A Survey of Pre-salt Carbonates and Reservoir Classification in the Santos Basin

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Abstract

This survey paper presents a comprehensive analysis of pre-salt carbonates and reservoir classification within the Santos Basin, emphasizing the integration of seismic interpretation, petrophysical analysis, and geological modeling to enhance hydrocarbon exploration and production strategies. The study explores the geological complexity of the Santos Basin, characterized by extensive pre-salt carbonate reservoirs formed during the Aptian stage of the Early Cretaceous period. Key methodologies include advanced seismic inversion techniques and machine learning applications, which significantly improve the accuracy and efficiency of subsurface interpretations. The use of innovative tools, such as the Fast Neutron Radiative Transfer technique, facilitates precise fluid quantification in geological cores, while Conditional Generative Adversarial Networks enhance the generation of geological facies models. The paper underscores the importance of data harmonization and the development of comprehensive ontologies, like GeoFault, to support interoperability among multidisciplinary geological projects. Future research directions focus on refining existing methodologies and exploring novel computational techniques to address the challenges posed by the heterogeneity and complexity of pre-salt carbonates. These advancements are critical for optimizing hydrocarbon recovery and ensuring the continued success of exploration and production activities in the Santos Basin.

1 Introduction

1.1 Structure of the Survey

This survey is systematically organized to elucidate pre-salt carbonates and reservoir classification in the Santos Basin, emphasizing the integration of seismic interpretation, petrophysical analysis, and geological modeling. It commences with an **Introduction** that highlights the significance of these elements in hydrocarbon exploration and production, followed by the **Background and Definitions** section, which provides a comprehensive overview of the Santos Basin's geological context and clarifies key terminologies pertinent to hydrocarbon exploration.

The core study is structured into thematic sections. The **Pre-salt Carbonates in the Santos Basin** section examines the geological characteristics and significance of these formations as hydrocarbon reservoirs. The **Reservoir Classification** section investigates methodologies and criteria for classifying reservoirs, underlining their strategic importance in exploration efforts. The **Seismic Interpretation** section elaborates on the role of seismic data in deciphering subsurface structures, including advanced inversion techniques and machine learning applications that enhance interpretation processes.

Petrophysical Analