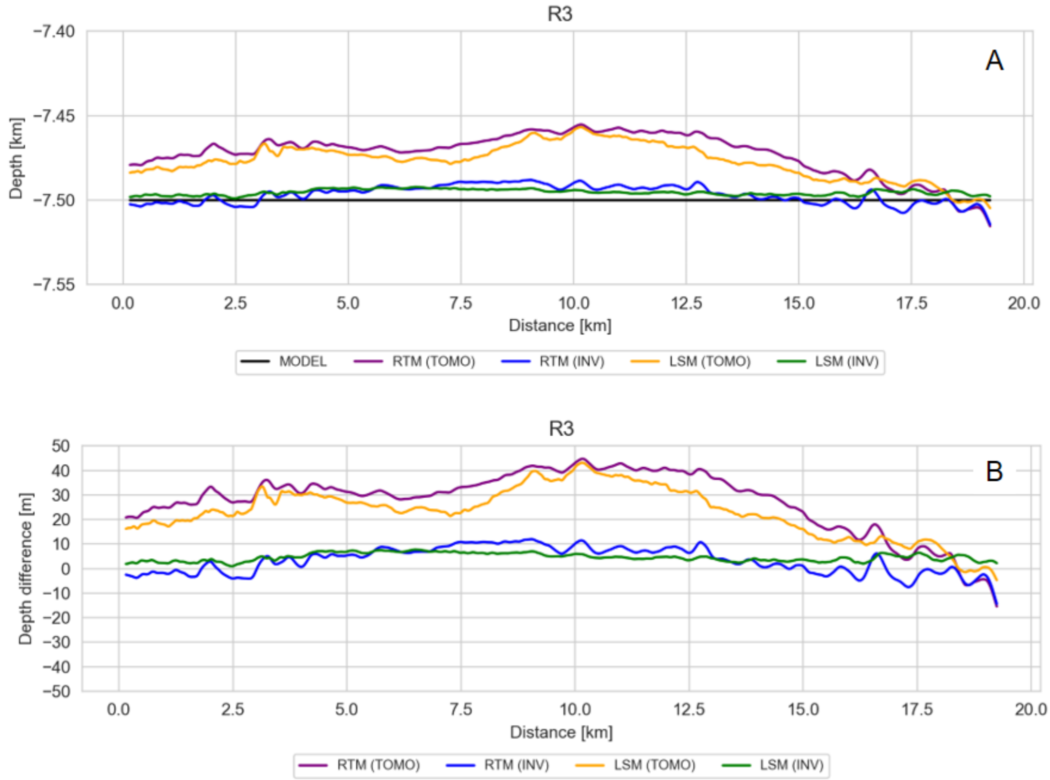



**Figure 13**: Depth positioning obtained from each of the four combination for R3 (A) and the differences having in consideration the reference model (B).

MODEL: positioning of R3 in the original model as described in figure 10 – Image **I**;

RTM (TOMO): results of the RTM application over the tomographic velocity model – Image **II**;

RTM (INV): results of the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **III**;

LSM (TOMO): results of the LSM compensation after the RTM application over the tomographic velocity model – Image **IV**;

LSM (INV): results of LSM compensation after the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **V**.

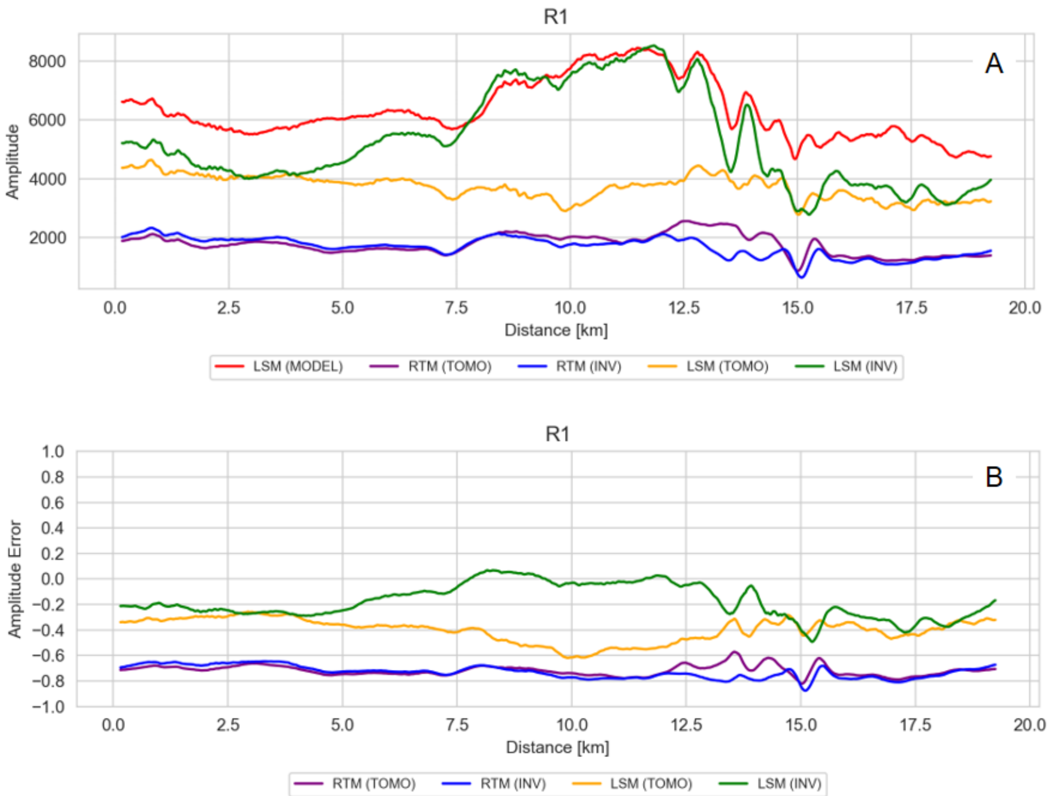



**Figure 14**: Amplitude value obtained from each of the four combination for R1 (A) and the differences having in consideration the reference least-squares migration technique applied over the reverse time-migration using the stratified velocity model that was the base of the acquisition simulation – our "perfect seismic data" (B).
LSM (MODEL): our "reference" amplitude response calculated in the seismic migrated data (RTM using the original stratified velocity model to simulate our acquisition plus the LSM compensation – Image **I**;
RTM (TOMO): results of the RTM application over the tomographic velocity model – Image **II**;
RTM (INV): results of the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **III**;
LSM (TOMO): results of the LSM compensation after the RTM application over the tomographic velocity model – Image **IV**;
LSM (INV): results of LSM compensation after the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **V**.

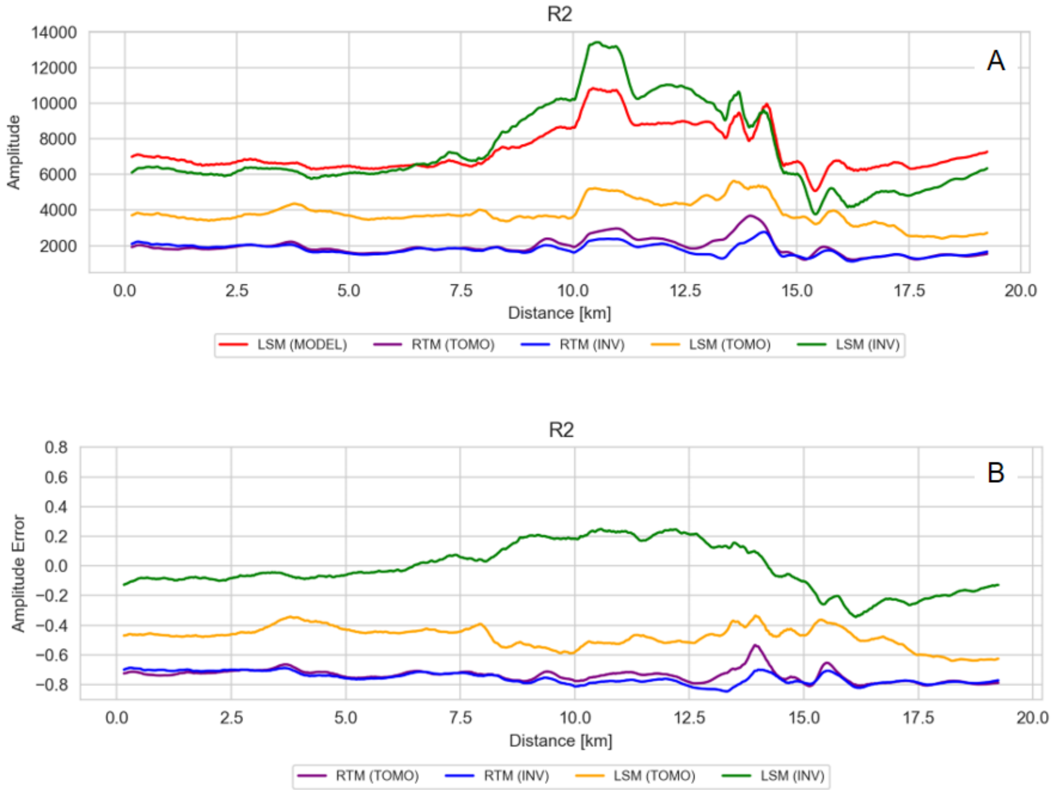



**Figure 15**: Amplitude value obtained from each of the four combination for R2 (A) and the differences having in consideration the reference least-squares migration technique applied over the reverse time-migration using the stratified velocity model that was the base of the acquisition simulation – our "perfect seismic data" (B).
LSM (MODEL): our "reference" amplitude response calculated in the seismic migrated data (RTM using the original stratified velocity model to simulate our acquisition plus the LSM compensation – Image **I**;
RTM (TOMO): results of the RTM application over the tomographic velocity model – Image **II**;
RTM (INV): results of the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **III**;
LSM (TOMO): results of the LSM compensation after the RTM application over the tomographic velocity model – Image **IV**;
LSM (INV): results of LSM compensation after the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **V**.

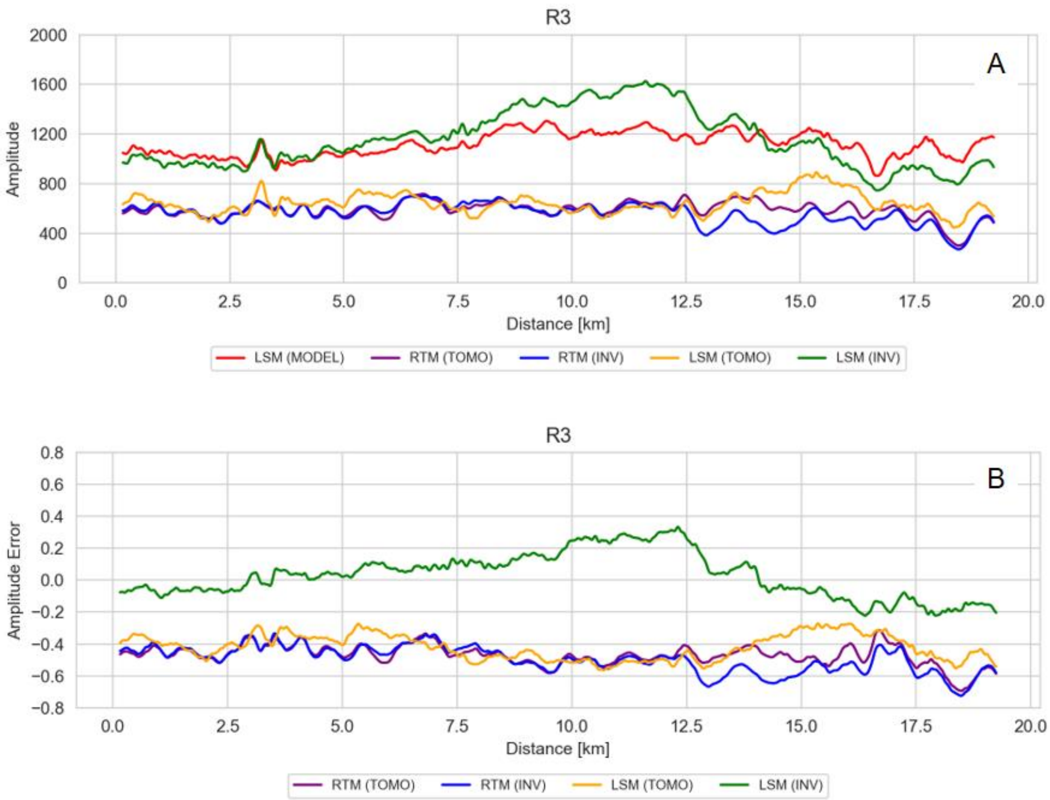



**Figure 16**: Amplitude value obtained from each of the four combination for R3 (A) and the differences having in consideration the reference least-squares migration technique applied over the reverse time-migration using the stratified velocity model that was the base of the acquisition simulation – our "perfect seismic data" (B).
LSM (MODEL): our "reference" amplitude response calculated in the seismic migrated data (RTM using the original stratified velocity model to simulate our acquisition plus the LSM compensation – Image **I**;
RTM (TOMO): results of the RTM application over the tomographic velocity model – Image **II**;
RTM (INV): results of the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **III**;
LSM (TOMO): results of the LSM compensation after the RTM application over the tomographic velocity model – Image **IV**;
LSM (INV): results of LSM compensation after the RTM application over the stratified velocity model delivered from the inversion process using the RTM (TOMO) as input – Image **V**.

## 4. Discussions:

We choose here four aspects to investigate in the obtained results: image quality, frequency content, accuracy in depth predictions, and amplitude response.

### 4.1. Image Quality:

To guide the analysis of image quality, we selected four regions in the geological section used for forward finite-difference modeling (Figure 17A – ellipses w, x, y and z), where we can explore the differences in the modeled scenarios. Figure 17B shows the modeled reference scenario (Image **I**), while panels 17C-17F show, respectively, the results of Images **II**, **IV**, **III** and **V**.

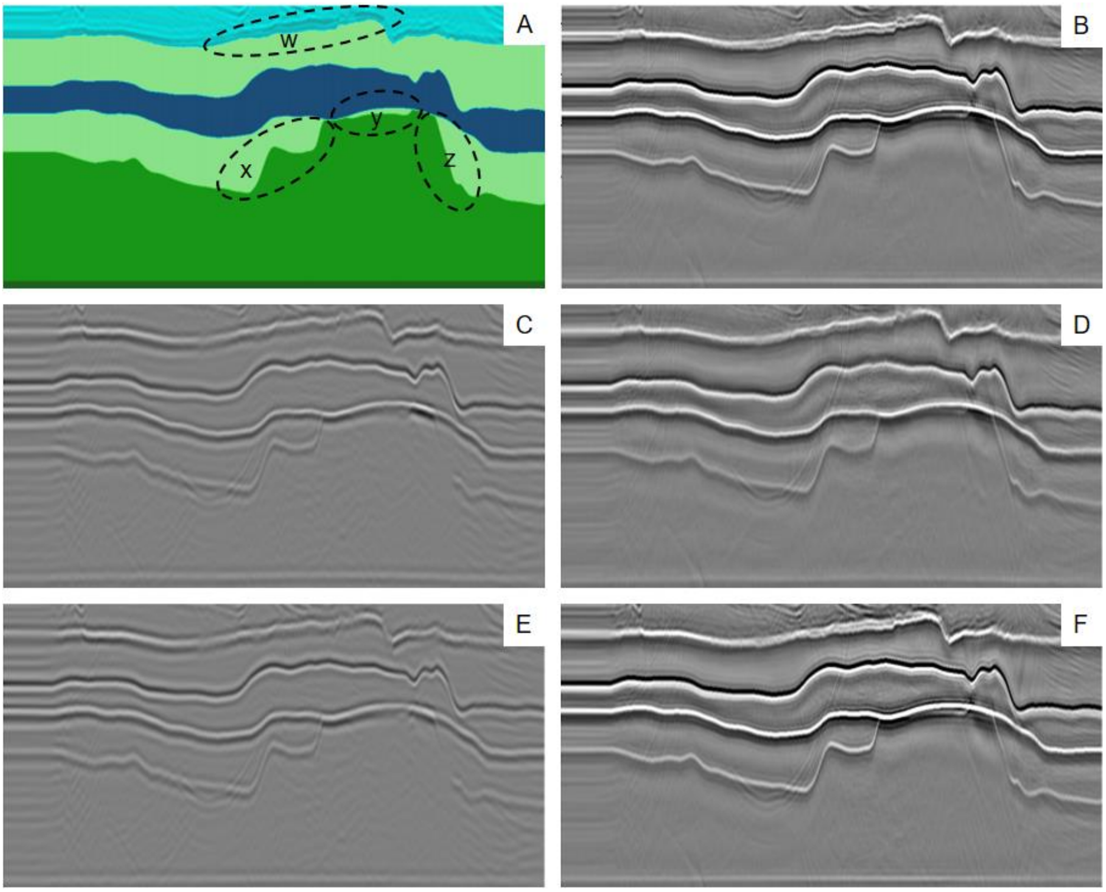



**Figure 17**: Panels for visual inspection of data quality.
A: Geological model used for forward finite-difference modeling. Ellipse "w" highlights a portion at the base of salt, with two interfaces, which we are interested into; ellipse "x" indicates a step-like feature; ellipse "y" shows a thin layer we would like to resolve in our seismic data, and ellipse "z" a steeply dip inclined surface.
B: Reference dataset, migrated using model in panel A and LSM (Image **I**).
C: Image migrated with velocity from tomography of field data (Image **II**)
D: Result of application of LSM to image C (Image **III**)
E: Image migrated with updated velocity model, after inclusion of data from seismic inversion (Image **IV**)
F: Result of application of LSM to image E (Image **V**)

In ellipse "w" we have 2 horizons at the base of salt, which we would expect to resolve in the migrated image; ellipse "x" shows a continuous horizon with significant depth variations and steep dip; ellipse "y" displays a thin bed below a structurally complex overburden and ellipse "z", another strong dip. All four features seem to have been properly imaged in the reference scenario, which was migrated with the same model used for forward modeling and had its amplitude compensated through LSM.

The resulting image using velocity from tomography (Figure 17C) fails to reproduce any of the four highlighted features the RTM algorithm, despite using a tomographic velocity model, is unable to recover the minute details that we are interested in. Application of LSM to this image results in Figure 17D, which shows significant improvement in the continuity of the horizons over the initial result (Figure 17C), despite not reproducing the main highlighted features.

By improving the tomographic velocity model with the insertion of salt stratification, using as proxy for that the results of the acoustic inversion, we can re-migrate the synthetic data (RTM), obtaining the image shown in Figure 16E. The result is in fact very similar to the one in Figure 17C, showing what seems to be little to no improvement. However, when LSM is applied using the updated velocity model, the result (Figure 17F) shows the same continuity gains as in Figure 17D, but now with increased resolution.

This does not come as a surprise: the quality of seismic images is strongly dependent on the velocity models used for the migration (Huang *et al.*, 2017), particularly in complex areas such as salt flanks and subsalt zones (Zhang and Sun, 2009; Jones and Davison, 2014). Therefore, building geologically constrained velocity models, accounting for salt stratification, is imperative when imaging the pre-salt targets in Santos Basin. The combination of a suitable migration algorithm with LSM allowed for further enhancement of the final image.

### 4.2. Frequency Bandwidth:

As the goal of LSM is to recover the true reflectivity of the medium, the outcome of the process usually has a wider power spectrum, when compared with standard migration algorithms. Once the images were built in depth domain, to investigate the power spectrum, we converted the modeled images to the time domain, using as conversion the velocities of the respective migration models. The results can be seen in figure 9. All the images were converted using a four-millisecond sampling, and the display frequency is limited to 45 Hz, since this was the maximum frequency used in the RTM algorithms and, consequently, the LSM algorithms. Each curve is individually normalized to its peak power spectrum.

The curves in figure 9 give us the quantitative confirmation of the analysis performed in figure 16: the application of LSM leads to a visible broadening of the data bandwidth, even for the tomography velocity model (orange versus purple lines). It is in accordance with the analytical demonstration described by Pereira-Dias *et al.* (2017). When accurate velocity is considered in the stratified model, the improvement in bandwidth is even more significant (green versus blue lines), achieving results very close to the modeled data (gray), and reinforcing the interpretation that velocity stratification (via acoustic inversion), combined with least-squares migration, yields better results.

### 4.3. Depth Positioning:

Depth positioning is another important criterion to evaluate velocity models. Figures 11, 12 and 13 show that the models with stratified salt deliver good results in comparison to those using the tomographic model, with a significant improvement for horizons R2 and R3. The results are further improved by application of least-squares migration.

At the shallowest level R1, there is an area where the difference between Images **III** and **I** (reference scenario) is significant. That small portion is located under a steep dip on the top of salt (see Figure 10), and it is likely that little to no energy reflected on this structure was "registered" in our modeling, as we assume a streamer acquisition, which limits the recording offsets. The inversion method is hence not able to properly recover the model properties in this region, delivering impedances that are not suitable for a correct velocity model building. As we move deeper in the data (horizons R2 and R3), this effect becomes milder, and the depths obtained with the updated velocity model are much more accurate.

Huang *et al.* (2010), after evaluating seismic images for the pre-salt prospects in Santos Basin, attributed the poor depth predictability (predicted seismic depths *vs*. measured depths by the wells) to the simplicity of the velocity models used for migration. Falcão (2017) later presented results comparing Kirchhoff and RTM migration, using velocity models both with and without salt stratification, and emphasized the importance of considering the heterogeneity in the salt velocity models. As we can see in our results, the stratified velocity model delivers good depth prediction even without the LSM compensation, reinforcing that stratification is a good starting point for velocity model improvement. The depth accuracy becomes even better with the application of LSM, particularly for regions with poor illumination (like horizon R1).

### 4.4. Amplitude:

Figures 14, 15 and 16 show the amplitude response at levels R1, R2 and R3, respectively. It is clear for all three horizons that the combination of stratified velocity model and least-squares migration delivers better results (compared to the reference model), thus improving quantitative seismic interpretation. Again, there is a small region in horizon R1 where this combination does not yield the most accurate result, and least-squares migration seems to be the sole responsible for the amplitude improvement, regardless of the chosen velocity model. We believe that this outcome is again caused by the lack of registered reflections in this area, due to the steep salt top. The fact that reflectors R2 and R3 do not show this behavior reinforces this hypothesis, as this effect becomes less significant with increasing depths. This suggests that, besides proper depth positioning, the correct characterization of salt heterogeneity in the velocity models has potential to deliver more accurate amplitude responses for the pre-salt targets in the Santos Basin, as pointed in some previous works (Ji *et al.*, 2011; Wang *et al.*, 2017; Fonseca *et al.*, 2018; Dias *et al.*, 2019; Shadrina *et al.*, 2020).

## 5. Conclusion

Accounting for the heterogeneity of salt is pivotal for subsalt imaging. Most wells drilled in the Brazilian pre-salt reservoirs have identified salt stratifications, so any velocity model built in the area should account for this information. However, migration alone might not be enough to deliver true amplitude response. Starting from a real dataset, we built elastic property models and simulated a seismic acquisition. The synthetic data was processed using different, attainable scenarios of velocity model building and imaging techniques. Migration of the synthetic data with a stratified salt velocity model was able to produce significant improvements in depth positioning, when compared to the use of a velocity obtained from tomography of field data.

Despite the use of an accurate velocity model, uneven illumination caused by acquisition geometry or complex overburden can create amplitude variations that are not lithological. Least-squares migration is a handy tool to address this issue, but lack of a detailed velocity model for the salt section leads to poor outcomes: the comparison of modeled results with a reference scenario showed that several geological features were not properly imaged.

As anticipated, we defend that the combination of both methods is be the best choice for seismic imaging in this complex environment: the combined application of these techniques leads to improvements in the seismic images, with better depth positioning, resolution, event continuity and amplitude balance. The desirable consequence is that reliable seismic images bring forth a reduction in seismic uncertainties, as well as accurate rock property estimation and better identification of the internal architecture of the reservoirs, which are essential to improve reservoir characterization and to allow better decision making.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Anexo A6:

***The Impact of Heterogeneous Salt Velocity Models on the Gross Rock Volume Estimation: an Example from the Santos Basin Pre-Salt, Brazil***

Petroleum Geosciences, petgeo2020-105.

Submetido em 25/09/2020.

Maul, A., Cetale, M., Guizan, C., Corbett, P.,
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# Petroleum Geoscience

## THE IMPACT OF HETEROGENEOUS SALT VELOCITY MODELS ON THE GROSS ROCK VOLUME ESTIMATION: AN EXAMPLE FROM THE SANTOS BASIN PRE-SALT, BRAZIL.

--Manuscript Draft--

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| **Short Title:** | IMPACT OF SALT VELOCITY FOR VOLUME ESTIMATION |
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| | María González, M.Sc. |
| **Abstract:** | The thick and heterogeneous salt section in the Santos Basin, offshore Brazil, imposes great challenges to access the pre-salt reservoirs, especially in relation to seismic imaging, signal quality, and depth positioning. Part of the problems are linked to the current velocity models for the salt section, which, in the vast majority, considers the salt behavior similar to halite, taking into account that, in the Santos Basin, halite makes up to 80% of the mineral present. The insertion of salt stratifications in the velocity models, based on seismic attributes, is a new approach that has achieved good results in the last decade, especially for depth positioning. In this work, we compare the benefits of different velocity models, considering or not the salt stratification insertion, comparing the gross rock volumetric variation above the oil-water contact. The results have significant effects on the depth positioning of the events and volume estimation, showing that the more complex the velocity models are, the more confident the resulting information is. |
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**Cover Letter**

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September 25th, 2020

Dear Editor of Petroleum Geoscience,

We wish to submit an original research article entitled "THE IMPACT OF HETEROGENEOUS SALT VELOCITY MODELS ON THE GROSS ROCK VOLUME ESTIMATION: AN EXAMPLE FROM THE SANTOS BASIN PRE-SALT, BRAZIL" for consideration by Petroleum Geoscience.

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

Several studies describe ways in building seismic velocity models for migration purposes, especially for geologically complex areas. In the Santos Basin, Brazilian offshore, after the discovery of the pre-salt province, the salt section and its heterogeneities are the key aspects reflecting this complexity. Besides the seismic processing importance regarding imaging, the rock-volume quantification is another important aspect for the industry. This study presents several approaches in building velocity models for the salt section and shows how to analyse the results prior to any well-data calibration, only observing the differences between well-markers and seismic depth positioning scenarios, delivered by the suggested approaches. It integrates physical, mathematical and geological foundations by combining seismic attributes, statistical and geostatistical techniques, and stratigraphy to generate the model scenarios, allowing the difference quantification, essential for uncertainties analysis. Among the huge amount of seismic and well data available in the Santos Basin, we took a small set of them establishing comparison for the small part as well as for the whole dataset, which allows us to confirm that this simple methodology is feasible for other areas under similar geological complexity. Our main hypothesis was the increase of the geological concepts along the velocity model task would result in results that are more reliable. The incorporation of the seismic-stratigraphic interpretation of intrasalt sequences of the Ariri Formation, based on sedimentary cycles of evaporites successions, delivered the best results, confirming our hypothesis. Additionally, we quantified the volume variation considering the five scenarios and we presented maps showing where the main differences among the models are. We discussed the application to industry and the potential extension to other similar projects, where the salt complexity is a mandatory aspect to deal with. We truly believe that the novelty of this applicable-research mainly resides in the gross-rock volumes quantification and uncertainties, especially where the geological complexity is present, not only in the Santos Basin but also in widespread seismic-dependent hydrocarbon basins.

Thank you for your consideration of this manuscript.

Sincerely,

Alexandre Maul

**THE IMPACT OF HETEROGENEOUS SALT VELOCITY MODELS ON THE GROSS ROCK VOLUME ESTIMATION: AN EXAMPLE FROM THE SANTOS BASIN PRE-SALT, BRAZIL.**

**IMPACT OF SALT VELOCITY FOR VOLUME ESTIMATION.**


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## Abstract

The thick and heterogeneous salt section in the Santos Basin, offshore Brazil, imposes great challenges to access the pre-salt reservoirs, especially in relation to seismic imaging, signal quality, and depth positioning. Part of the problems are linked to the current velocity models for the salt section, which, in the vast majority, considers the salt behavior similar to halite, taking into account that, in the Santos Basin, halite makes up to 80% of the mineral present. The insertion of salt stratifications in the velocity models, based on seismic attributes, is a new approach that has achieved good results in the last decade, especially for depth positioning. In this work, we compare the benefits of different velocity models, considering or not the salt stratification insertion, comparing the gross rock volumetric variation above the oil-water contact. The results have significant effects on the depth positioning of the events and volume estimation, showing that the more complex the velocity models are, the more confident the resulting information is.

**Keywords**

salt stratigraphy, seismic velocity, pre-salt, Santos Basin, volumetric uncertainties

## Introduction

Imaging rocks through thick evaporitic salt sequences poses depth conversion challenges in geophysics. The simplest models for salt assume uniform velocities for pure halite. In reality a "salt" section is made up of many evaporitic lithologies (in many cases dominated by halite) and these deposits - originally sub-horizontal at time of precipitation - are often highly deformed. Complex stratigraphy and deformation leads to severe depth conversion challenges. The thick and heterogeneous evaporitic salt section in the Santos Basin, offshore Brazil, is a classic example where effectively image the pre-salt reservoirs, especially in relation to seismic imaging, signal quality, and depth positioning requires sustained investigation.

Evaporites represent only 2% of the sedimentary record, however they are related to nearly 50% of the main hydrocarbon reserves in the world (Warren, 2016). Of the 120 giant or large hydrocarbon discoveries between 2000 and 2012, 56% have evaporite seals (Bai and Xu, 2014).

The pre-salt play of the South Atlantic has become a major global resource play during the last decade. The first well to reach the pre-salt reservoirs, in the Brazilian Southern continental margin, was concluded in September of 2005. The oil and gas production of the pre-salt reservoirs in the Santos Basin started in 2009 in the Lula field. Currently, after drilling more than 200 wells, the proven reserves for the pre-salt section correspond to about 60% of the existing 15 billion boe of the Brazilian reserve; the average daily production is more than 2100 barrels/day, with some wells producing over 40000 barrels/day (Ávila, 2020). Since then, several giant oil fields were discovered in water depths circa 2000 m, especially lead by Petrobras-operated consortium, all of them with oil production from the Barra Velha and the Itapema Formations.

The saline evaporites are in average 2.5 km thick, varying from few metres to almost 3 km (Mohriak *et al.*, 2012), and acted as effective seals for the Aptian carbonate reservoirs (Carminatti *et al.*, 2008). A detailed analysis of the intrasalt heterogeneity in the Santos Basin is possible due to high-quality seismic data and well log acquired over the basin. The evaporitic sequence in the Santos Basin, offshore Brazil, has attracted great attention during the last two decades due to the discovery of these supergiant fields in the pre-salt carbonate province (Carlotto *et al.*, 2010).

Saline evaporites start to precipitate when the carbonate evaporite sequence stops. Babel and Schreiber (2014) mentioned an example from McCaffrey *et al.* (1987), which used a brine from the Caribbean seawater, to show how the saline evaporites are formed. Considering a close system, i.e., without fresh or saline water influx, until 10% of evaporation of the brine occurs, only gypsum precipitates. After, from 10% until 70% only halite precipitates, and beyond 70% of evaporation, the bittern salts are formed. This process, called brining-upward, reflects the increasing ionic concentration inside the brine. After burial, the desiccation of gypsum converts it into anhydrite. However, in nature there is no closed systems. Therefore, water influxes can reverse the order of salts precipitation, and vice-versa. The reverse process is called brining-downward recording the decreasing ionic concentration of the brine. These processes of brining upward and downward form cycles of salt precipitation (Freitas, 2006; Gamboa *et al.*, 2008; Rodriguez *et al.*, 2018; Pontes, 2019; Teixeira *et al.*, 2020).

Since the start of the post-salt reservoir production in Brazil, several studies emphasised the strong influence of salt tectonism on the oil and gas accumulations (Guardado *et al.,* 1989; Mohriak *et al.*, 1990; Demercian *et al.*, 1993; Mohriak *et al.*, 1995; Rangel *et al.*, 2003), pushing the interest in salt-driven accumulation researches. The timing of salt welding and halokinesis-related listric faults, associated with rollover structures, resulted in perfect conditions for the oil migration from the pre-salt source rocks to post-salt reservoirs (Guardado *et al.*, 1989; Brun and Mauduit, 2008). Additionally, salt flow deformed and pushed up the overlying strata forming the oil traps. As consequence, while the post-salt reservoirs led to the investigation of salt-associated structures, the development of the pre-salt reservoirs faced another challenge: problems in drilling thick salt sections demanded efforts for the internal characterisation of the evaporite sequence.

Drilling through salt is a big challenge once the salt minerals have contrasting elastic properties, viscosities and mechanical behaviours (Strozyk, 2017). High-viscosity and high-density contrasts of the multi-layered evaporites exert strong influence on the salt movement, which depends on stress, temperature and mechanical properties (Li *et al.*, 2012). Mg-K-rich salts (also called bittern salts) have very low viscosity when compared to sedimentary rocks. This characteristic implies in short-term creep and squeezing behaviours that may cause stuck pipe, borehole collapse, washout, and fluid losses during drilling (Dusseault *et al.*, 2004; Costa *et al.*, 2011). Therefore, identification of the carnallite, sylvite and tachyhydrite prior drilling is key for operational safety, as well as to add financial value to the project.

Mohriak *et al.* (2008) observed “enigmatic reflections” at the top of the evaporitic sequence, interpreting those as intercalations of carbonate and siliciclastic rocks intruded by salt diapirs. However, intensive drilling activity in the pre-salt reservoirs revealed that the reflections within the salt walls were intercalations of stratified evaporites and the strong “enigmatic reflector” at the top of evaporitic sequence is the response of the abrupt contrast of acoustic impedance between the Albian sediments and the anhydrite caprock. An intense well drilling campaign aiming at the pre-salt reservoirs revealed the existence of features inside the salt section, in the Santos Basin, that are formed by elastic response of the intercalations of different salt types (Freitas, 2006; Gamboa *et al.*, 2008; Jackson *et al.*, 2015; Maul *et al.*, 2015).

Freitas (2006), studying the salt section in the Santos Basin (the Ariri Formation) and using well information, identified dozens of salt precipitation cycles of 4$^{th}$ and 5$^{th}$ orders forming part of a 3$^{rd}$ order salt precipitation sequence. Rodriguez *et al.* (2018) using the internal seismic features inside the salt section and well information, quantified the halite contents and divided the Ariri Formation in four main units, supporting cyclicity described by Freitas (2006).

However, the halokinesis implies in difficulties to recognise the cycles in nature. Many drilled wells sampled the salt section in allochthonous salt portions, which simply turns the salt cycle's characterisation in wells solely an impossible task. Therefore, the seismic attribute response to characterise the evaporitic cycles becomes increasingly important.

The amplitude response of internal reflections inside the salt were formed by the impedance contrasts of different minerals (Freitas, 2006; Gamboa *et al.*, 2008). The variations can be positive, from the bittern salt to halite or anhydrite, or from halite to anhydrite, and negative from anhydrite to halite or bittern salt, or from halite to bittern salt. The intercalation of interval velocities, in accordance with those observed in the well, resulted in a "geologically interval velocity model", more reliable for the evaporitic section. However, even with acceptable results regarding the seismic illumination studies, amplitude uncertainties, and depth positioning, the classification was still qualitative and presented many seismic ambiguities.

To overcome issues related the qualitative and quantitative analysis and seismic ambiguities, several studies have been conducted using the approach of building more geologically-guided velocity models for the salt section in the Santos Basin. A significant improvement in the methodology was noticed when the model-based seismic inversion was introduced in the geological velocity model building workflow (Meneguim *et al.*, 2015; Yamamoto *et al.*, 2016; Barros *et al.*, 2017; Teixeira *et al.*, 2017; Toríbio *et al.*, 2017; Teixeira and Lupinacci, 2019).

The absence of sonic log in the evaporitic section compromises the analysis of the velocity model. Aiming to circumvent this problem, Amaral *et al.* (2015) proposed an approach using the well-cutting descriptions and handmade interpretation establishing the mineral occurrence at well location. Having this information, they filled the missing log gaps with the interpreted lithology, without assigning any property value. This simplest approach allowed to have a more precise frequency occurrence giving an idea about how properties behave at each well position. Further, Barros *et al.* (2017) carried out the first attempt at inverting a seismic data (model-based approach) using the well-cutting samples to fill the missed sonic-log-acquisition information. In that study, they used a constant value for each described lithology, reflecting the average of the interval velocity property, measured where the sonic log was acquired.

Simplified models, which appraise the thick salt bodies as a homogenous mass, attribute to evaporite-dominated formations a constant interval velocity of about 4500 m/s. This emerges from the fact that halite typically dominates these sequences, and this value corresponds to the average value for the halite mineral. In the Santos Basin, salt successions contain a proportion of about 80% halite (Maul *et al.*, 2019). The aim at including the intrasalt velocity in the robust velocity models led to the investigation of the seismic response of the evaporites. Seismic amplitude responds to the relative variation of acoustic impedance, which in turn, is closely related to the interval velocity. Based on the relative nature of seismic data, Maul *et al.* (2018b) proposed a nomenclature for the assemblage of the salt in three types: low-velocity salts (LVS), halite and high-velocity salt (HVS). Low-velocity salts comprise carnallite, sylvite and tachyhydrite, having interval velocities lower than halite; High velocity salts (HVS), comprise anhydrite and few occurrences of gypsum, having interval velocities greater than halite. The authors, based on the study of 182 boreholes, reports 3 to 13% with an average of 7% of LVS, the HVS occurrence variating from 8 to 17% with an average of 12% and the halite variating from 71 to 88% with an average of 81%.

Besides other advantages, the application of heterogeneous salt velocity models provides better depth positioning using seismic data. Regarding the variation of gross rock volumes (GRV) above the oil-water (OW) contact, Meneguim *et al.* (2015) reported a difference between the models (tomographic velocity model and stratified velocity model delivered from their inversion study), of about 3%. Paes *et al.* (2019), inserting other elements such as mapping criteria and signal quality reached a difference of about 2% in GRV above the OW contact. Previously, Underhill and Hunter (2008) working with a field in the North Sea introduced halite pods to perturb the velocity model that was considering anhydrite only, also identifying this model perturbation as a source for volumetric calculations of the studied fields.

It is well known any seismic migration arises some uncertainties regarding depth positioning. The main task of seismic migration is to build reliable seismic images (Yilmaz, 2001; Etris *et al.*, 2001; Robein; 2003; Rosa, 2018). Roque *et al.* (2017) considered how the information related to depth positioning varies when considering seismic migrated data in both time and depth domains, reporting differences from 1 to 5% of gross rock volume (GRV).

The main objective of this work is to demonstrate how the GRV determination of pre-salt projects can be affected by the consideration of proper saline evaporitic velocities. We discuss the impact of considering several velocity models for the saline evaporitic section and running a calibration process. The idea is to add reliable confidence to the decision making among the project phases.

**Background geology**

The Santos Basin is the largest salt basin in the Brazilian coast. Its history starts with the breakup of Gondwana super continent in the Early Cretaceous, whereby the South Atlantic Ocean began to open (Kukla *et al.*, 2018). The basin covers an area about 350 000 km$^2$ and is bounded by the Cabo Frio High in the Northeast and the Florianopolis High in the South (**Fig. 1**).

The Santos passive marginal basin evolution comprises four unconformity-bounded tectono-sedimentary mega sequences (Ponte and Asmus, 1978; Chang *et al.*, 1992): the continental rift stage with fluvial and lacustrine sediments dated as Late Jurassic/Early Cretaceous; the Aptian transitional evaporites stage; the Albian restricted marine carbonates; and the open-marine mega sequence, dated from the Cenomanian to Present. The revised stratigraphy of the Santos Basin (**Fig. 2**), generally mentions the rift, transitional (post-rift) and drift phases (Moreira *et al.*, 2007).

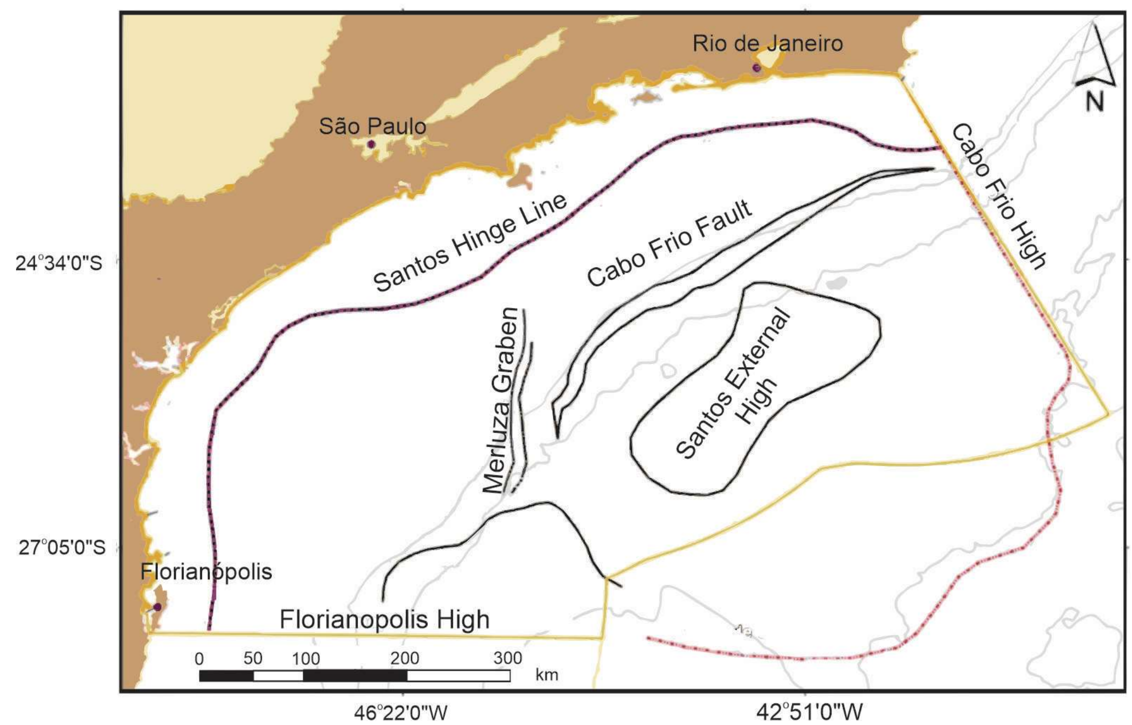


**Fig. 1**. Location and limits of the Santos Basin (Adapted from Garcia *et al.*, 2012).

The Late Aptian saline evaporitic sequence, named Ariri Formation, consists of the main subject of the present work. It has an average thickness of 2500 m, deposited during a short time-period in the transition from continental to oceanic conditions. The salt layer is present across the West African and Brazilian conjugate continental margins (Karner and Gamboa, 2007). This evaporitic sequence is part of the sag phase (Gamboa *et al.*, 2008). It was deposited during the period of thermal subsidence since the Early Aptian, when it was initially filled by lacustrine to restricted marine carbonates (Mann and Rigg, 2012; Quirk *et al.*, 2012), including coquinas, stromatolites, grainstones, laminites and spherulites, which represent the main pre-salt reservoir rocks (Faria *et al.*, 2017).

During the Barremian-Aptian ages, the eruption of the Parana-Etendeka continental basalt province formed the Walvis Ridge Volcanic High and the Rio Grande Rise, which is presumably responsible for the isolation of the South Atlantic Basin from the open-marine system (Davison *et al.*, 2012; Homrighausen *et al.*, 2019). The thick evaporite Ariri Formation precipitated in this hypersaline sea (Demercian 1996; Karner and Gamboa, 2007).

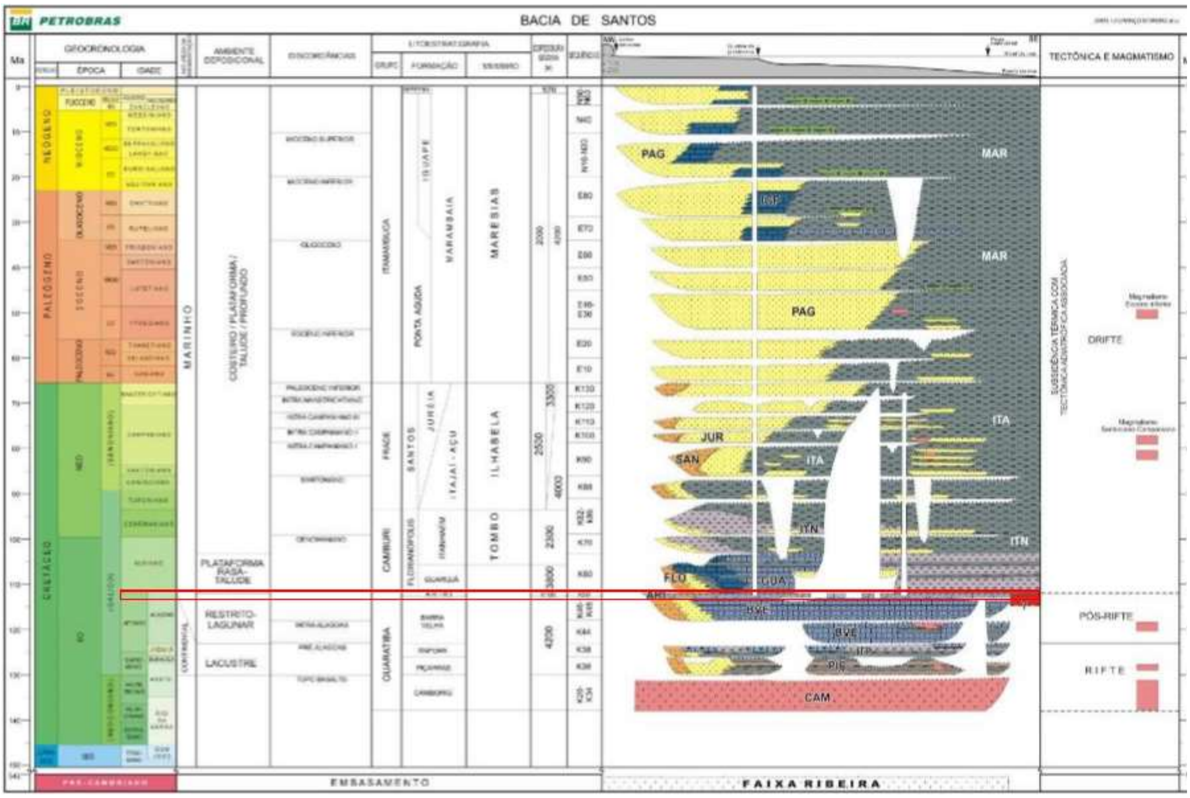

**Fig. 2**. Stratigraphic Chart of the Santos Basin illustrating the short period of deposition of the Ariri Formation. Adapted from Moreira *et al.* (2007).

The absence of clastic and carbonate rocks in the Ariri Formation suggests a fast precipitation of the evaporites. Freitas (2006) attempted to adjust the Milankovitch cycles to the cyclostratigraphic interpretation using well and seismic data and proposed an estimated interval of 400-600 Ka for the whole deposition of the evaporite sequence in the Santos Basin. High-resolution carbon isotope interpretation suggests an age between 125 and 130 Ma, whereas Ar-Ar dates indicates 111 to 116 Ma (Tedeschi *et al.*, 2017), in accordance with the 113 Ma maximum age of deposition proposed by Karner and Gamboa (2007). These estimated periods of deposition are in accordance with the global studies (Schreiber *et al.*, 2007).

The association of a hydrographically isolated and tectonically induced depression favoured the widespread evaporite deposition in the Late Aptian. The percolation of seawater through fractured volcanic highs possibly caused the enriching of the brine concentration, enabling the deposition of thick complex salt layers (Jackson *et al.*, 2000; Davison *et al.*, 2012). Several wells in the Santos Basin identify thick (up to 50 m) bittern salt layers inside the evaporitic successions (Amaral *et al.*, 2015; Maul *et al.*, 2018).

Posterior salt tectonic deformation generated many structures such as salt pillows, domes, walls, rafts and growth faults, especially involving the thick halite layers, predominant in the Santos Basin (Demercian *et al.*, 1993; Mohriak *et al.*, 1995; Demercian, 1996; Davidson *et al.*, 2012; Guerra and Underhill, 2012; Quirk *et al.*, 2012; Dooley *et al.*, 2015). More than an almost perfect seal for the hydrocarbon traps, the salt movement generates important structures acting as traps and allowing the hydrocarbon migration.

**Study area location and database**

The area of study has about 200 $km^2$ and it is located in the Southeastern Brazilian margin. It is inserted in the pre-salt province, which presents an area of about 380 000 $km^2$, and covers the Campos and Santos Basins (Davison *et al.*, 2012). The dataset contains 14 wells and a pre-stack depth migrated (PSDM) 3D seismic data. The boundary of the pre-salt province, the main oil & gas fields and an inset presenting the wells location inside the study area is presented next (**Fig. 3)**. Each well in the figure is indicated in capital letters and its correspondence to the official names presented in the following (**Table 1**). The reference section across several wells is explored through the results and analysis.

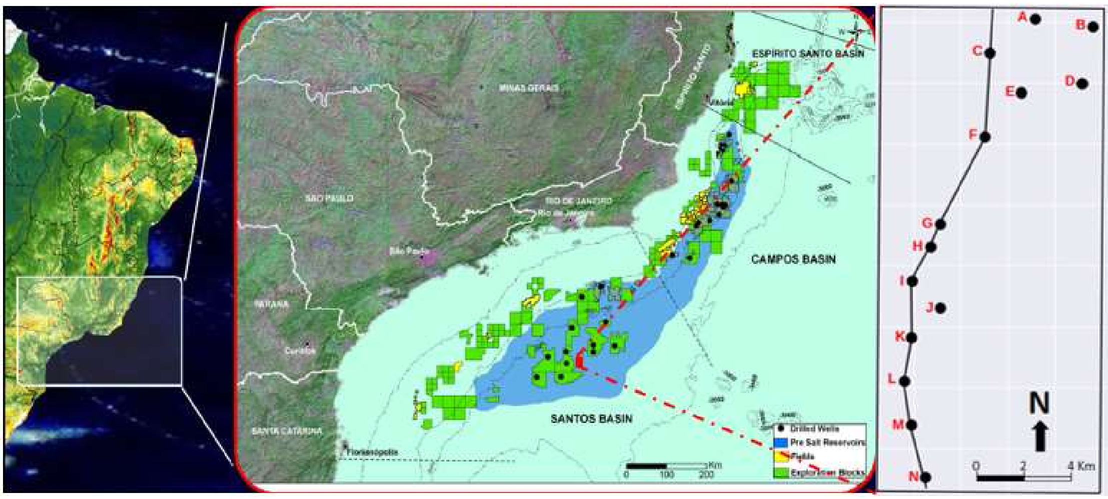


**Fig. 3.** Location of study area available data. Blue polygon delineates the pre-salt province for both Santos and Campos Basins, totalling an area of approximately 380 000 $km^2$. The water column varies from 2 to 3 km. Rightmost panel shows in detail the well locations (A to N) inside the 3D seismic volume zone (rectangle). Adapted from https://diariodopresal.files.wordpress.com/2010/.

**Table 1.** *Correspondence between the well designations used in this study and the official names from the Brazilian National Petroleum Agency (ANP).*

| This Study | ANP |
|---|---|
| A | 3-BRSA-788-SPS |
| B | 9-BRSA-1037-SPS |
| C | 8-SPH-23-SPS |
| D | 8-SPH-13-SPS |
| E | 7-SPH-14D-SPS |
| F | 7-SPH-8-SPS |
| G | 7-SPH-4D-SPS |
| H | 9-BRSA-928-SPS |
| I | 7-SPH-5-SPS |
| J | 9-BRSA-1043-SPS |
| K | 1-BRSA-594-SPS |
| L | 7-SPH-1-SPS |
| M | 7-SPH-2D-SPS |
| N | 3-BRSA-923A-SPS |

The Brazilian National Petroleum Agency (ANP) provided the dataset. The seismic data is a Kirchhoff PSDM that applied an isotropic interval velocity model, updated by inversion tomography, evaluating the gather panels. The evaluation of the time domain data presents a dominant frequency surround 20 Hz close to the base of the salt. Once we have this frequency contents, we assumed an interval velocity of 4500 m/s as reference, and we calculated the vertical seismic resolution as varying from 50 to 60 m (Widess, 1973). The details of the seismic survey used in this work are in the sequence (**Table 2**). Composite lithology descriptions, sonic logs, and drill cutting samples were available for all 14 wells.

**Table 2.** *Seismic data parameters (data provided by ANP).*

| **Acquisition Type** | **Streamer** |
|---|---|
| Total Number of Receivers | 240 |
| Receivers Interval | 25 metres |
| Minimum offset | 25 metres |
| Maximum offset | 6 kilometres |
| Receivers Depth | 6 metres |
| Number of Samples | 2001 |
| Sample Rate | 4 ms |
| Cut Source Frequency | 45 Hz |
| Type of Source | Ricker |
| Source Depth | 10 metres |

**Methodology**

The method used in this work provides a further application of three several routines (M#3, M#4 and M#5) developed and presented to build seismic velocity models for the saline evaporitic sections, additionally of two others: M#1 considering the salt section as a constant velocity model and another (M#2) considering one of standard way in building velocity models for seismic migration, i.e., adopting the inversion tomographic updating process. First, using the tomographic updated velocity model, we converted the PSDM from depth domain to time domain to generate our reference case. We explore five methods of building velocity models for the saline evaporitic section in the Santos Basin (**Fig. 4**).

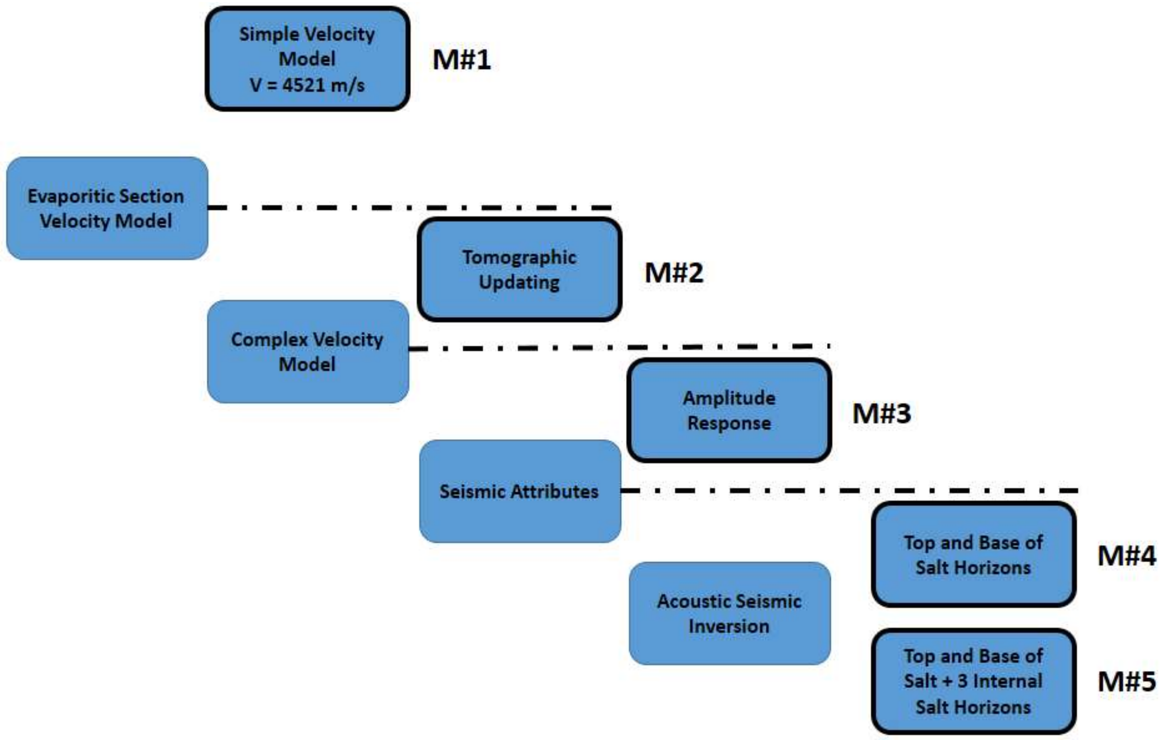


**Fig. 4.** Several methods in building compressional velocity models for the saline evaporitic section, having as examples the Santos Basin, Brazilian offshore.

Next, we presented our reference seismic section (see figure 3 for the location), displaying the top and base of the salt of the models (**Fig. 5**). A description of each velocity model for the salt section limited by these two horizons is provided below.

Model 1 (M#1) presents a constant velocity value for the entire evaporitic section, adopting 4521 m/s as a good approximation for the interval velocity of halite based on well-log analysis. This mineral is the most abundant in the saline evaporitc section in the Santos Basin, with approximately 80% of occurrence (**Fig. 6**).

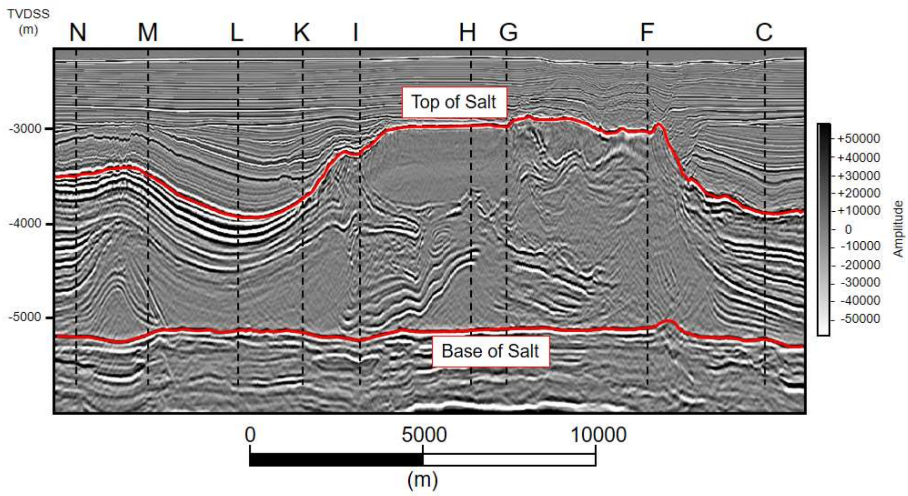


**Fig. 5.** Reference seismic amplitude section with the mapping of the top and the base of salt.

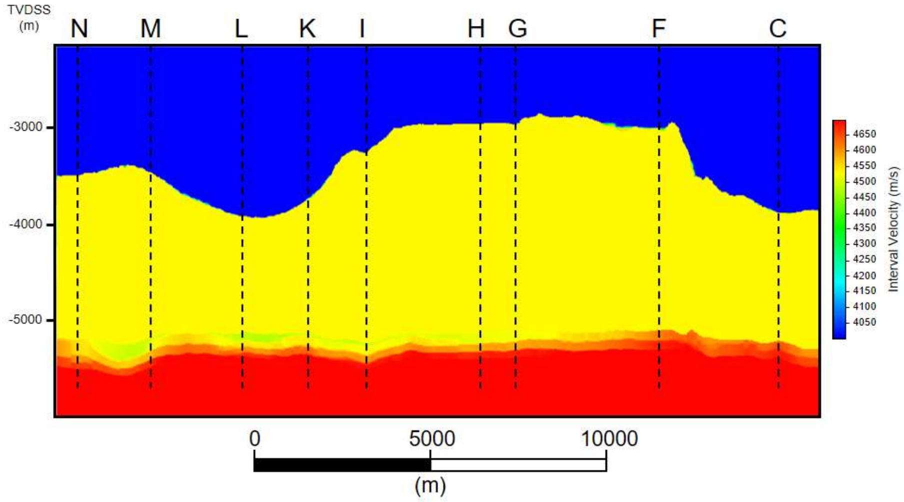


**Fig. 6.** The constant velocity model (M#1) presenting an interval velocity of 4521 m/s for the entire salt section.

Model 2 (M#2) reflects a step further during the seismic processing, after performing the tomographic update inversion in the almost constant initial model (**Fig. 7**). It is a mathematical solution for the velocity model, having the gather alignment control, prior to seismic migration process (Guo and Fagin, 2002). This tomographic updating inversion methodology is a standard way to prepare velocity models for seismic migration purposes.

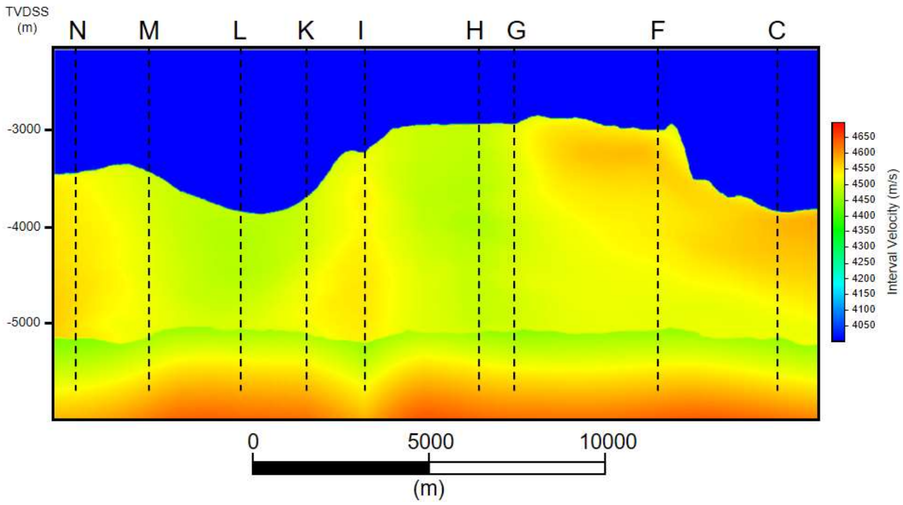


**Fig. 7.** The updated tomographic velocity model (M#2).

Model 3 (M#3), after seismic migration, takes an initial and constant velocity model (4521 m/s) and applies perturbations in order to increase the velocity according to the seismic amplitude response (**Fig. 8**). This methodology follows the statements presented by Falcão, (2017) and it is not a good approach to represent the low velocity salts (LVS) because it overestimates this facies (Maul *et al.*, 2018).

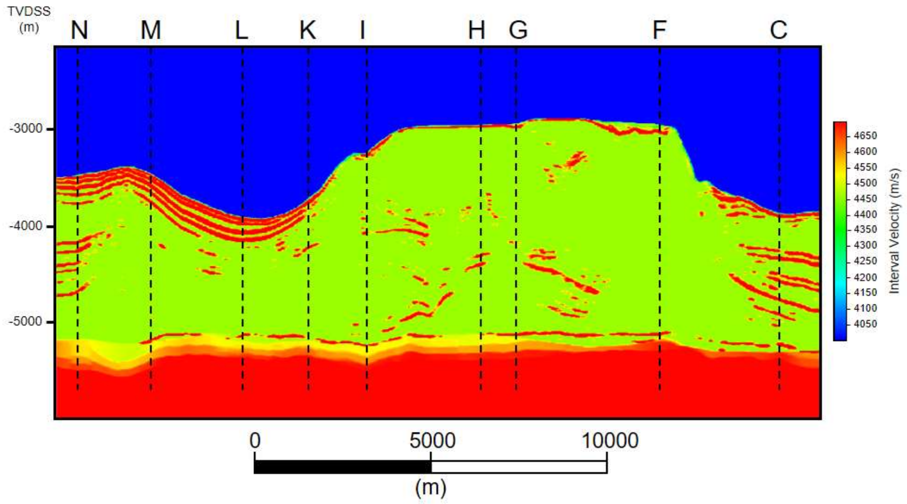


**Fig. 8.** The interval velocity model weighted by the amplitude response (M#3).

Model 4 (M#4) is a step further of the M#3, but instead of using the amplitude response to include the intrasalt velocity, it performs model-based seismic inversion as the boundaries of the model (**Fig. 9**). The description of the methodology is found in Yamamoto (2019).

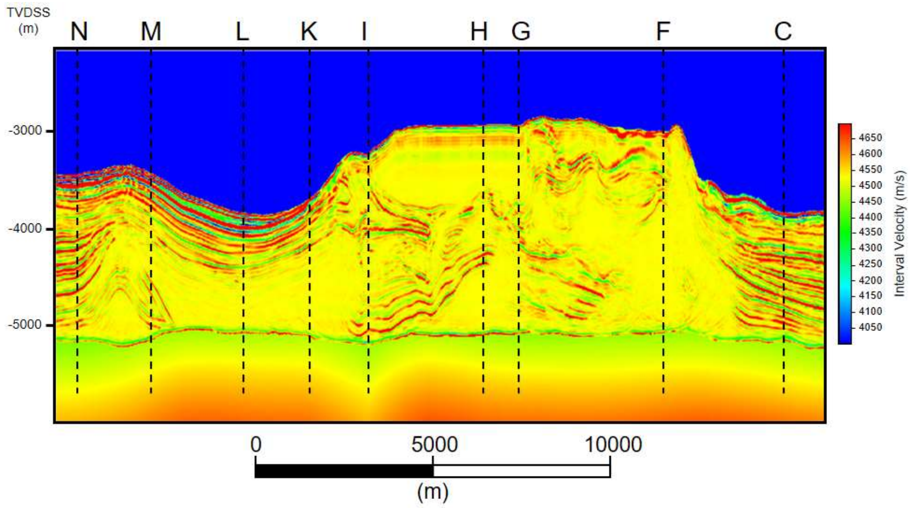


**Fig. 9.** The interval velocity model taking the model-based seismic inversion considering top and base of salt horizons (M#4).

Model 5 (M#5) takes a step further from M#4, adding three horizons to build the model for the inversion, additionally to the top and base of the salt. Those horizons were an attempt at reflecting the 4$^{th}$ order salt precipitation cycles in the Santos Basin. The cyclicity was already published by several authors, and was defined after analysis of lithological descriptions, well logs and drill cutting samples (Freitas, 2006; Gamboa *et al.*, 2008; Rodriguez *et al.*, 2018; Pontes, 2019; Teixeira *et al.*, 2020). The model we followed in this work is illustrated in the sequence (**Fig. 10**). The drill cuttings were mostly useful to recognize the dominant lithology and to infer the interval velocity in the absence of well logs. After including these stratifications, the new velocity model was created (**Fig. 11**). This methodology considering the salt cycles prior to the seismic inversion process is documented in Pontes (2019).

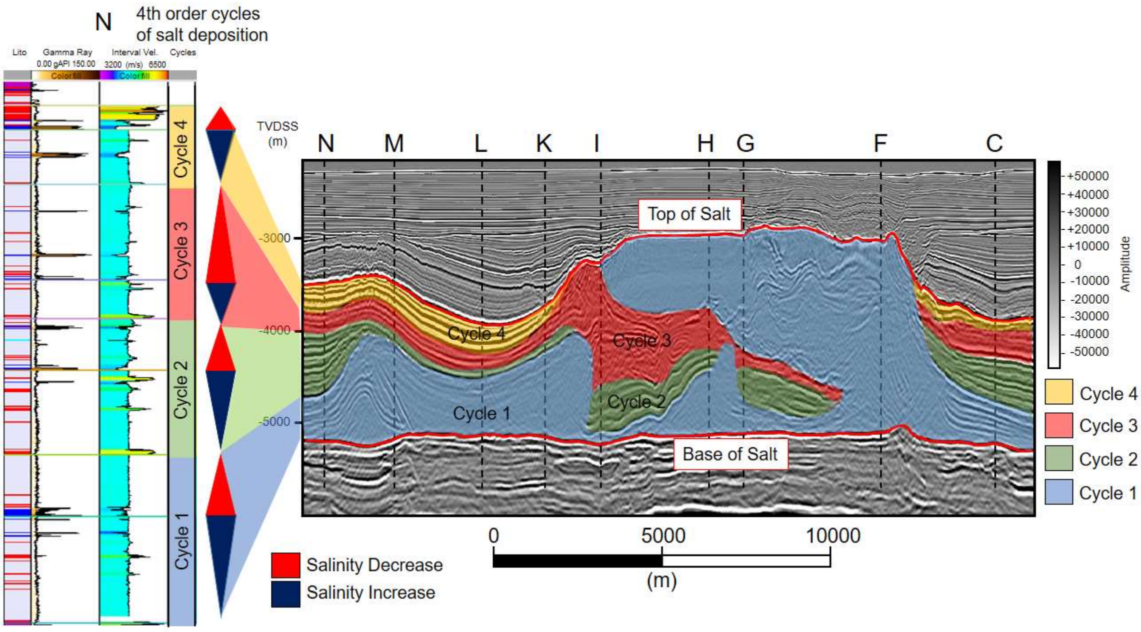


**Fig. 10.** Reference seismic amplitude section with the mapping of the top and the base of salt and the horizons representing the 4th order cycles of salt deposition recognized by several authors (Freitas, 2006; Gamboa *et al.*, 2008; Rodriguez *et al.*, 2018; Pontes, 2019; Teixeira *et al.*, 2020).

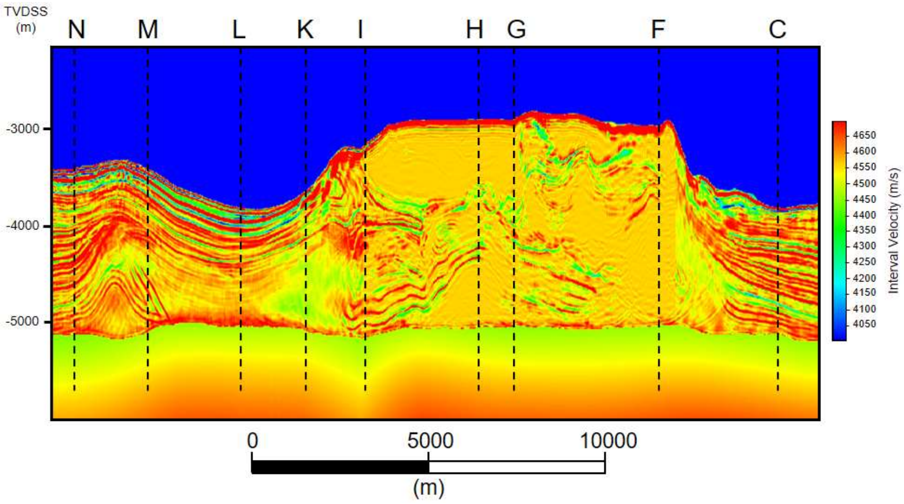


**Fig. 11.** The interval velocity model taking the model-based seismic inversion considering top and base of salt horizons besides 3 internal salt horizons (M#5).

Using all five models, we converted the time-domain horizon of the base of the salt and compared the results with the base of the salt at the well locations. Later, we performed a well-constrained calibration of the velocity models running the kriging with external drift (KED) algorithm in order to visualize in maps the differences. All the parameters of calibration are the same for each model, only varying the velocity of saline evaporitic section as an external drift. We are not proposing that the KED algorithm constitutes the best methodology, once this is not the scope of this work, however, several authors used this approach (Dubrule, 2003; Sandjivy *et al.*, 2003; Léron *et al.*, 2003; Doyen, 2007; Ferreira *et al.*, 2017).

**Results**

We investigated in detail the influence of the interval velocity on the depth positioning and GRV estimations. Using the sonic log from 14 wells, we calculated the interval-average velocity for each of the three salt groups (LVS, Halite and HVS) and the mineral assembly. That calculation estimates the standard deviation of each mineral group reflecting the dispersion of interval velocities to the averages (**Fig. 12**).

We emphasise some assumptions: 1) Halite presents the smaller velocity value dispersion and, since it represents about 80% of occurrence, this lithology controls the interval velocity behaviour in the salt section. 2) Salt mixtures (grouped as evaporites) can explain the high degree of dispersion, but still have similar interval velocity value as pure halite. The interval velocity for the evaporites (4548 m/s) is very similar to the halite (4521 m/s) due to the high percentage of halite (about 80%). However, it imposes a level of dispersion (+/- 223 m/s) that is about 2.5 times the halite dispersion (+/- 90 m/s). The mixture occurs due to the intense salt movement present in the basin; and 3) Both the LVS and HVS present larger dispersions, chiefly because they comprise different minerals with specific velocities. The small percentage of occurrence - in average 7% for LVS and 12% for the HVS - affects significantly the dispersions in these mineral assemblies than it affects the more abundant halite.

Other aspects must also be considered when analysing the well information in the evaporitic section. Among them, we cite the salt section thickness, the presence of gaps on the geophysical logs, especially at the top and the bottom of the section, where changes in drilling phase take place, the thickness of the basal anhydrite that is normally below the seismic resolution. All of these factors influence the interval velocity analysis, and are presented (**Table 3**).

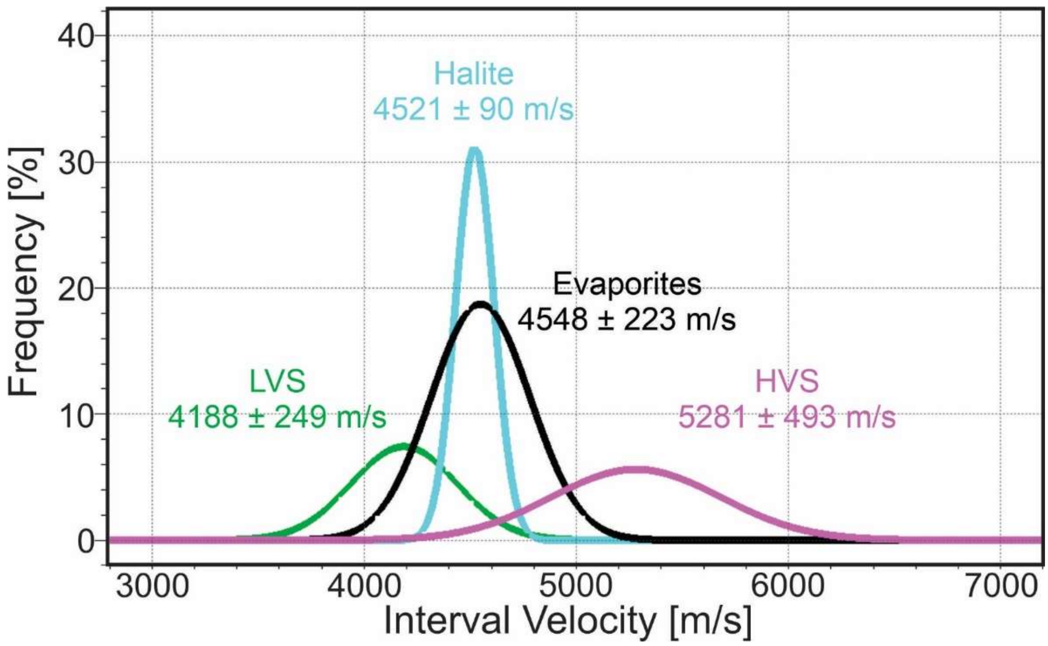


**Fig. 12.** Interval velocity distribution and dispersion considering the grouping as described as well as considering all the information together. Adapted from Maul *et al.* (2019).

**Table 3.** *Well data inventory of the 14 wells.*

| Well | Basal Anhydrite (m) | Salt Isopach (m) | Acquired Sonic Log ( %) | Log Gap ( %) | LVS Log & C.S. (%) | Halite Log & C.S. (%) | HVS Log & C.S. (%) | AVG INT Velocity (*) (m/s) |
|---|---|---|---|---|---|---|---|---|
| A | 12.90 | 1673.49 | 91.90 | 8.10 | 5.45 | 86.20 | 8.35 | 4589.59 |
| B | 13.80 | 2369.39 | 87.60 | 12.40 | 0.50 | 98.90 | 0.60 | 4550.39 |
| C | 12.90 | 1334.06 | 91.10 | 8.90 | 6.90 | 82.70 | 10.40 | 4599.39 |
| D | 11.50 | 2400.94 | 87.30 | 12.70 | 0.00 | 91.60 | 8.40 | 4609.57 |
| E | 11.14 | 2063.00 | 77.90 | 22.10 | 0.30 | 95.40 | 4.30 | 4578.44 |
| F | 17.50 | 2081.76 | 87.20 | 12.80 | 1.45 | 95.40 | 3.15 | 4565.87 |
| G | 13.57 | 2180.45 | 92.00 | 8.00 | 4.80 | 92.90 | 2.30 | 4547.58 |
| H | 11.50 | 2191.82 | 91.80 | 8.20 | 1.20 | 98.10 | 0.70 | 4548.81 |
| I | 13.80 | 2206.90 | 91.40 | 8.60 | 1.10 | 88.80 | 10.10 | 4618.07 |
| J | 13.40 | 2024.65 | 96.00 | 4.00 | 5.10 | 83.80 | 11.10 | 4611.00 |
| K | 11.50 | 1450.89 | 98.40 | 1.60 | 2.12 | 93.10 | 4.78 | 4575.41 |
| L | 29.40 | 1279.96 | 95.60 | 4.40 | 3.60 | 87.20 | 9.20 | 4602.48 |
| M | 11.65 | 1701.27 | 94.30 | 5.70 | 4.10 | 89.80 | 6.10 | 4577.95 |
| N | 13.30 | 1717.34 | 94.00 | 6.00 | 4.60 | 83.20 | 12.20 | 4620.87 |
| | | | | | | | | |
| **AVG** | **14.13** | **1905.42** | **91.18** | **8.82** | **2.94** | **90.51** | **6.55** | **4585.39** |
| | | | | | | | | |

* LVS: Low Velocity Salts; HVS: High Velocity Salts; C.S.: Drill Cutting Samples; AVG INT Velocity (*): Average Interval Velocity calculated using the acquired sonic log plus the cutting samples filling the gaps and the constant value per mineral/group as described in figure 12.

Additional steps improve the velocity models M#3, M#4 and M#5. For the model M#3, with velocity variations, we need to apply a constant value to the velocity. Here we decided to use the average of interval velocity value of 5281 m/s for HVS, as this method is only good enough to assign HVS value, considering the seismic resolution. The proper velocity analysis for the models M#4 and M#5 requires the conversion from the acoustic impedance property to the interval velocity. To this end, we reported to the high correlation between these properties applying the empirical polynomial fit (Maul *et al.*, 2019). The correlation between the acoustic impedance and compressional velocity based on our dataset is in the sequence (**Fig. 13**).

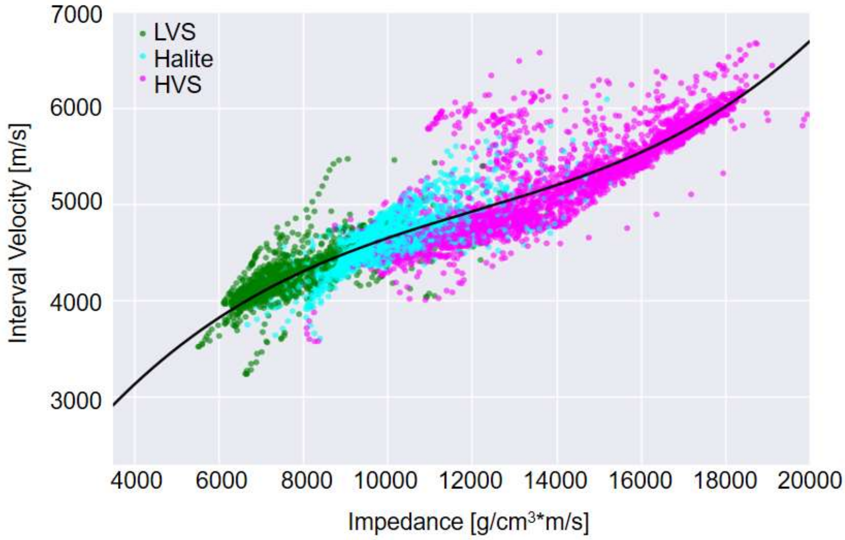


**Fig. 13.** Polynomial fit correlating the impedance with the interval velocity used to transform models M#4 and M#5, for the inversion process (details of the empirical polynomial fit can be found in Maul *et al.*, 2019).

When applying non-traditional approaches to build velocity models, such as M#3, M#4 and M#5, we need to smooth them. Even the continuous amplitude response model (M#3) might present discrete values stablished by the conditioning.  The models M#4 and M#5 commonly present higher frequency than standard velocity models. Therefore, we decided to perform a simple vertical smoothing.

We compared the depths of the seismic horizon and the well markers of the base of the salt for each well before performing the calibration with the well information. The depth difference of the base of the salt reflector in each model and the base of the salt well marker is showed (**Table 4**). The average difference (AVG D) reflects the addition of positive and negative difference values divided by the total number of wells (14).  The average of the difference modulus (AVG |D|) was also calculated to avoid the cancelation of positive and negative values, otherwise expressing the real differences of the velocity models.  We present the average of the difference modulus (AVG |D|) among the five models along the reference section (**Fig. 14**) - see figure 3 for wells and section location, and the difference modulus along the section, and additionally provides the total thickness of the saline evaporitic section at each well (**Fig. 15**).

**Table 4.** *Differences, in metres, between the well marker of the base of salt and the depth conversion of the base of salt seismic horizon taking the 5 models we previously described.*

| | Differences from well marker of the base of salt | | | | |
|---|---|---|---|---|---|
| **Well** | **M#1** | **M#2** | **M#3** | **M#4** | **M#5** |
| **A** | -51.75 | -46.18 | -21.94 | -12.86 | -5.91 |
| **B** | -15.30 | -33.38 | -17.22 | -12.44 | -13.36 |
| **C** | -19.83 | -6.15 | -9.29 | -5.16 | -1.54 |
| **D** | -18.18 | -34.22 | -16.29 | -6.24 | -8.46 |
| **E** | 13.51 | 9.62 | 8.80 | 8.06 | 6.54 |
| **F** | -22.33 | -20.05 | -24.45 | -18.75 | -9.91 |
| **G** | -6.39 | -10.08 | -1.54 | 4.47 | 0.31 |
| **H** | -13.54 | -9.03 | -9.39 | -9.94 | -7.66 |
| **I** | 13.72 | 15.88 | 5.45 | 4.12 | -0.98 |
| **J** | 13.70 | 6.23 | 7.81 | 7.33 | -6.16 |
| **K** | -12.59 | -3.93 | -8.26 | -7.86 | -5.72 |
| **L** | -21.76 | -19.78 | -19.09 | -15.30 | -11.82 |
| **M** | -20.72 | -10.18 | -8.72 | -4.67 | -4.38 |
| **N** | 22.36 | 14.81 | 6.53 | 9.74 | 5.83 |
| **AVG D** | **-9.93** | **-10.46** | **-7.69** | **-4.25** | **-4.52** |
| **AVG\|D\|** | **18.26** | **17.11** | **11.77** | **9.07** | **6.33** |

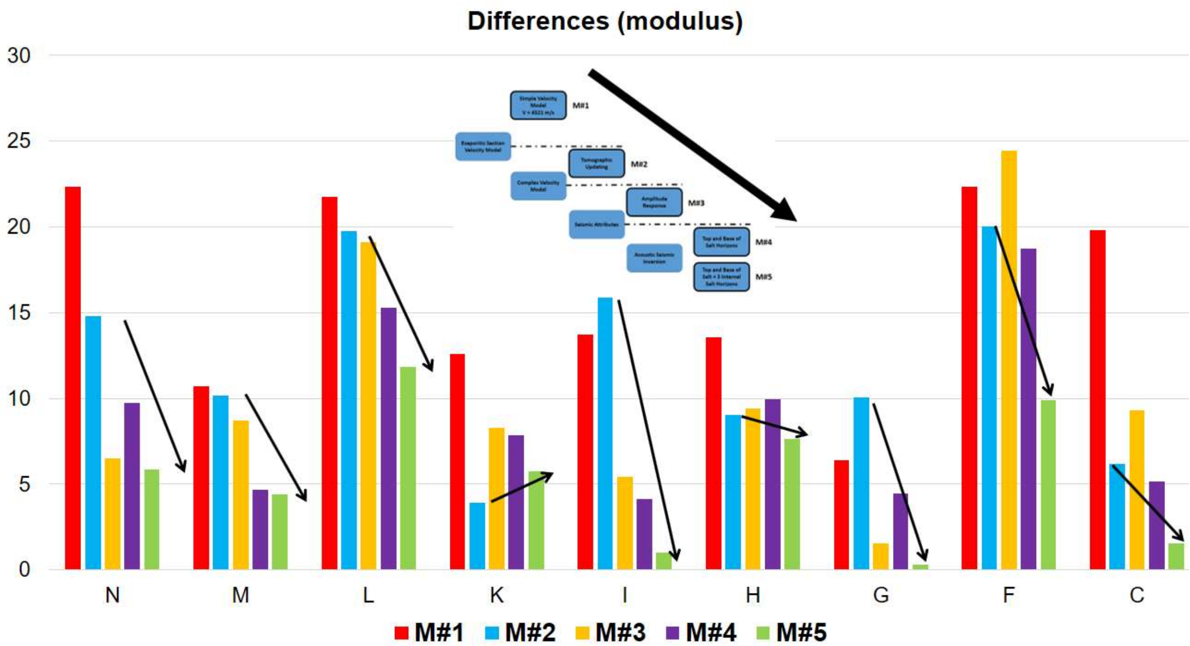


**Fig. 14.** Depth positioning differences (modulus, in metres) per well comparing the “base of salt” official well marker and the seismic event after the time to depth conversion without calibration of the five models. The thin arrows at the well locations represent the difference comparisons between the tomographic model (M#2) and the model M#5 that best fits with the existing geology. The thick arrow at workflow (middle above) reflects way of the increasing correspondence of the models with geological complexity.

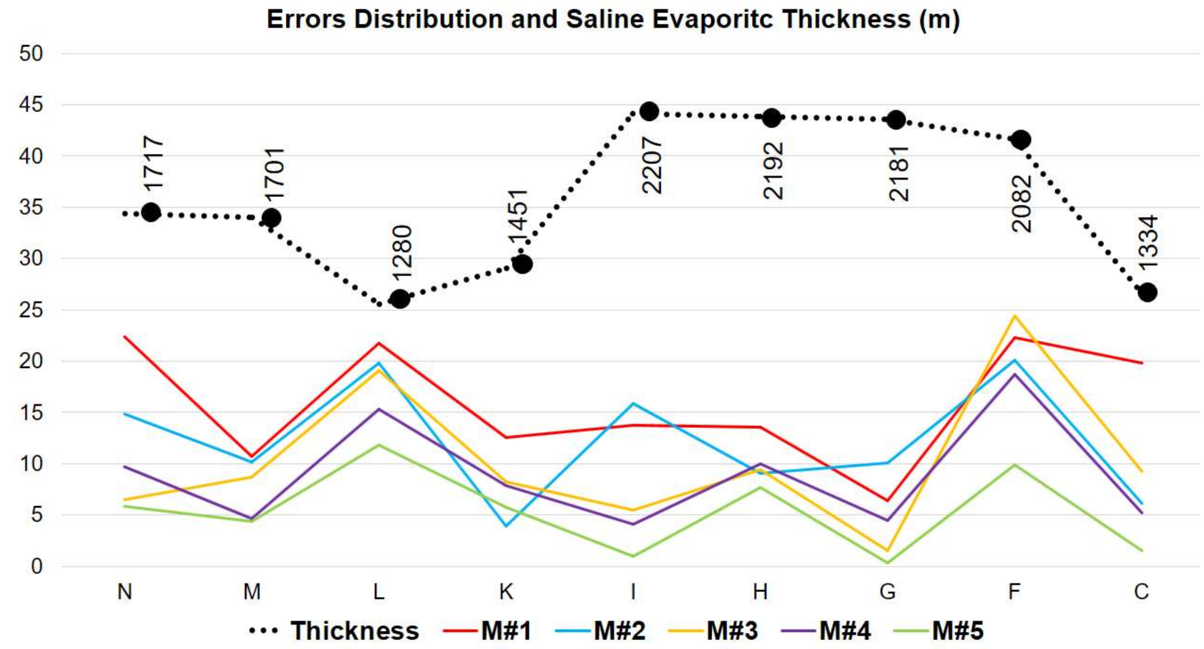


**Fig. 15.** Measured differences (modulus, in metres) and the evaporitic section total thickness at each well. The wells are oriented as in the section presented in figure 3 (the thickness information are not following the scale of the chart).

We performed the calibration of the five models with the well velocities, adopting the kriging with external drift (KED) algorithm. Firstly, we converted the interval velocity to the average velocity and used it as the drift information. The relation between the well marker (depth) and the correspondence of time well tie gave us the average velocity at the well markers and these were adopted as the hard information for the kriging process. All the remaining aspects, such as the searching and analysis parameters, spherical and isotropic variogram considering 10% of the samples, average distance among wells as radius of influence are the same for the models. We did not change the velocities of the pre-salt and the post-salt sections.

After the calibration of the five models, we converted the time-domain horizon of the base of the salt and plotted the results taking the oil-water (OW) contact as reference in order to emphasize quantify the main volumetric variations of the models (**Fig. 16**). For the five models, we present the well-calibrated surfaces of the base of salt, intercepted by the oil-water contact of - 5130 m.

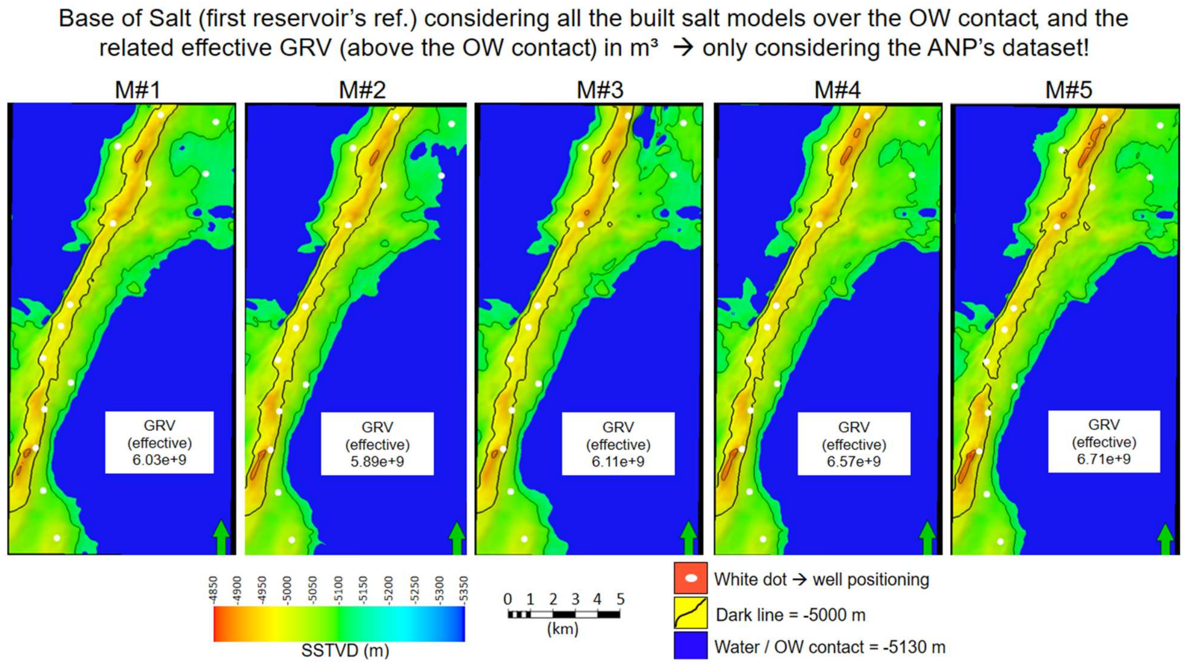


**Fig. 16.** Calibrated maps of the base of salt of the five models (M#1, M#2, M#3, M#4 and M#5) intercepted by an OW contact (SSTVD -5130 m), and the effective GRV (above the OW contact) per each model.

After performing the GRV calculation above the OW contact, we built a chart (**Fig. 17**) demonstrating how the GRV varies among the models. In the chart, the lowest GRV corresponds to the tomographic velocity model (M#2) and highest GRV resulted from the velocity model including the intrasalt cycles (M#5).

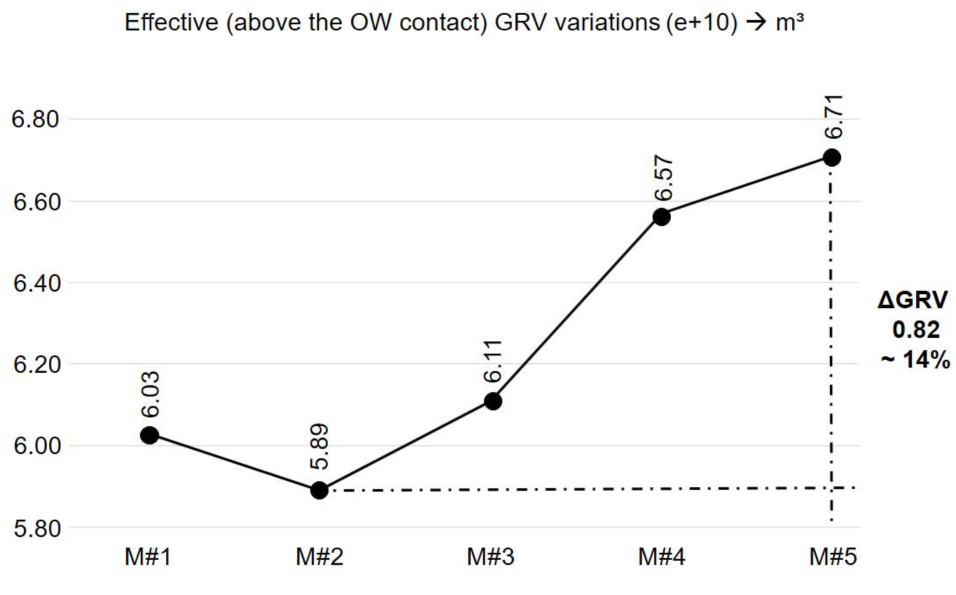


**Fig. 17.** GRV (in million cubic metres) calculated for the five models (M#1, M#2, M#3, M#4 and M#5). An estimated difference of 14% in GRV is observed between M#2 (the reference model) and model M#5 (seismic inversion considering the intrasalt cycle).

**Discussion**

The saline evaporitic section in the Santos Basin is clearly delimited by two horizons, the top and the base of salt, and its positioning is very well defined without the need of synthetic seismogram control. The base of salt represents the top of the reservoirs in the Brazilian pre-salt plays. This geological feature shows a positive response reflecting the interface between moderate-impedance halite and the high-impedance reservoir caprock. During the calibration process, we measured the final depths of the halite per well and at the positive time peak from the seismic data at the well locations. Having this information, we calculated the average velocity at well locations for all the five models. The basal anhydrite average thickness nearly 14 metres - see table 3 for details - is below the seismic resolution, here varying from 50 to 60 metres. Therefore, even assuming it is reasonable to consider it when performing uncertainty analysis, this analysis was not accounted for the volumetric calculation.

The average interval velocities taken from the sonic logs for different salt assemblies are respectively: 4188 m/s for LVS; 4521 m/s for halite; 5281 m/s for HVS; and 4548 m/s for all the evaporates as presented in figure 13. Using the drill cutting samples as reference, we included the pseudo velocities information along sonic-log gaps, and determined the average interval velocity of 4585 m/s for the 14 wells. This analysis reinforces the fact that we must deal with the velocity variations inside the salt section in order to get reliable models and its related uncertainties.

The tomographic velocity model updating (M#2) is still one of the standard models for the oil & gas industry, which delivers good seismic images, however it does not present a clear match with the internal stratigraphy in the saline evaporitic section. As mentioned by Guo and Fagin (2002), the tomographic process is a mathematical approach searching for the gather alignments and is a powerful tool, although not necessarily honoring the existing geology. Differently, the models M#3 (amplitude response) and M#4 (model-based seismic inversion, in that case only considering the horizons of the top and base of the salt) gave us good results also related to the internal features. However, when we quantify the error, M#5 delivers the best results. This model, besides using the top and base of salt during the seismic inversion, also considers three other internal horizons reflecting $4^{th}$-order cycles of evaporite deposition.

The sum of depth positioning modular differences from the well markers and unconstrained depth-converted horizons of the base of the salt shows a decrease from 17.11 m to 6.33 m for M#5, which suggests that this is the most precise model as we see consulting table 4 and figure 14.

Comparing the errors of different models in the reference section, figure 14, only the well K reports an increase of the forecasted error (from -3.93 m to -5.72 m). The well H penetrated high complex and folded structures related to intense salt flow, consequently, in response to the intense mixture of salt types, the error decrease from M#2 (9.03 m) to M#5 (7.66 m) was irrelevant. All other models for well H have the same magnitude of errors (M#1 = 13.54 m; M#3 = 9.39 m; and M#4 = 9.94 m). For all the remaining wells, the errors decrease with the inclusion of the geology complexity in model M#5, see table 4 and figure 14.

Despite the qualitative analysis, figure 15 shows that, in general, the errors tend to increase where the section is thinner. Maul *et al.* (2019) suggest that the percentage of HVS is higher in thin salt sections. Lachmann (1910) and Arrhenius (1913) both referenced in Dooley *et al.* (2015) described Rayleigh-Taylor (R-T) instability, which serves as theoretical basis for the understanding of this phenomenon. The authors defended that it promotes the movement of the more mobile salts (LVS and Halite) to areas of smaller pressures, for instance domes, allowing the concentration of HVS in thinner portions. The predominance of halite induces its dominant behavior in the entire salt section, therefore, at the thin portions, the interval velocity increases following the higher amounts of HVS. Even with the best applied model (M#5) the calibration process is essential in order to honor the well information. Using kriging with external drift (KED) algorithm to produce the maps presented in figure 17, we can estimate how the GRV varies above the OW. Among the five models, the larger difference is between M#2 and M#5, showing that the volumetric uncertainty is captured when analyzing the results delivered from these models. Considering the oil-saturated GRV, we quantified a positive variation of 14% from M#2 to M#5, which can accommodate an order of 3% of oil volume variation, with an average total 20% reservoir porosity.

**Conclusions**

The velocity model of saline evaporitic section in the Santos Basin represents over than 50% of the entire velocity model. Thus, this portion has strong influence on the establishment for the position of the reservoir structures in the pre-salt section. Therefore, lacking its proper representation, especially the absence of geological complexity, imposes a huge risk for the development of pre-salt fields. In this work, we show methodologies to build velocity models for the salt section considering the heterogeneities observed in the amplitude seismic response and well logs.

Even if the predominance of halite is more than 80% in average, the stratifications inside the salt section, suggest the presence of other types of evaporitic minerals. The identification, separation and quantification of LVS and HVS proved to be a powerful tool to build reliable velocity models for several applications in the oil & gas industry. Among them, it is the GRV quantification above OW contact, as demonstrated in this work.

After testing five interval velocity models for the salt section, we confirmed that the salt-cycle inversion approach (M#5), inserting salt heterogeneities related to cycles of salt precipitation, delivers the more accurate depth prediction, decrease the sum of absolute imprecision from 17.11 m to 6.33 m in average

We performed the well calibration and quantified the oil-saturated GRV for each one. That information allowed us to calculate the difference among the models. In our case, the previous base scenario following the tomographic update (M#2) delivers the smaller volume among the five. The salt-cycle inversion approach (M#5) delivers the larger GVR volumes above the OW contact, consequently increasing oil volume estimations adding a valuable contribution for infill drilling campaigns.

As the thick salt section in the Santos Basin in not homogenous, the uncertainties related to depth positioning when assuming less geological scenarios for the salt section in terms of velocity can mislead project decisions. The approach to build the velocity models is well documented, and feasible, not overtaking any project time-line.

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**Data and materials availability**

Data associated with this research are not public in respect of ANP´s statement, and cannot be released, but are available from the corresponding author on reasonable request.

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Anexo B1:

***Evaporitic Section Characterization and Its Impacts over the Pre-Salt Reservoirs, Examples in Santos Basin, Offshore***

Rio Oil & Gas 19th ed., Expanded Abstracts, IBP. 2018. Rio de Janeiro, RJ, Brazil.

Maul, A., Cetale, M. & Guizan, C.

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# EVAPORITIC SECTION CHARACTERIZATION AND ITS IMPACT OVER THE PRE-SALT RESERVOIRS, EXAMPLES IN SANTOS BASIN, OFFSHORE

Alexandre R. Maul[1], Marco A. C. Santos[2], Cleverson G. Silva[3]



## Abstract

The combination of seismic attributes and well information represents a good way to identify, quantify, as well as to characterize the existing stratifications inside the evaporitic section in Santos Basin. The incorporation of those intra-salt heterogeneities, or stratifications, allows to build enhanced seismic images, providing confident uncertainty analysis including both depth positioning and seismic signal quality, better accuracy in the flow rates estimation, regarding production and injection rates and better prediction of the operational aspects during the wells construction. However, dealing with salt stratifications is quite complicated especially regarding the seismic resolution and the small number of wells or log gaps in some of them. Here we describe a straightforward methodology to circumvent some of the mentioned problems, presenting the benefits of applying stratified models and their impact over several projects.

**Keywords:** Attributes. Stratification. Evaporites. Uncertainty estimation.

## 1. Introduction

The first drilled well to reach the Santos Basin Pre-Salt reservoirs, at the Brazilian southeastern continental margin, in September 2005, crossed an evaporitic section of approximately 2000 meters, in order to access deep reservoirs about 5000 meters below sea floor. Around 200 wells were drilled in the Santos Basin reaching the Pre-Salt reservoirs (Maul, 2017). The production in this section already exceeds 1 million barrels of oil equivalent per day, through several fields.

To reach the reservoirs several problems have been mentioned for both seismic imaging and safe operations. As per the seismic point of view, the work performed by Jones and Davison (2014) mentioned the problems when interpreting inside and around salt bodies, once these bodies create pitfalls to the interpreter. Concerning the safety operational aspect, Maia and Poiate Jr. (2008) mention the need to consider the salt as not homogeneous for security purposes.

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Currently, in the exploration and production petroleum industry, the evaporitic section is not considered as a homogenous one, composed by halite only, even knowing that this mineral is the predominant one (over 80%) among all other minerals. The other minerals are divided into 2 groups. The first one represents the High Velocity Salts – HVS (Anhydrite and Gypsum). The other group represents the Low Velocity Salts – LVS (Tachyhydrite, Carnallite and Sylvite). There are many works emphasizing this heterogeneity aspect (e.g.: Jackson et al., 2015; Maul et al., 2015, Gobatto et al., 2016, Barros et al., 2017, Fonseca et al., 2018, Cornelius and Castagna, 2018).

This work will cover many aspects and benefits when considering the stratification inside the salt section, using seismic attributes, ensuring the data spatiality and honoring the well data information. This combination permits to build more realistic models for the evaporitic section, allowing the construction of better seismic images, enhancing model interpretations as well as robust lithological predictions when drilling new wells. We exemplified the results giving emphasis for the Santos Basin. However, the applications could be expanded to cover almost the entire extension of the Pre-Salt reservoirs in Santos and Campos Basins (Figure 1).

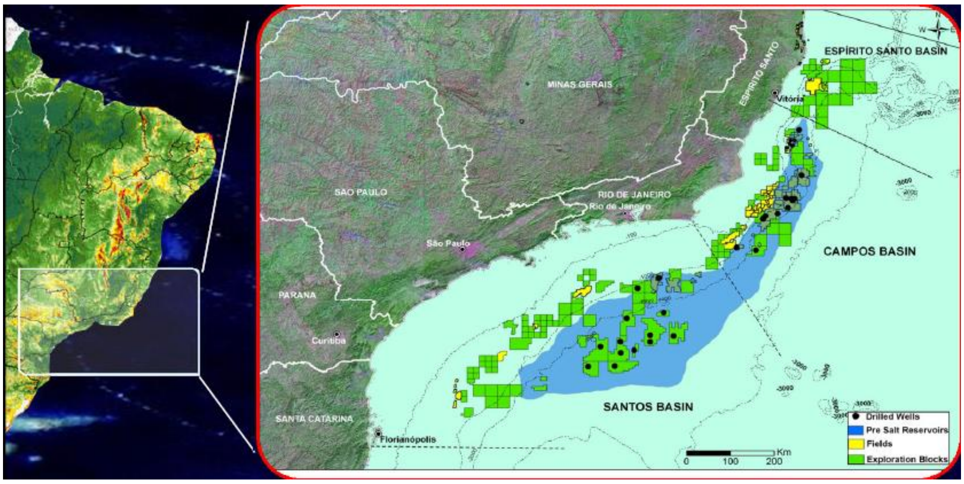


Figure 1. Location of Campos and Santos Basins. The blue polygon limits the pre-salt reservoirs, where several occurrences of hydrocarbons in Pre-Salt section were discovered, totaling an area of approximately 350,000 $km^2$ in water depths in the range between 2000 and 3000 m. Modified from https://diariodopresal.files.wordpress.com/2010/.

## 2. Methodology

The method here used was established by Maul et al. (2016) and first presented by González et al. (2016). This methodology suggested a workflow to insert stratification inside salt sections covering lithology description, initial velocity model, acoustic inversion study, seismic facies classification and uncertainty analysis as described in figure 2.

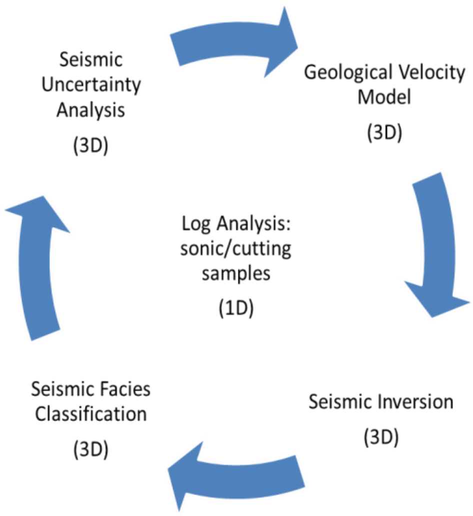


Figure 2. Proposed workflow to generate a more realistic seismic velocity model. Adapted from Maul et al. (2016) in González et al. (2016).

For this methodology, the first and mandatory step is to evaluate the 1D information well by well. The idea is to explore the log data in order to better characterize the salt section. Well log data are not usually continuous in most wells and to complete the information we used drilled- cutting samples, as suggested by Amaral et al. (2015). In the sequence, we built a 3D section model (stratified model for the salt section), using one of the three proposed methods:

a) Velocity model + Instantaneous Amplitude Response (Maul et al., 2015; Jardim et al., 2015; Falcão et al., 2016);
b) Seismic Inversion (Meneguim et al., 2015; Yamamoto et al., 2016; Barros et al., 2017);
c) Facies Classification (Meneguim et al., 2015; Teixeira et al., 2017; Fonseca et al., 2018);
d) Uncertainty Analysis (Maul et al., 2015; González et al., 2016, Gobatto et al., 2016).

It is important to mention that this workflow is a recursive approach, not ending in the first passage. It could be applied covering all the steps or some of them, depending on the available time and purpose. As observed in the loop illustrated in figure 2, one output serves as input for the next step.

## 3. Stratification Modeling Results

As mentioned, it is important to complete the log information for each well in order to access any reliable statistical analysis, mainly regarding the properties behavior. In that sense, Maul (2017) presented a compilation, covering several Pre-Salt fields in Santos Basin, after completion of the log gaps with drill cuttings data (Table 1).

Following the proposed workflow, using the simplest approach, i.e., the combination between velocity and any instantaneous seismic attribute, it was possible to observe a good matching of the modeled stratification over the seismic response (Figure 3).

Even with these suitable results, when using the amplitude response only, the delivered information returned several uncertainties or ambiguities. The main problems were related to resolution, wrong lateral lobe characterization as stratified response and absence of well calibration. Therefore it was suggested to enhance the stratification modeling using seismic inversion (figure 4) and, in some cases, the facies analysis (Figure 5), to circumvent those problems, or at least to enhance de interpretation honoring the well data.

Table 1. Salt proportions and interval velocities (m/s) for nine fields from Santos Basin.

| Field | # Wells | % LVS | LVS AIV | % Halite | HALITE AIV | % HVS | HVS AIV | WIV |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 8 | 4018,56 | 83 | 4480,88 | 8 | 5210,27 | 4462,56 |
| 2 | 29 | 9 | 4218,47 | 82 | 4563,69 | 9 | 4975,84 | 4567,53 |
| 3 | 17 | 12 | 4054,42 | 77 | 4498,25 | 12 | 4989,92 | 4505,66 |
| 4 | 3 | 13 | 3971 | 71 | 4507,09 | 16 | 4927,59 | 4505,04 |
| 5 | 5 | 3 | 4167 | 84 | 4538,00 | 13 | 5123,33 | 4576,00 |
| 6 | 7 | 3 | 4264,19 | 80 | 4509,87 | 17 | 5061,36 | 4596,05 |
| 7 | 72 | 8 | 4122,33 | 81 | 4526,47 | 11 | 5105,84 | 4560,03 |
| 8 | 25 | 4 | 4182,53 | 88 | 4533,59 | 8 | 5003,35 | 4547,16 |
| 9 | 4 | 6 | 4055,63 | 81 | 4486,58 | 13 | 5077,49 | 4535,67 |
| **TNW** | **182** | | | | | | | |
| **AVG** | | **7** | **4117,13** | **81** | **4516,05** | **12** | **5052,78** | **4539,52** |

LVS: Low Velocity Salts; HVS: High Velocity Salts; AIV: Average Interval Velocity; WIV: Weighted Interval Velocity; TNW: Total Number of Wells; Interval Velocity (m/s); AVG: Average. Modified from Maul (2017).

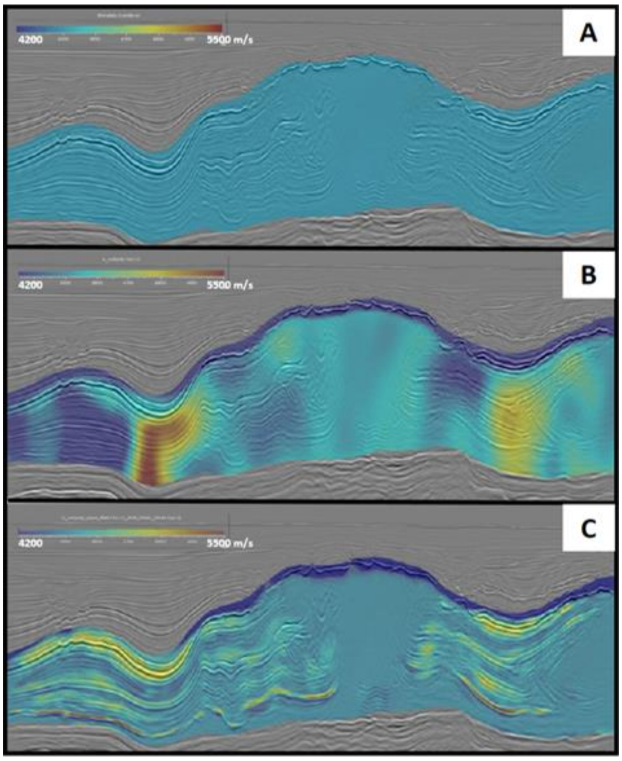


Figure 3. Salt interval velocity model overlapping a seismic section. A: Constant velocity model (4,500 m/s); B: Tomographic velocity model updated over the constant velocity model; C: Stratified velocity model built using the constant velocity model plus the amplitude response. Adapted from Maul et al. (2015).

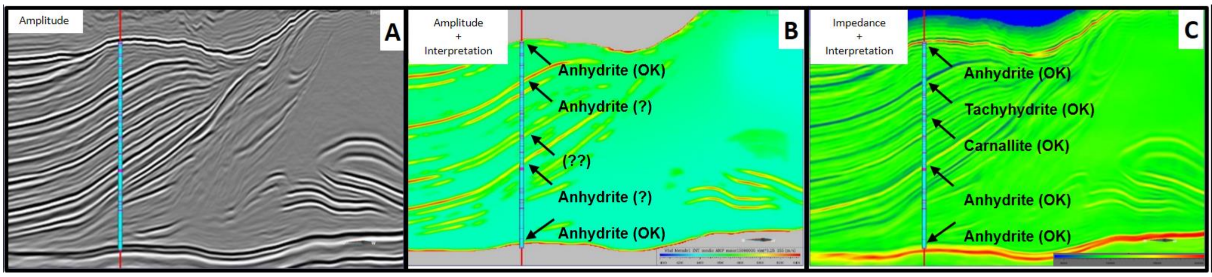


Figure 4. Comparison of modeled results (Amplitude + Velocity X Impedance). Observe the accuracy in interpretation, both the high velocity and low velocity salts using the impedance, which was not possible when using the amplitude, which captures the high velocity salts only. Adapted from Gobatto et al. (2016).

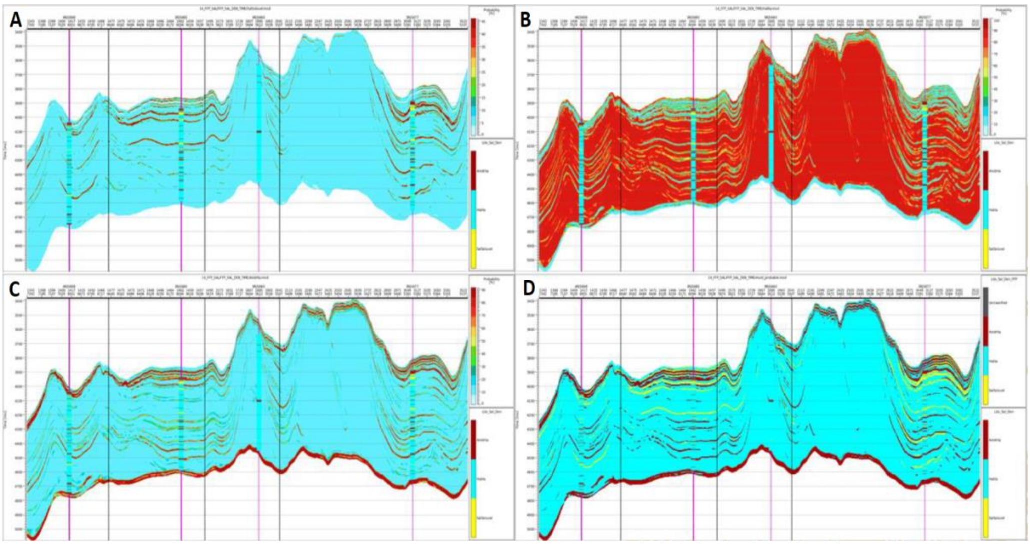


Figure 5. Probability "salt" occurrence: A: Low Velocity Salts; B: Halite; C: High Velocity Salts; D: Most probable salt: Blue – Halite; Red – High Velocity Salts; Yellow – Low Velocity Salts. Adapted from Teixeira et al. (2017).

## 4. Examples of Stratification Modeling Applications

The stratification inside the salt section is a reality. Therefore, the stratification information must be considered in order to generate better geological models. Following we will present few results considering the salt stratification:

### 4.1. Vertical positioning uncertainties

Meneguim et al. (2015) used the stratified model in order to evaluate its influence in terms of target depth positioning. In their work, considering few assumptions about the velocity to use, they reported about +/- 3% of variation in terms of rock volume above the oil-water contact.

### 4.2. Illumination Studies

Figure 6 illustrates how the insertion of stratification information, before the illumination study, can influence the model response. In this case, for a given horizon, the seismic amplitude response was extracted and it was compared with the simulated amplitude response considering or not considering the stratification.

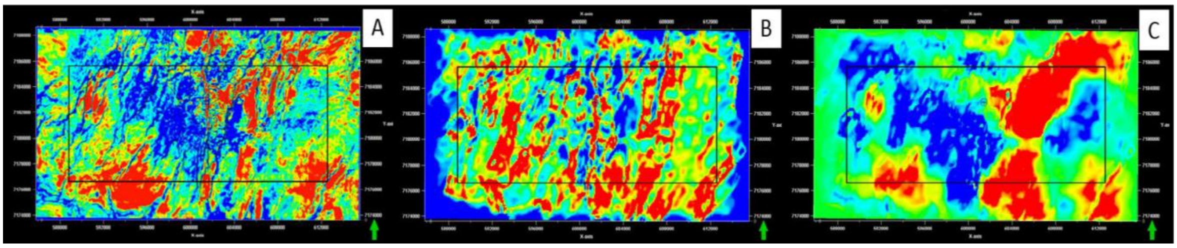


Figure 6. Ray trace illumination study results. A: Instantaneous amplitude response over the horizon of interest; B: Simulated amplitude response over the horizon of interest WITHOUT considering stratifications; C: Simulated amplitude response over the horizon of interest considering stratifications. Images kindly provided by the Geophysicists Rejhane Santos, Roberto Dias and Rodrigo Link (2014).

Evaluating the results it is possible to observe in figure 6 that the amplitude response observed in map B does not match that observed in "A" and that the majority of features observed in "C", despite the smoothed appearance is present in "A".

### 4.3. Signal Quality (Amplitude)

Figure 7 illustrates how the signal response (amplitude) at a given target is influenced by the salt velocity model above when considering or not considering the salt stratification (Maul et al., 2015). The authors also proposed a way to identify and to quantify the uncertainties of target position without knowing the salt velocity model of the section above (figure 8).

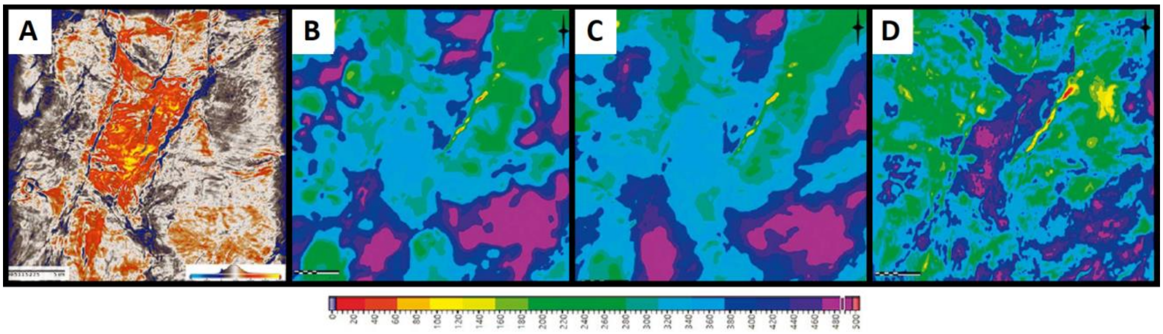


Figure 7. Obtained hit-maps at the same target (base of salt) considering different approaches for the salt section: A: Instantaneous amplitude response over the horizon of interest; B: Hit-map using the salt velocity model from the processing as input; C: Hit-map using a constant (4500 m/s) salt velocity model as input. D: Hit-map using the stratified salt velocity model obtained from the proposed methodology as input. Observe the same heterogeneity behavior in "A" and "D", not present in "B" and "C". Adapted from Maul et al. (2015).

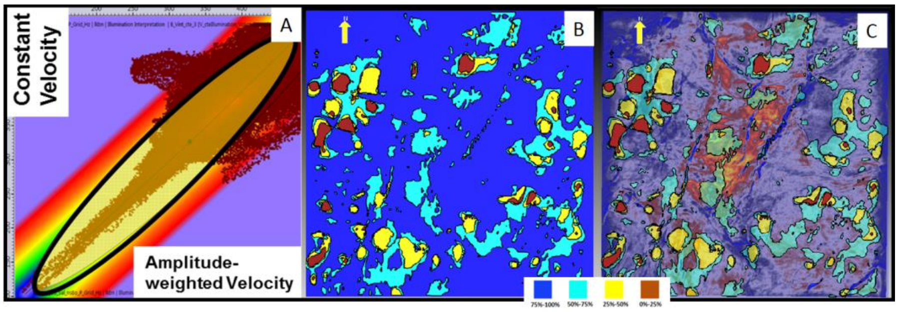


Figure 8. Amplitude response quantitative uncertainty analysis: A: Example of a cross-plot between any two models. The central area (black ellipse) shows the higher similarity; B: Sum of the difference between any two maps. The blue shades show the higher similarity, independent of the used model. Other colors represent decreasing similarities (lower level of confidence). C: The same similarity map "B", filtering out the higher confidence levels (dark blue), overlapped over the extracted amplitude response (figure 6A), indicating the lower confidence response (brown and other colors) in terms of amplitude response when unknowing the salt model above the target. Adapted from Maul et al. (2015).

### 4.4. Seismic processing

One of the key aspects to consider when building seismic images for complex areas, as are the Pre-Salt reservoirs, is to build reliable velocity models for seismic migration purposes. Therefore, the salt section above those reservoirs should not be treated as a homogenous one. Gobatto et al. (2015) emphasized that salt stratification insertion allowed less computational effort for both gather alignment and tomographic inversion, generating more feasible seismic images. Figure 9 illustrates the better gather alignment when inserting the stratifications.

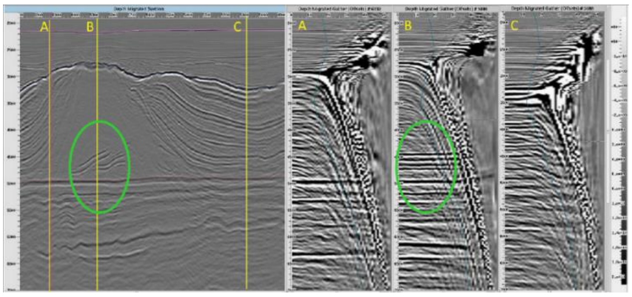


Figure 9. Seismic section illustrating three gather panels and their positions in a stacked section. Observe the deformed stratifications (green ellipse) at position "B". In panel (B) we observe a perfect alignment of the reflectors (green ellipse) only after the salt stratification insertion. Adapted from Gobatto et al. (2016).

### 4.5. Geomechanical simulation studies and safety drilling operation

Regarding geomechanical simulation studies, the knowledge of the sealing cape rocks is one of the most important aspects to consider. For the Pre-Sal reservoirs, the salt section is the cape rock and obviously, the salt stratification must be considered when analyzing its sealing effectiveness. The methodology described above gives the best estimation of heterogeneity locations, providing ways to consider appropriate geomechanical values, even for thin layers, around few meters, like the ones reported at the "base of salt.

Additionally, enhanced drilling strategies delivers greater operational security. Teixeira et al. (2017) using acoustic inversion plus Bayesian´s facies classification reported the success when analyzed "blind wells" against drilling problems such as pipe imprisonment (Figure 10). In this work the authors also explain how to generate a geomechanical property (Young Modulus) from seismic information (P-impedance) (Figure 10).

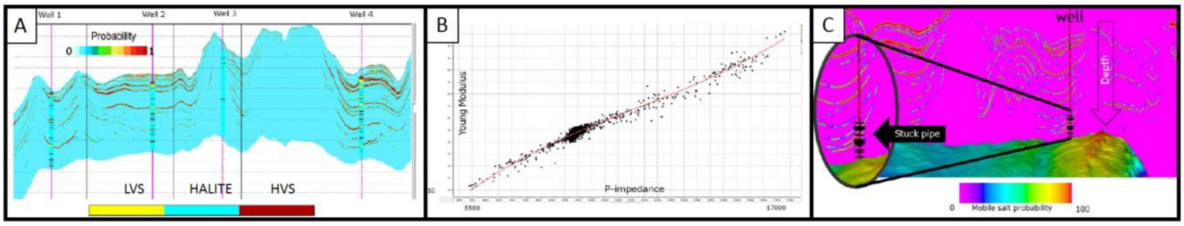


Figure 10. Forecast for drilling problems events. A: Section illustrating the most probable facies: LVS; Halite; HVS; B: Cross-plot illustrating how to calculate a property from another (Young Modulus from P-Impedance); C: Details of an imprisonment-drilling event (a "blind test" over a generated model not using this "blind test"). Adapted from Teixeira et al. (2017).

## 5. Conclusions

The obtained results reflect the benefits of salt stratification insertion in velocity models for many disciplines. There are several examples such as seismic illumination studies in order to define the best parameters when acquiring a new seismic data, the illumination evaluation in terms of amplitude quality and uncertainties, the uncertainties regarding vertical and horizontal target positioning, the creation of more realistic velocity models for migration purposes, allowing better seismic imaging and consequently enhancing the seismic interpretation.

Regarding geomechanical analysis, the usage of the methodology presented herein allows increased accuracy in terms of production and injection rates once it gives better information regarding the lithology and mechanical properties of the cape rocks.

Finally, the proposed methodology provides the means to better represent the evaporitic rocks to be drilled in new wells, minimizing the risks of unexpected fluid loss or pipe stuck.

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Anexo B2:

***Estratificações da Seção Evaporítica na Bacia de Santos: Realidade, Necessidades e Aplicações***

49º Congresso Braisleiro de Geologia. 2018. Rio de Janeiro, RJ, Brasil.

Maul, A., Cetale, M. & Guizan, C.

# ESTRATIFICAÇÕES DA SEÇÃO EVAPORÍTICA NA BACIA DE SANTOS: REALIDADE, NECESSIDADE E APLICAÇÕES

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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, silvita 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

Anexo B3:

***Improving Seismic Images for the Pre-Salt Reservoirs when Updating Salt Stratified Velocity Models***

16th International Congress of the Brazilian Geophysical Society & EXPOGEF. Rio de Janeiro, Brazil. 2019. SBGf.

doi: 10.22564/16cisbgf2019.040.355.

Maul, A., Cetale, M., Guizan, C., Boechat, J.B., González, M., Yamamoto, T., Teixeira, L., Pontes, R. & Fonseca, J.

# Improving Seismic Images for the Pre-Salt Reservoirs when Updating Salt Stratified Velocity Models

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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, 19-22 August 2019.



## Abstract

In complex areas such as the Pre-Salt Section in the Santos Basin, Brazilian offshore to represent as feasible as possible the geology using seismic images is a big challenge. One of the main causes of the observed imaging problems is the evaporitic section considerations in terms of velocity for the migration purposes. Ones consider this section as having an almost constant value (close to 4,500 m/s) which represent the halite behavior, the most abundant mineral in this section. Other, over these models, perform the tomographic inversion updating to give to the velocity model all the mathematical necessity to build confident seismic images. We believe we need to build starting velocity models reflecting any existing geological features prior to apply the mentioned tomographic updating. In this sense, we proposed the insertion of the so-called stratifications inside the evaporitic section taking an adaptation of the model-based seismic inversion. Having this new velocity model reflecting the stratification, we indicate the same tomographic update approach to add to the geological constrains the mathematical complementation. Finalizing, we performed the migration once again and compared the results.

## Introduction

Ji *et al.* (2011) defended the idea that homogenous velocity for the salt section affects the images under the salt section. They cited the weakness and discontinuity in seismic reflection, diffractions-like events and misinterpretation as the main problems when considering those homogeneous models.

Jones & Davison (2013, 2014) mention many difficulties for the seismic imaging near salt bodies, using the Santos Basin, Brazilian offshore as the main example. They cite the inaccurate interval velocity assumption or representation for the salt section as the probable cause of this difficulty. They also observe some features such as inter bedded layers (our stratifications), overlying layers (our so-called superior anhydrite or the Albian rafts presence) and salt flanks (encompassed within the HSD – Hidden Stratified Domain as postulated by Maul *et al.*, 2018b).

Jackson *et al.* (2015) emphasize the presence of “enigmatic structures” within the salt section in Santos Basin. In Mohriak *et al.* (2008) we found the first statement of the term “enigmatic reflectors” which we believe has the same meaning of the “enigmatic structures”. These features are inter bedded layers is seismic terms, *i.e.* the stratifications caused by the mineral variation when they were formed during the evaporation process of brines.

Since 2015, several results related to the salt stratification modelling intending to enhance the Pre-Salt projects have been presented (Maul *et al.*, 2015, Jardim *et al.*, 2015, Meneguim *et al.*, 2015). From the methodology development diverse application have took advantage when using this strategy of modelling those stratifications. The more promises applications are related to uncertainties (Maul *et al.*, 2015; Jardim *et al.*, 2015), geomechanics (Toríbio *et al.*, 2017, Teixeira *et al.*, 2018) and seismic migration (Gobatto *et al.*, 2016, Fonseca *et al.*, 2018, Maul *et al.*, 2018a).

Related to seismic migration tasks, until the beginning of the years 2000, the evaporitic section in the Santos Basin, offshore Brazil, was usually considered as almost constant (interval velocity around 4,500 m/s), or over this applying some tomographic inversion operation in order to update the needed interval velocity observing gather alignment behaviors.

Even knowing the tomographic inversion help the entire migration process it is not a perfect solution for the velocity models updating (Guo & Fagin, 2002). These authors emphasize the needed of incorporating a reasonable geological knowledge into any velocity modelling workflow. Potentially, the FWI (*Full-Waveform Inversion*) methodology can generate high-resolution velocity models (Vigh & Starr 2008), and those models are currently indicated when using the RTM (*Reverse Time Migration*) technique. However, according to Vigh *et al.* (2009), one of the main challenge when using the FWI technics is to produce (or to reproduce) a good starting velocity model to be used to forecast seismic data with geological confidence regarding the subsurface geology, where it has been acquired.

In this paper, we present seismic images built adopting as input the interval velocity model generated through the stratification modelling. In this case, we updated the initial model (the stratified salt one) by using tomographic inversion and the chosen migration algorithm was the Kirchhoff one.

**Method**

The methodology used in this project follows the stated one presented by Maul *et al.*, 2015 and represented in a workflow first presented by González *et al.*, 2016. This method/workflow allows the insertion of the salt stratification or the layered salt by using a seismic acoustic inversion approach as postulated by Meneguim *et al.* (2015). This gives to the section the needed heterogeneity, especially to generate the initial velocity model for the tomographic updating process, which precedes the chosen migration process.

To ensure the efficiency of the application methodology (*i.e.* to generate the stratified model) we performed the tomographic inversion process and the gather alignment panels. For this process we used as the initial interval velocity model both approaches: the standard one that consider an almost constant interval velocity model for the evaporitic section, and the stratified one generated by the acoustic seismic inversion process, as tested and presented in Gobatto *et al.* (2016), Fonseca *et al.* (2018) and Maul *et al.* (2018a).

**Results and Discussions**

The methodology used in this project follows the stated one in Maul *et al.* (2015) and represented in a workflow first presented by González *et al.* (2016). This method/workflow allows the insertion of the salt stratification or the layered salt, given to the section the needed heterogeneity, especially to generate the initial velocity model for the tomographic updating prior to the migration task.

To ensure the efficiency of the application methodology (i.e. to generate the stratified model) we updated the initial model using the tomographic inversion analyzing the gather alignment panels and the built seismic images.

Figure 1 shows few wells drilled in the Santos Basin emphasizing the stratification presence in all of them.

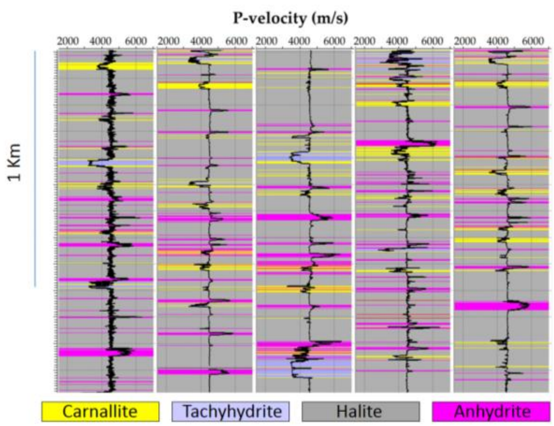


***Figure 1**: Identified stratifications inside the evaporitic section Adapted from Maul et al. (2018a).*

The first thing we must consider when working with the heterogeneity inside the salt section is related to the mineral variation presence, their frequency and their property value variation. In this sense, Maul et al. (2018a) presented a table (Table 1) summarizing the study of almost 200 well drilled in Santos Basin reflecting the average behavior for each studied field, based on the grouping they used: Low Velocity Salt (LVS); Halite and High Velocity Salt (HVS).

Figure 2 illustrates, for a small piece of wells how the velocity can vary among the minerals. In this study, we considered the variation presented in this picture (in this case the average value per mineral).

Figure 3 illustrates how we represented the velocity model for the salt section considering the stratification insertion using the acoustic inversion approach.

Figure 4 illustrates the gather alignment panels allowing the comparison of both approach: to be using the standard way of tomographic updating of the salt flooded salt model x the tomographic updating over the stratified salt model. It is important to mention the tomographic update in a mandatory task in both cases. The main difference when adopting the stratified model is to reduce the number of iterations during the inversion tomographic process without any reduction in terms of delivered data.

According to the images we can see in figure 5, despite the gain related the computation cost, the image quality has also increased considering the image focusing, the structural representation, the vertical positioning/behavior, etc.

| Field | Wells | LVS | Halite | HVS |
|---|---|---|---|---|
| 1 | 20 | 8% | 83% | 8% |
| 2 | 29 | 9% | 82% | 9% |
| 3 | 17 | 12% | 77% | 12% |
| 4 | 3 | 13% | 71% | 16% |
| 5 | 5 | 3% | 84% | 13% |
| 6 | 7 | 3% | 80% | 17% |
| 7 | 72 | 8% | 81% | 11% |
| 8 | 25 | 4% | 88% | 8% |
| 9 | 4 | 6% | 81% | 13% |
| | 182 | 8% | 81% | 12% |

***Table 1**: Table summarizing the mineral occurrency LVS; Halite and HVS) among several fields projects in the Santos Basin. Adapted from Maul et al. (2018a,b).*

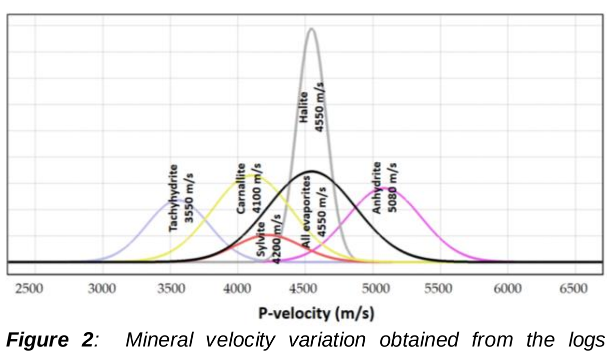


***Figure 2**: Mineral velocity variation obtained from the logs considering a piece (around 10 wells) among the 182 ones mentioned in Figure 1.*
*Adapted from Maul et al. (2018a).*

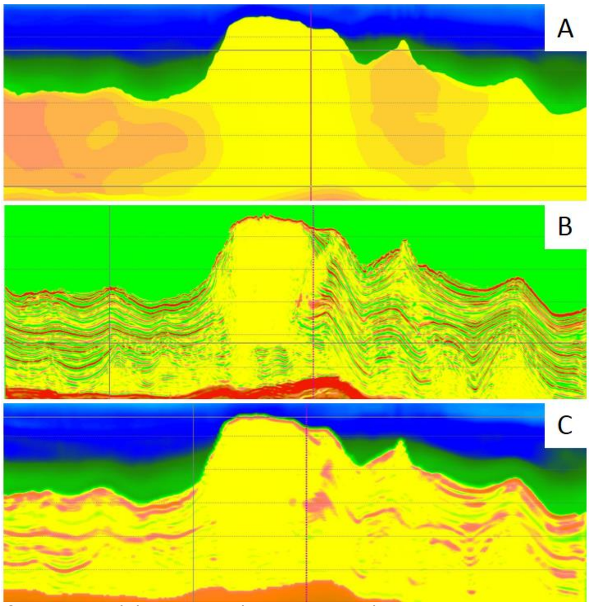


***Figure 3**: Salt heterogeneity representation:*
*A → Needed inversion tomography iteration to correct the almost constant interval velocity model using the gather alignment as criteria-control;*
*B → Seismic acoustic inversion results (model-based approach) illustrating the existing stratification controlled by the amplitude response and for the well information;*
*C → Interval velocity model obtained from the inversion results (in this case, after applying a polynomial transformation guided by the well logs, we smoothed the model vertically.*
*Adapted from Yamamoto et al. (2018) in Maul et al. (2018a).*

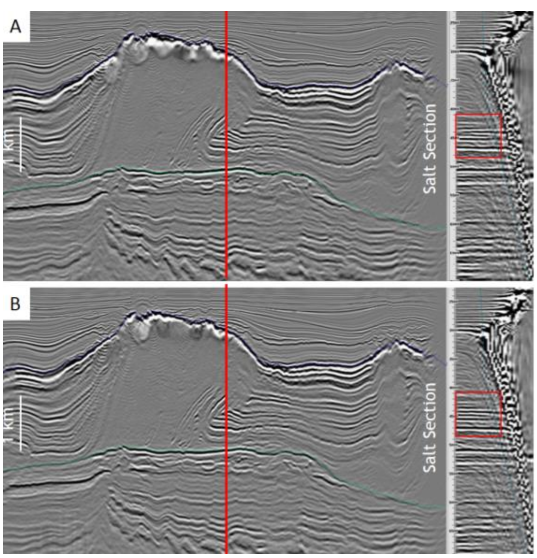


***Figure 4**: Migrated seismic section and a piece of a seismic gather panel illustrating the obtained alignment considering:*
*A → The starting velocity model almost constant after three tomographic inversion iterations;*
*B → The staring velocity model delivered by the stratification insertion after one tomographic inversion iteration.*
*Observe the same level of gather alignment in both examples, which implies in a reduction of computational cost when considering the stratified model.*
*Adapted from Maul et al. (2018a).*

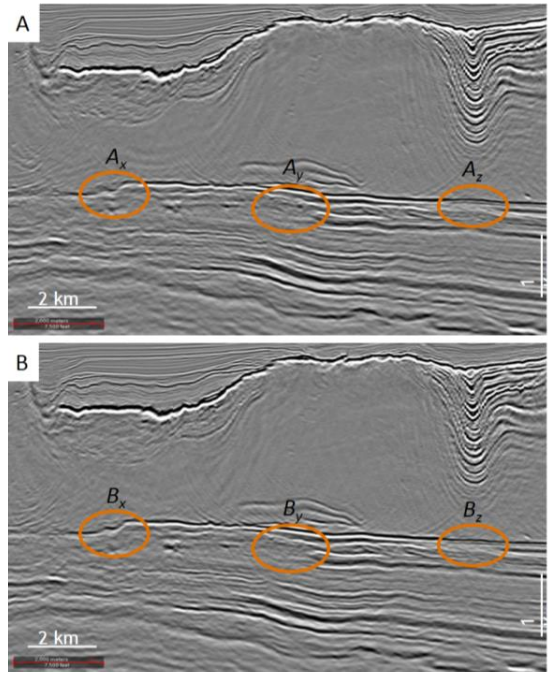


***Figure 5**: Migrated seismic sections using both models:*
*A → The starting velocity model almost constant after three tomographic inversion iterations;*
*B → The starting velocity model delivered by the stratification insertion after one tomographic inversion iteration.*
*Observe the better imaging when using the model with the stratification insertion (positions Bx over Ax and By over Bx) and the vertical more coherent positioning in Bz than Az (in this part it important to notice the salt behavior above the analyzed point!)*
*Adapted from Maul et al. (2018a)*

### Conclusions

To improve seismic images in complex areas such as for the Pre-Salt reservoir in Santos Basin the chosen migration algorithm plus the more feasible interval velocity model containing the reliable geology features seems to be mandatory.

The insertion of the existing evaporitic stratifications using the *model-based* acoustic inversion approach is a reality, giving to the “salt section” an important contribution in terms of geology and the related property such as the needed starting interval velocity for any updating technique (tomography, FWI). By using this methodology, the computation effort decrease as we reduce number of iteration intending to get the gather alignment prior to the final migration process.

Despite this computational effort decreasing the most important statement when applying this combined approach (to perform the velocity update over the stratified salt model plus the good migration algorithm) delivers more reliable seismic images covering several aspects: better representation of structures, geological events continuity, depth predictions, signal quality, etc.

We still believe the anisotropic considerations, if needed for the salt section, could also consider this stratified model as the initial one.

We tested this methodology in several projects driven to the seismic processing. Beyond this processing process, we also tested those models for seismic design (illumination studies), uncertainty analysis, security in well drilling, geomechanical flow simulation, etc. Therefore, despite matters related to any seismic ambiguity, seismic resolution, we do believe it is an approach to consider in all projects for the Pre-Salt section.

It also important to take care about other relevant aspects in terms of velocity model building not only for the salt section as described in this paper. Our group is also researching and applying similar methodologies, in this case, reflecting the needed geology reflected into the velocity models, such as the Albian rafts in Santos and Campos Basins, to insert structural complexity (folds and faults), etc.

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Anexo B4:

***Salt Stratification Insertion to Build Velocity Models and its Impacts for Uncertainties Analysis and Seismic Imaging***

82nd EAGE Conference and Exhibition. 2020. Amsterdam, The Netherlands.

Trabalho aceito, mas apresentação cancelada

Maul, A., Cetale, M., Guizan, C. & Corbett, P.

# Salt Stratification Insertion to Build Velocity Models and its Impacts for Uncertainties Analysis and Seismic Imaging

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**(3) Heriot-Watt University, Edinburgh, UK**

## Summary

The pre-salt reservoirs in the Santos Basin, Brazil are below salt sections varying from few meters to more than two kilometers thick. This section, as well as most salt sections around the world, is not fully composed of halite. Even this assumption may be reasonable for some purposes, the necessity to introduce more geology regarding mineral variations is needed. Several earlier publications have been summarized and it can be recognised that the halite content is about 70-90% in the thicker portions, and something about 50-70% in the thinner portions. Enhanced seismic images are great examples of the method application. Despite the great advantages of considering the heterogeneous salt velocities, assigning the right stratification compressional velocity is difficult and uncertain. Besides, the authors assume that to state those values is a great uncertainty source for the method. Here, we want to demonstrate how to build salt velocity model, from the simplest to the complex way one, and how they affect the seismic imaging, the event positioning, helping to add more value to the project.

## Introduction

Since the first discoveries in the pre-salt reservoir (Santos Basin, offshore Brazil) in 2005, more than 300 wells were drilled in order to reach the carbonate reservoirs in the Barra Velha and Itapema formations. These Aptian-aged formations represent the initial stage of the evaporitic phase within this basin. In order to reach these pre-salt reservoirs, it is necessary to drill through the saline evaporitic section (Ariri Formation) and can range from a few meters to more than two kilometres in thickness. However, as in many basins around the world, the evaporitic section is not fully composed of halite. In past years, due to the absence of detailed knowledge about the salt composition (or, sometimes, lack of computational power to properly address it, especially in terms of seismic processing), treating this section as homogeneous (with halite properties) was considered acceptable. This assumption delivered quite reasonable results, particularly if we consider that drilling through the salt layer was the exception, rather than the rule. With the discovery of the pre-salt reservoirs, however, this changed. Greater understanding of the salt layer results in improvements in several activities in the field assessment and development workflow, like illumination studies for seismic acquisition, seismic processing, uncertainty analysis for depth positioning, seismic signal quality, and geomechanical simulation studies, to cite a few.

In this revision study, we present the latest in terms of the evaporitic layer characterisation, focusing in the Santos Basin and presenting some case studies. The methodology was initially developed to characterise the evaporitic section using well data and seismic amplitude data. This idea evolved into using seismic inversion data, considering only the top and base of the evaporitic section to guide the low frequency model. In parallel, facies classification was also incorporated. Later, due to the absence of drilled wells to control the seismic inversion or facies classification in exploration areas, the use of "masks" from seismic attributes and/or pseudo-well information has also provided improved results. Our last developments include incorporating more geology in the low frequency model, by adding some internal horizons in the salt layer – what some authors deem internal salt cycles (Freitas, 2006; Gamboa *et al.*, 2009; Pontes, 2019).

## Method and Developments

There is plenty of information in the literature describing the difficulty to perform good seismic migration when not considering the heterogeneities of the evaporitic section (Ji *et al.*, 2011), as well as the difficulty to build accurate seismic images near to evaporitic bodies, due to significant lateral velocity variations (Jones and Davison, 2014). Huang *et al.* (2010) defend the idea to use tomography to update the velocity model, in an attempt to represent the layered evaporites in the Santos Basin. Maul *et al.* (2015) mention the necessity of incorporating observed heterogeneities in the evaporitic section, the so-called “salt stratification”, in order to ensure proper image focusing below the evaporitic section, which is crucial both for structural interpretation and for using seismic attributes as drift for distribution of log-derived properties.

We summarize the understanding of the level of geology for an evaporitic section in Figure 1, where we present a few ways to build the velocity model for this section. The models increase in complexity, starting with a simple approach or assumption, which considers this section as homogenous (a halite layer) and evolves with the incorporation, in steps of increasing complexity, of more details in the salt later.

The compressional velocity distribution is another key important factor to consider when building velocity models for the salt section. In the majority of the consulted well we can see the halite predominates, reaching percentages of about 70-90% in the thicker portions. However, this percentage decreases to something about 50-70% in the thinner portions. Maul *et al.* (2019) present a table (Figure 2) containing 182 wells split by fields, summarizing the percentage for each studied fields, grouping the evaporites in three categories: LVS (Low Velocity Salts) mainly composed by tachyhydrite, carnallite and sylvite; the halite by itself (the background evaporite); and HVS (High Velocity Salts), composed by anhydrite and gypsum.

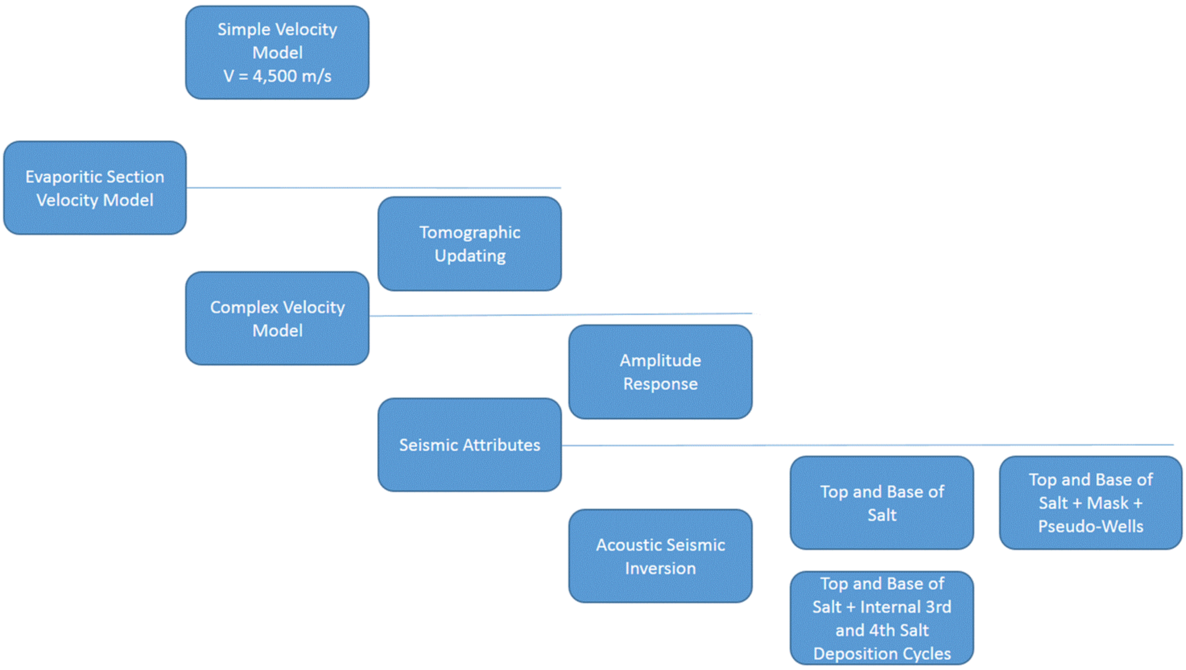


***Figure 1*** *A simple workflow showing several ways to build velocity models for the evaporitic section, starting from a homogeneous model and evolving too many ways of inserting the heterogeneities necessary to improve the quality of the seismic data, especially inserting more geology.*

Using the information from figure 2 and taking into the account the compressional velocity variability measured in the studied wells it is possible to generate PDF distributions for each group and compute its average values (Figure 3). In this case it was just computed the arithmetic average but other ways and to compute the average, such as using the harmonic approach seems to be feasible due to the high "frequency" content of compressional velocity when the layering is considered.

| Field | # Wells | % LVS | LVS ACV | % Halite | Halite ACV | % HVS | HVS ACV | WCV |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 8 | 4,018.56 | 83 | 4,480.88 | 8 | 5,210.27 | 4,462.56 |
| 2 | 29 | 9 | 4,218.47 | 82 | 4,563.69 | 9 | 4,975.84 | 4,567.53 |
| 3 | 17 | 12 | 4,054.42 | 77 | 4,498.25 | 12 | 4,989.92 | 4,505.66 |
| 4 | 3 | 13 | 3,971.00 | 71 | 4,507.09 | 16 | 4,927.59 | 4,505.04 |
| 5 | 5 | 3 | 4,167.00 | 84 | 4,538.00 | 13 | 5,123.33 | 4,576.00 |
| 6 | 7 | 3 | 4,264.19 | 80 | 4,509.87 | 17 | 5,061.36 | 4,596.05 |
| 7 | 72 | 8 | 4,122.33 | 81 | 4,526.47 | 11 | 5,105.84 | 4,560.03 |
| 8 | 25 | 4 | 4,182.53 | 88 | 4,533.59 | 8 | 5,003.35 | 4,547.16 |
| 9 | 4 | 6 | 4,055.63 | 81 | 4,486.58 | 13 | 5,077.49 | 4,535.67 |
| TNW | 182 | | | | | | | |
| AVG | | 7 | 4,117.13 | 81 | 4,516.05 | 12 | 5,052.78 | 4,539.52 |

***Figure 2*** *Salt proportions and compressional velocity (m/s) for nine fields (182 wells) inside the Santos Basin. LVS: Low Velocity Salts; HVS: High Velocity Salts; ACV: Average Compressional Velocity; WCV: Weighted Compressional Velocity; TNW: Total Number of Wells; Compressional Velocity (M/S); AVG: Average. Adapted from Maul et al. (2019).*

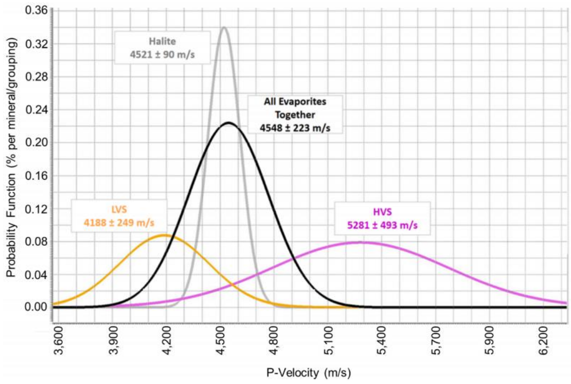


***Figure 3*** *PDF of mineral compressional velocity variation obtained from the well logs considering a sample of 10 wells, among the 182 ones summarized in figure 2. Adapted from Maul et al. (2019).*

Complementing this previous approach, Meneguim *et al.* (2015) developed a way to compute the gross-rock volumes (GRV) above a reference level for different evaporitic section scenarios, ranging from homogenous (pure halite) to heterogeneous layers. Paes *et al.* (2019) adapted this solution by adding the uncertainty of seismic resolution to the calculation of GVR. Regarding the salt cycles inclusion prior to the seismic inversion, Pontes (2019) has also tested the same kind of calculation. The different methodologies delivered similar results, indicating that the GRV can vary from 2% to 6% when considering or not the salt stratification. This last author also measured the differences between the forecasted and detected pre-salt reservoirs, considering homogeneous and heterogeneous models, as well as the inclusion of salt cycles to control the velocity model, concluding that the most accurate model is the one having the salt cycles for the inversion process.

There is plenty of literature discussing the internal layering of the evaporitic section in the Santos Basin. Gamboa *et al.* (2009) mention the existence of four major evaporitic depositional cycles observed in seismic data and well information, corresponding to stratigraphic events of 3$^{rd}$ and 4$^{th}$ orders. They use the idea defended by Freitas (2006), who mapped these cycles using well information from dozens of minor cycles (4$^{th}$, 5$^{th}$ and 6$^{th}$ orders). Later, Jackson *et al.* (2015) proposed a classification that presents a correspondence with the one presented by Gamboa *et al.* (2009). Pontes (2019) has shown the advantages of including the evaporitic cycles of deposition for any seismic process. Fiduk and Rowan (2012) described a similar classification for these four main units, with some differences on how the basal units are split.

The described concepts have been applied in many real projects. Maul *et al.* (2018) present a compendium of applications based on the methodology of stratification of the evaporitic section, covering several E&P areas. We highlight a case study presented by Fonseca *et al.* (2018) where the authors compare seismic sections migrated with a velocity model with and without the salt model. The salt stratification leads to the enhancements in image focusing/sharpening, characterisation of geological features, attenuation of pull-up and pushdowns features, and cost reduction due to fewer number of iterations needed to update the velocity model, using tomographic inversion prior to migration. Figure 4 exemplifies these results.

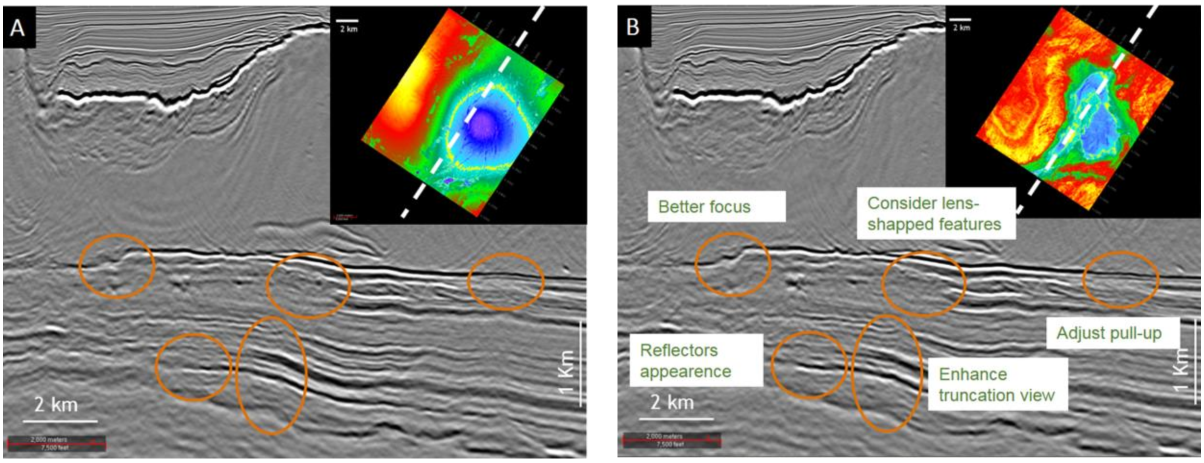


***Figure 4*** *Comparison of migrated seismic without (A) and with (B) the salt stratigraphic insertion in the evaporitic section. The seismic image presented in (B) is much more accurate than the one presented in (A). The only difference between their processing is the velocity model in the evaporitic section. The modification led to a more heterogenic and geological aspect for the evaporitic section, as can be confirmed looking at the average maps for each model (upper right corner of each section). The map considering the salt stratification (B) is more heterogeneous than the smoothed one presented in the standard model (A). Both cases consider isotropic Kirchhoff Pre-Stack Depth Migration. Figure used under permission of the authors (Fonseca et al., 2018).*

## Conclusions

Before the discovery of the pre-salt reservoir in the Santos Basin, many seismic processes in the area modelled the evaporitic section as homogenous. Intense exploration and drilling activity stablished the basin as a new important play, and the necessity to perform high-resolution geological characterisation of the reservoirs pushed the development of several methodologies, especially the ones linked to the seismic activities. One of these methodologies is insertion of stratification inside the evaporitic section, using seismic attributes combined with well information. This methodology is becoming the standard approach for pre-salt plays. The results have proven its utility in several disciplines subjects, as mentioned in the introduction part and all these improvements add value to the project, increasing the return on the invested capital.

## Acknowledgements

The authors would like to thank Petrobras for providing the data, and for permission to publish this work. We also thank the other colleagues who contributed to this abstract.

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Anexo C1:

***Observing Amplitude Uncertainties for a Pre-Salt Reservoir Using Illumination Study (Hit-maps)***

77th EAGE Conference and Exhibition. 2015. Madrid, Spain.

doi: 10.3997/2214-4609.201412921.

Maul, A., Jardim, F., Falcão, L. & González, G.

MADRID 2015
1-4 June 2015 | IFEMA Madrid

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# Observing Amplitude Uncertainties for a Pre-salt Reservoirs Using Illumination Study (Hit-maps)

A.R.M. Maul (Petrobras), F.J.S. Jardim (Petrobras), L.F.F. Falcao (Petrobras) & G.A.G.S. Gonzalez* (Paradigm)

## SUMMARY

Several discoveries were announced in pre-salt section in Brazilian Basins. There are several discussion regarding the correct way to build the best velocity model for migration purpose (algorithms, constant velocity, isotropy, FWI). These discussion look for how to build the best image only. The amplitude response seems to be a consequence of this built image.

We present a method for uncertainty analysis in seismic illumination studies. Different velocity models were built in order to better understand their impact over the obtained hit-maps (ray-tracing method). The original velocity model is used as reference to compare the initial hit-map against others obtained using different velocity models. Cross-plots are used to assess areas where response values are divergent or where there is greater uncertainty in seismic illumination, and consequently in seismic amplitude response for the reservoir characterization.

With original velocity model as input, we constructed four scenarios regarding the velocity of the evaporitic layer: (1) using the original velocities; (2) constant velocity for the evaporitic complex; (3) geostatistical extrapolation of wells logs; (4) conditioning the evaporitic complex velocity using amplitude as weight factor.

This method can be used to investigate uncertainties and emphasize where amplitude response can be used properly for reservoir characterization.

## Introduction

Several discoveries have been announced in Santos and Campos Basins in pre-salt layers (Barra Velha and Macabu Formations). There are many discussions regarding the correct way to build the best velocity model for migration purposes (algorithms, constant velocity, tomography, isotropy x anisotropy, FWI). These discussions usually look for how to build the best image only.
In a reservoir characterization is usually considered that the amplitude response is due only to the impedance contrast of rocks. However, it is known the amplitude response depends on several factors such as geology complexity, acquisition parameters, processing strategy, etc. (Hari Lal *et al*, 2010). The presence of both homogeneous and layered evaporites and faults that could overhang the carbonates and mini-basins in the post-salt section makes the velocity model building workflow more challenging when compared to other areas such as in the Gulf of Mexico (Zhang *et al*, 2008 and Huang *et al*, 2009) (Figure 1).

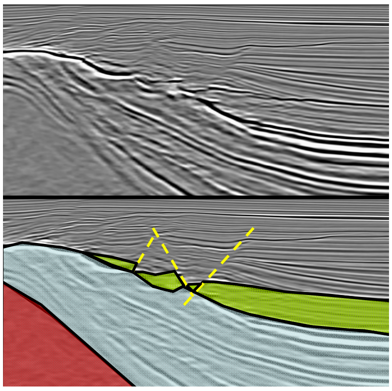

***Figure 1*** *Complex geological scenario: seismic section and schematic interpretation. Green represents the post-salt carbonates, blue the stratified evaporites and red the domic salt.*

Due to the difficulty to ensure which are the main factors that cause these amplitude uncertainties, it is mandatory to evaluate the amplitude response before using it. Furthermore is reasonable to add the geology complexity in the velocity model construction, frequency content and other considerations.
We present a method for uncertainty analysis in seismic illumination studies. Different velocity models were built in order to better understand their impact over the obtained hit-maps (generated by ray-tracing method). The original processing velocity model is used as reference to compare the initial hit-map against others obtained using different velocity models. Cross-plots are used to assess and to identify areas where response values are divergent, or in other words, where there is greater uncertainty in seismic illumination, and consequently for the seismic amplitude response.
This method can be used to investigate and compute uncertainties and emphasize where the amplitude response can be used properly for reservoir characterization.
One seismic amplitude map of reservoir top was extracted from the seismic cube migrated using the original velocity (Figure 2).

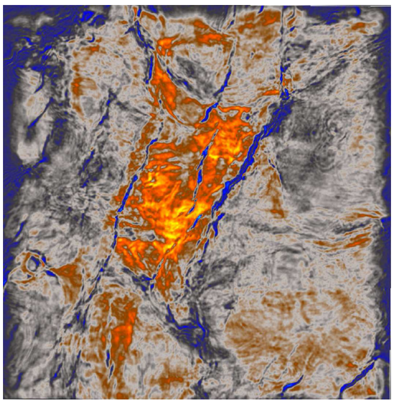

***Figure 2*** *Seismic amplitude map of the reservoir top. Demonstrates a distinctive NE-SW related to carbonate build-ups and faults. Orange amplitude delimits the reservoir.*

**Methodology for input generation**

Four velocity models were constructed with specific consideration for the evaporites layer to perform the illumination study in an isotropic approach:

- The interval velocity obtained from seismic tomography in the pre-stack depth migration processing (Figure 3A).
- A model with constant velocity for the evaporitic complex. Velocity was estimated from a statistical analysis of the instantaneous velocity using 4 wells (Figure 3B).
- A velocity model derived from a seismic pattern recognition study and a geostatistical approach for extrapolation of the velocity logs. A volumetric seismic facies analysis over the calculated seismic energy defined two domains: stratified (high energy) and homogeneous (low energy). A grid deformed by seismic interpretation was built for the well-log velocity extrapolation and treatment in the stratified domain. In the homogeneous domain a constant velocity was considered (4500 m/s) (Figure 3C).
- A velocity model generated with amplitude as a weight factor into the evaporitic complex in order to achieve better representation of the heterogeneities. Based on velocity logs and lithological interpretation, high positive amplitudes were assumed as Anhydrite (interval velocity = 5900m/s), low negative values as Carnallite (interval velocity = 3900m/s) and intermediate values as halite (interval velocity = 4500m/s) (Figure 3D).

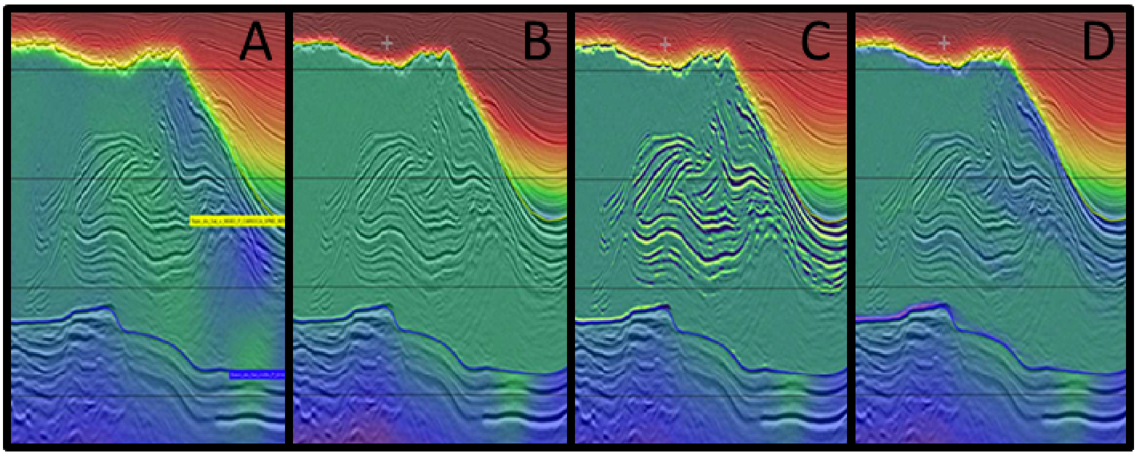


***Figure 3** Original salt velocity model **(A)**; Constant salt velocity **(B)**;Geostatiscal Approach using the logs **(C)**;Weighting the salt velocity using the amplitude signal **(D)**.*

**Methodology for hit-maps construction**

Subsurface illumination analysis provides a technology bridge for understanding the dependencies of the velocity model, migration parameterization and seismic acquisition on the seismic image (Laurin *et al*, 2004a and Laurin *et al*, 2004b).
A ray tracing in batch approach that quantifies the relation between the surface acquisition geometry and the subsurface angles in target areas was used in order to obtain the hit count maps for each velocity scenario. Input for this tool includes the velocity model and the structural map (isotropic assumption).
Several considerations and parameterizations (aperture, maximum input offset, opening angles and ray filters) were tested to find a unique template for the ray tracing processes for each velocity model.
For this analysis were generated four hit-count maps to be considered (Figure 4).

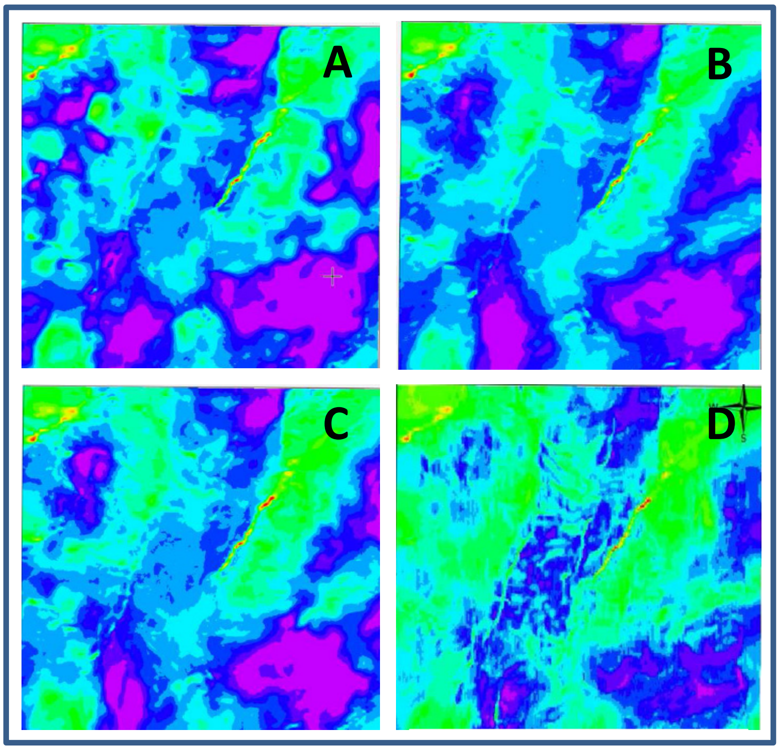


***Figure 4*** *Hit-maps from the ray tracing, considering: the original velocity model as input **(A)**; a constant velocity for the evaporites layer **(B)**; a velocity model built through a combination of volumetric facies classification and a geological/geostatistical approach **(C)** and the velocity model weighted by the amplitude response into the evaporites layer **(D)**.*
*Cold colors (blue tons) represent zones with more successful rays. The high values southeast region matches with the salt layer thinning.*

**Methodology for results analysis**

The first evaluation was to compare all the hit-maps, the extracted seismic amplitude and the evaporites layer thickness map together. The goal was try to identify how the interval velocity and the evaporites layer thickness influence over the instantaneous amplitude of the reservoir top.
Then was used the proposed cross-plotting approach to appraise the several hit-maps obtained and the identification of regions where the response values are divergent.
These divergent regions were plotted over the amplitude map (reference case) in order to create a highlighting map that offers the confidence degree for the amplitude response for reservoir seismic characterization studies (Figure 5).

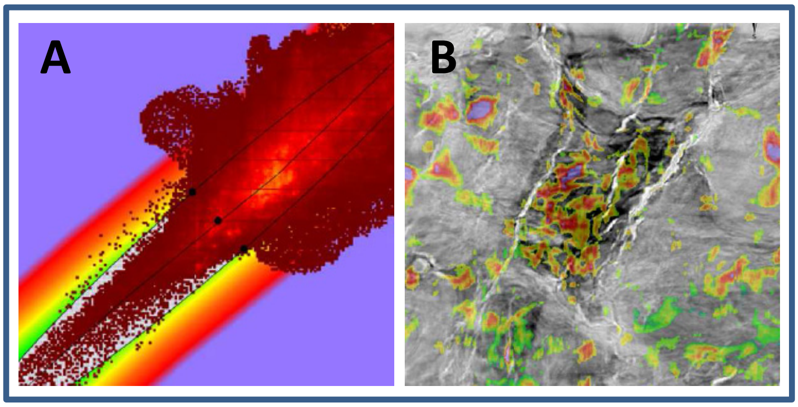


***Figure 5*** *Hit-maps cross-plot. In this particular case, most of the points are well correlated. Observed dispersion could be interpreted as areas of lower amplitude confidence **(A)**. Hit-maps crossploting analysis. High-lighting map over amplitude map suggesting lower confidence areas **(B)**.*

## Conclusions

As expected the way to build the velocity model influences the ray tracing study. Build an accurate interval velocity model is a key point to have a representative image response. The use of the amplitude response versus hit-maps indicated the portions where the amplitude response could be used with confidence to populate reservoir properties as a trend guide.
The uncertainties estimation of this kind of study is an important tool as it takes in account several approaches and consideration during quantitative seismic interpretation processes.
The models created by velocity logs extrapolation and based on amplitude better represent the subsurface heterogeneities, if compared to the original model. A combination of these two methods should be evaluated.
The used ray–tracing method is more indicated for low complexity in terms of geology once it needs to take smoothed velocity model which is not the case for the studied area. There are other approaches for these scenarios such as wave front construction (WFC), finite differences, and complete wave equation.

## Acknowledgments

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Anexo C2:

***The Impact of Salt Overburden Characterization over the Brazilian Pre-Salt Reservoirs***

15th International Congress of the Brazilian Geophysical Society & EXPOGEF
Rio de Janeiro, Brazil. 2017. SBGf.

Speaker: "*Quantitative Reservoir Characterization and Uncertainties Workshop"*

Maul, A.

# The Impact of Salt Overburden Characterization over the Brazilian Pre-Salt Reservoirs

Alexandre Maul (Petrobras)



## Workshop Guidelines

Quantitative reservoir characterization aims to estimate reservoir properties from geophysical data, by combining rock physics, seismic modeling, and inverse methods, along with geological knowledge.

Static reservoir model predictions are generally affected by several sources of uncertainty. These sources include errors, noise, and limited resolution of the geophysical measurements, approximations of the physical relations, and spatial heterogeneity.

Another important source of uncertainty is the geologic scenario uncertainty. A mathematical framework for the quantification of uncertainties in the data and models and for the propagation of uncertainty in reservoir model predictions is then required, in order to assess the risk in reservoir forecasts.

In this workshop, advanced modeling approaches and uncertainty quantification methods will be discussed with the goal of developing new strategies and best practices to improve the reservoir description and the model predictions. Topics will include (but are not limited to) approaches for addressing: Geologic uncertainties; Depositional and structural uncertainties; Seismic imaging and velocity uncertainties; Rock physics uncertainties; Seismic inversion uncertainties; Flow simulation uncertainties.

## Invited Presentation

The idea of this presentation is to summarize all the evolution and results in being applying the developed methodology to incorporate stratification within salt section in Santos Basin to stimulate discussions regarding uncertainties when using it for several purposes in seismic studies.

The obtained results to be presented refer to:

- Uncertainties in

To characterize any kind of reservoir good quality seismic images are essential. Besides, accurate depth estimation is mandatory for any seismic usage. Hence, it is necessary to design robust seismic acquisition as well as a good strategy regarding processing. Both must be focused on the interest reservoir.

Getting inside at each step of subsurface image building, it is notable that the used velocity model plays a big role for the final result.

In order to have a better comprehension of the reservoirs through seismic we must have a reliable model about what is above them, particularly the P-Wave velocities. This could be partially reached with mathematical concepts/approximations as tomography, for instance.

However, the majority of velocity models generated only by tomography do not properly represent geological features as demonstrated in Falcão et al. (2014). Incorporating rock knowledge above the reservoir, in terms of velocity models, has demonstrated great potential to solve this matter. When used in reprocessing, improves the seismic image quality, as shown in Gobatto *et al.* (2016). Besides this, for illumination studies such as Jardim *et al.* (2014), Maul *et al.* (2015) and Jardim et al. (2015) have demonstrated better results.

Excellent examples of velocity fields including geology have appeared when an effort was made to create better images of pre-salt reservoirs in Santos Basin. Maul et al. (2016) demonstrated how to incorporate stratifications on evaporitic salts layer and several usage for this kind of approach.

The main objective of this work is to present how we build velocity models in some areas of Santos Basin using geology as constrains. This knowledge is derived from previous seismic image constructed using available dataset. The key aspect to be focused is the velocities determination inside evaporitic salts section including its observed stratification. Beyond this we will explore how to manage honoring well depths, information from logs, seismic attributes, adjustment of depth migrated gathers and defining velocity values to fill information gaps.

## Method

In González *et al*. (2016) it is proposed iterative workflows integration to generate more realistic geological seismic velocity models (figure 1). Therefore, as a new image is built, it is possible to use it to update and refine the velocity model enhancing seismic image until the objective resolution and quality is good enough.

A geological reservoir model is always supported with well data: logs, cores and plugs. The same methodology should be applied when building geological velocity models. A detailed well data analysis for salt section was first described by Amaral *et al*. (2015). After that, we enter in the loop of assembling the velocity models that honor both geology and seismic.

The first presented strategy to incorporate stratification within evaporitic salts layer uses amplitudes variation to match different kinds of salt (Oliveira *et al*., 2015). However, only amplitude usage to discriminate changes in thin stratification may be a pitfall due to side lobes from other reflections. As per Meneguim *et al*. (2015), an alternative way to enhance the thin stratification recognition considers seismic model based acoustic inversion.

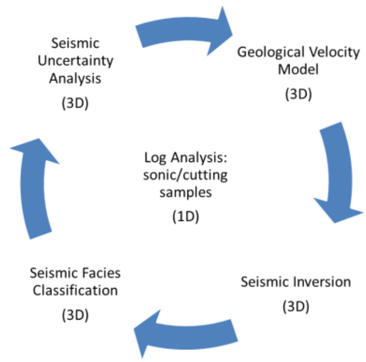


**Figure 1:** The proposed workflow to generate a more realistic geological seismic velocity model (adapted from Maul *et al*., 2016 *in* González *et al*., 2016).

Getting inversion results, it is necessary to create a function to transform AI (acoustic impedance) in feasible P-wave velocity values. Therefore we can use well logs to cross-plot the sonic velocity against AI calculated from sonic and density, as shown in figure 2.

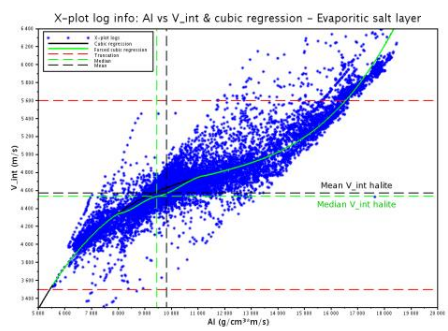


**Figure 2:** Well logs X-plot within evaporitic salts layer of one specified field in Santos Basin. It is made to determine a third degree polynomial regression correlating AI and P-Wave velocity.

As we can see in figure 2, the green and black dashed straight lines are calculated reference values from well analysis. Black is the mean correspondence and green median one. The red dashed straight line is the used truncation values to construct the velocity model. The black solid curve is the regression itself, and the green solid curve has an adjustment trying to match AI median value to halite velocity median value which represents more than 80% within evaporitic salts section.

Finally, the first geological velocity model representing stratification within evaporitic salts section is built. Then, a new seismic data migration is performed enabling evaluation of new seismic images.

The referred seismic analysis considers the integration of all available information. The first aspect to take into account in this integrated analysis is the gathers alignment. The second one corresponds to depth position observed in drilled wells. Several velocity model versions are created in order to obtain the most appropriated seismic response in terms of quality and depth positioning.

**Results**

We believe the stratification incorporation within evaporitic salts section using velocity models for pre-salt fields in Santos Basin should be a standard input for seismic depth migration.

Besides seismic processing, this kind of model could be used in several other areas, eg: geomechanics, seismic acquisition illumination studies, uncertainties in terms of amplitude quality, lateral and depth positioning, well drilling projects, etc.

A Santos Basin particular area is shown in figure 3. The used velocity model to build the seismic image does not represent any stratification as noticed in seismic amplitude.

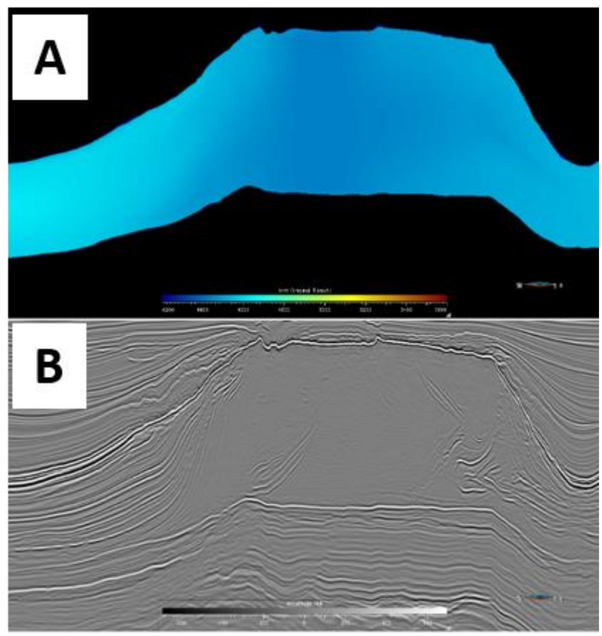


**Figure 3:** (A) Velocity from tomography not considering any stratification within salt layer (B) Amplitude seismic section showing stratification within salt layer. It is important to mention this velocity was used to generate the amplitude image.

To assemble a more realistic geological velocity model considering the needed stratification as described in our methodology, we performed an amplitude and inversion analysis showing results to be verified from figure 4.

Figure 4A represents acoustic inversion performed in amplitude data (figure 3B). After that, velocity values from inversion were calculated using the equations described in figure 2.

Figures 4B and 4C show first and last tested velocity models to migrate data, respectively. Some issues regarding the transition between velocity models 4B to 4C are relevant and will be addressed once several test models were created.

Here, we will discuss the subject concerning the regression to be used to calculate velocity from AI. The first velocity model we were able to test migration is represented in figure 4B. It was built simply by applying demonstrated black regression. The depth migrated gathers showed reasonably flat events within evaporitic salts section. However, when compared with well depth values, we noticed that velocities must be lower than the used one. That was the motivation to change our function between AI and P-Wave velocity, using the green curve instead the black one. Even though the well depths were honored, events in gathers were no more flat, suggesting velocities were lower than needed.

As the first used criteria is to get alignments over gathers, we stated to keep black solid line regression. To fit well depths was adopted another strategy lowering velocities where no stratification events were presented within evaporitic salts section, especially in dome and/or diapiric domains. In these areas it is suggested the salts were mobilized mixing all the moveable salts: halite, carnalite, tachydrite. Justen (2014) demonstrated lower velocity in salt section reflects more than only halite velocity (4500m/s) reducing in average the measured velocities. For that reason regions were generated inside evaporitic salt section corresponding to domes/diapirs.

In seismic amplitude data, domes in evaporitic salts section are easily identified by the absence of reflections (see figure 3B). Then those regions could be established through energy seismic attributes, and lower velocities would be assigned for them, as demonstrated in figure 4C.

Getting the appropriated regions (domes/diapirs) the problem relies on what is the velocity value to be considered for those domains. Any values (from 4400 to 4500 m/s) are supposed to deal with alignment on gathers, affecting only depth. Figure 5 presents seismic migrated sections varying built velocity models. Figure 5A represents the amplitude image using original tomography model (previous processing). Figure 5B represents the same section considering the modeled velocity built in described workflow.

The gather displayed in figure 5 was chosen to demonstrate domes and stratifications together for better comparison. Both models seem to return good seismic image regarding gather alignment and depth position. Anyhow, the highlighted area demonstrated a gain in amplitude response when using geological velocity model with minimum tomography effort to obtain the gather alignment.

Depending on the project, this domes areas can be created with another approach. In Carvalho (2012) was demonstrated the mapping of cycles within evaporitic salts section. Therefore, if the area has this kind of information (the mapping of internal cycles) could be possible to change velocity values inside the domes/diapirs region.

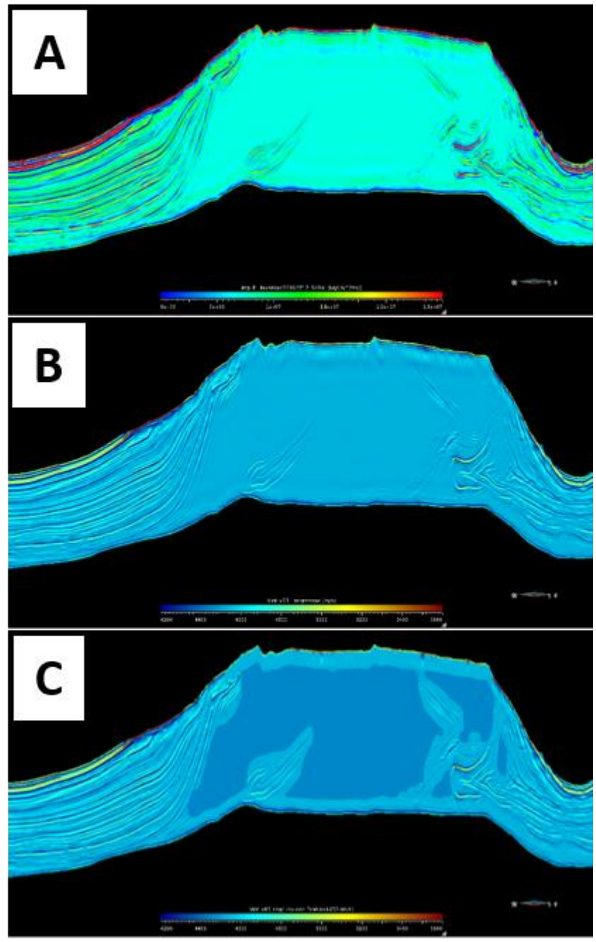


**Figure 4:** (A) Acoustic impedance derived from inversion of amplitude seismic data; (B) Calculated velocity using inversion and regression curve; (C) Adapted velocity to adjust wells with migrations.

In the end of this workflow, was created just one deterministic geological velocity model to recreate the seismic image. Although, with acoustic inversion would be possible to simulate seismic facies using probabilistic density functions from well data as described in Meneguim *et al*. (2015), creating velocity models to perform seismic uncertainty regarding depth positioning.

Other approach for this model construction could be verified in Borges *et al*. (2015) and Borges (2016). These authors suggested a trend to increase/decrease the velocity models in complex areas.

## Conclusions

Geological velocity models have been showing improvement in final products derived from several seismic processes where they are necessary as input. However, we have to remember, it is still just a model from indirect measures and, by definition it is wrong or at least naive. Hence we will always have space to develop models reflecting more and more the reality.

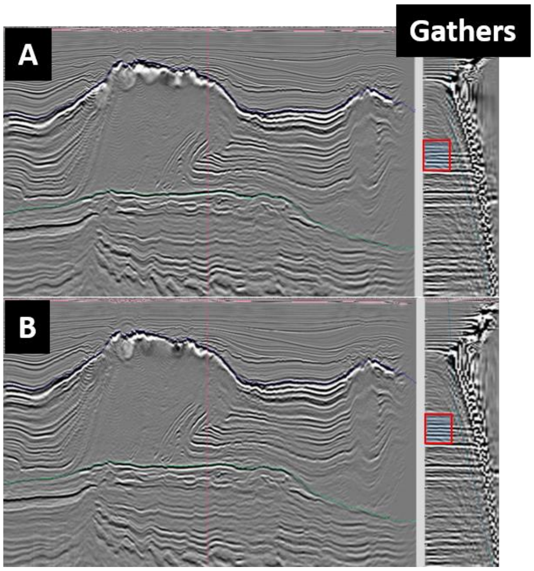


**Figure 5:** Same stacked amplitude section with different velocity models as input to migration. Red line on section represent the trace depth migrated gathers on section side. The letters refer to the used velocity model:
(A) Original velocity from tomography shown in figure 3A;
(B) Geological velocity chosen as shown in figure 4C.
The red boxes on gathers highlight stratification events, demonstrating recuperation and enhancement of events.

In case of Santos Basin, stratification incorporation within evaporitic salts section is just the first step to improve seismic image and depth estimation of pre-salt reservoirs. Further we need to dedicate studies to model velocities honoring geology on post-salt layer, as well as anisotropic considerations.

To incorporate more geology, information is required. Therefore, to determinate velocity values above reservoir, well data logs also should be acquired on previous layers before reach the objective. For instance, evaporitic salts layer need more logs information.

Converging to a geological velocity model and the construction of a good seismic image that honor all available information has been possible due to migration tests on data while assembling the model.

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Anexo C3:

***Modelling Intra-Salt Layers when Building Velocity Models for Depth Migration. Examples of the Santos Basins, Brazilian Offshore***

SEG Technical Program Expanded Abstracts 2018. Society of Exploration Geophysicists. Anaheim, CA, USA.

doi: 10.1190/segam2018-2996209.1.

Maul, A., Fonseca, J., Teixeira, L., Barros, P., Boechat, J.B., Nunes, J.P., Yamamoto, T., González, M. & González, G.

Modelling intra-salt layers when building velocity models for depth migration. Examples of the Santos Basins, Brazilian offshore

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**Summary**

Building seismic velocity models honouring complexities evident from seismic data is fundamental to generate inputs for several applications in seismic modeling and imaging. This is particularly important for complex areas, such as the Pre-Salt section of Santos Basin, in the Brazilian offshore.

We present a methodology to build velocity models incorporating the geological features identified in legacy seismic data for this basin. Of particular interest is, the internal stratification within the salt section. To characterize a geological layer we propose the use of model-based impedance that combines the geological knowledge from wells and seismic interpretations using rock property relationships.

The results are shown in both gathers and stacked migrated sections with improvements in the flattening and the focusing of target reflectors. This approach can also be extended to generate an input velocity model for FWI migration process.

**Introduction**

The Brazilian oil & gas industry is undergoing a huge increase in activities since the Pre-Salt reservoir province has been discoveried in 2007, and subsequently, developed. Seismic imaging technology followed on and moved towards this new and challenging target, pointing to a new big issue: how to deal with the evaporitic salt section, commonly just called as "salt". Complex stratifications within the salt section and huge variations in salt thickness and topography contribute to create an environment where standard seismic imaging techniques are no longer applicable. This has created research activities devoted to improve the existing seismic capabilities, both in the industry and the academia. The results when applying this approach have some impact on several studies, ranging from seismic modelling and processing to reservoir simulation and well stability.

To build velocity models better representing areas with great geological complexity is one of the biggest challenges related to seismic migration process. Jones & Davidson (2014) have presented and discussed many examples in which enhanced velocity models increase significantly the quality of seismic images around, under and inside salt bodies.

Wang et *al*. (2017) mentioned that a carefully designed seismic acquisition and a good migration strategy combined with a good velocity model increases the chances to preserve the seismic signal under salt layers.

This paper describes an approach for building velocity models consonant with the local geology (such as the internal stratifications within the salt section) combining seismic attributes and facies analysis. Also mentioned are the applications in seismic processing (Fonseca et *al.*, 2018).

The results can also be useful for several other applications such as uncertainty analysis regarding both depth positioning and signal quality, seismic acquisition design, inversion studies, geomechanical simulation studies, and well drilling safety. We will focus on the quantitative seismic inversion approach and its benefits for seismic reprocessing, as described by Gobatto et *al.* (2016).

**Methodology, Applications and Examples**

The method was first presented by Maul et *al.* (2015) and then explored how to insert the straitifications using amplitude response inside the salt section and its usage for illumination studies. González et *al.* (2016) presented the workflow stablished by Maul *et al.*, (2016) in order to model any salt stratification for Pre-Salt projects (figure 1).

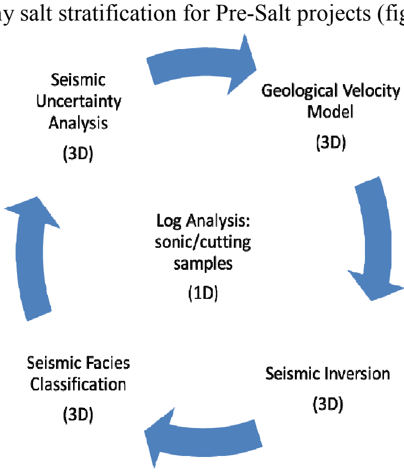


Figure 1: Proposed workflow to generate a more realistic seismic velocity model (*adpated from Maul et al., 2016 in González et al., 2016).*

Meneguim et *al.* (2015) have discussed the benefits of using acoustic inversion and facies classification to model stratifications inside the salt section in Santos Basin.

However, only appraisal wells had the required elastic logs necessary for the inversion process. To overcome this very common limitation, Barros et *al.* (2017) presented a method to fill these well log gaps in the salt section allowing a more controlled seismic inversion.
Teixeira et *al.* (2017) illustrated the benefits of inserting the stratification using seismic inversion and seismic facies classification to generate calibrated information for geomechanical simulations and rock drilling forecast in terms operational safety. These authors have presented that the compressional velocity for evaporate rocks have a strong relation with the acoustic impedance, proposing cubic equations to relate them. Therefore we generate interval velocities from model-based acoustic inversions for salt rocks. Additionaly, this concept could be extended for the carbonate rocks. Figure 2 illustrates the relation between compressional velocity and acoustic impedance from well logs data for the salt section.

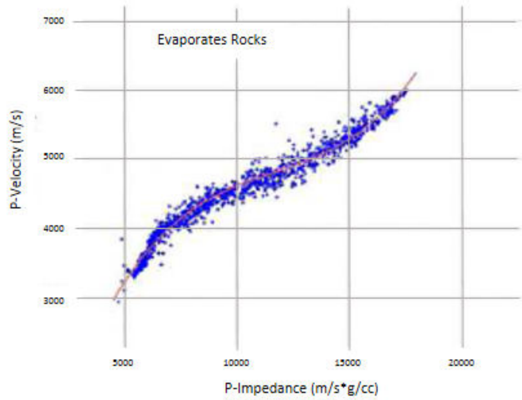


Figure 2: Relation between compressional velocity and acoustic impedance for Evaporates Rocks *(adpated from Fonseca et al., 2018).*

The relation illustrated in figure 2 was applied on acoustic impedance from sesimc inversion in order to generate a P-Velocity model to be used for migration process as shown in figure 3. In this paper we not are intent on discussing other known problems regarding migration process concerning both the Pre-Salt and the Post-Salt velocity behavior, only the more feasible velocity for the salt section.

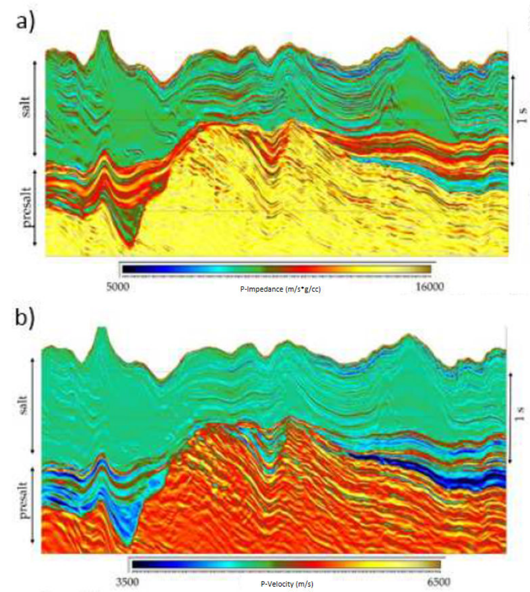


Figure 3: (a) P-Impedance of the Salt Section and the Pre-Salt Section and (b) generated compressional velocity after applying the cross-plot rules on the P-impedance volumes. *(adpated from Fonseca et al., 2018).*

Gobatto *et al.* (2016) and Fonseca *et al.* (2018) had proved the benefits when using the salt stratification for migration purposes. Through figure 4, the last authors showed the enhancements of resolution when including the stratified salt model into the initial velocity model to perform seismic tomography updates for migration process.

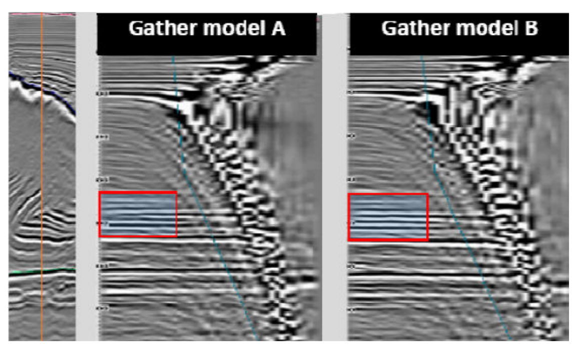


Figure 4: Subset of a migrated amplitude section. The orange line represents the trace whose depth migrated gathers are displayed. The letters refer to the velocity model: (A) Previous velocity model from tomography and (B) updated velocity model with the salt region modelled through impedance. The red boxes highlight stratification events, demonstrating an enhancement of such events within the salt section. (Adapted from Fonseca et *al.*, 2017 *in* Fonseca et *al.*, 2018).

Finally, the figure 5 demonstrates the obtained gain on an amplitude seismic sections with better focusing in the base of salt which is mapped as the top of the first Pre-Salt reservoir in many projects, and in the underlying formation**.**

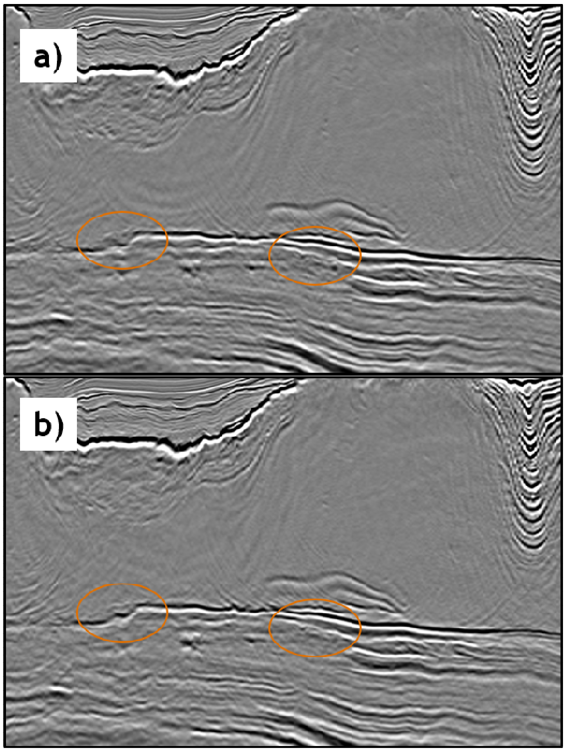


Figure 5: Seismic amplitude migrated with different velocity models: (a) tomography-only and (b) salt inversion. The orange ellipses highlight the base of salt and the reflector continuity.

## Conclusions

Studying the Pre-Salt reservoirs is a complex task, not only because of the type of rocks, but also because of the heterogeneity of the overburden and the structural features. The presented workflow for building seismic velocity models attemps to improve the model building better representing the geological characteristics of the salt section, giving more realistic inputs and facilitating interpretations as well as any other data analysis.

As described in this work, geological features must be considered when building velocity models for seismic processing purposes. The salt section, in particular, must be represented as an inhomogeneous section instead of an almost constant P-velocity section as found after the so-called salt-flooding processing. Even after a tomogaphy updating process, when the velocity is no longer almost constant, it presents several artifacts or "bull-eyes" still not honoring the geology. In contrast our workflow to represent salt heterogeneities is heavily supported by rock property analysis from well and seismic data.

We also suggest that geological-constrained velocity models built using the presented workflow are good initial models for the Full Waveform Inversion (FWI) method since they improve the convergence and prevent from the local minima during the FWI process.

We also advocate that the applications of these models have shown more consistent results, enabling better understandings of seismic responses and better reservoir characterization. Several other areas such as illumination studies, inversion studies, facies classifications, depth uncertainties, geomechanics and safety operational aspects in drilling process have also benefited from this metodology.

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Anexo D:

***O Sal Estratificado e sua Importância na Modelagem de Velocidades para fins de Migração Sísmica***

Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2017.

**Lívia Falcão**

Orientador: Marco Cetale

Coorientador: Alexandre Maul

Avaliadores:

Djalma Manoel Soares Filho; João Batista Boechat;

Luiz Alberto Santos; Wagner Lupinacci

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***Uma Metodologia para a Caracterização da Formação Ariri utilizando dados de Poços e Inversão Sísmica***

Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2019.

**Thiago Yamamoto**

Orientador: Wagner Lupinacci

Coorientador: Alexandre Maul

Avaliadores:

Álvaro Favinha Martini; Antônio Fernando Freire; Marco Cetale

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

Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2019.

**Rodrigo Pontes**

Orientador: Cleverson Guizan

Coorientador: Alexandre Maul

Avaliadores:

Álvaro Favinha Martini; Antônio Fernando Freire

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***Novo Método para Identificação de Estratificações de***
***Sal utilizando Machine Learning sobre Atributos Sísmicos***

Dissertação de Mestrado. UFF. Dinâmica Oceânica e Costeira. 2020.

**Flávio Mesquita**

Orientador: Marco Cetale

Coorientador: Alexandre Maul

Avaliadores:

Alex Laier Bordignon; Marcos de Carvalho Machado

Anexo E:

1. Borges, F., Apoluceno, D., Selbach, H., Maul, A. & Lima G. ***Thickness-based Approach for Evaporites Seismic Velocities in Campos Basin***. 14th International Congress of the Brazilian Geophysical Society & EXPOGEF. Rio de Janeiro, Brazil. 2015. SBGf. doi: 10.1190/sbgf2015-158.

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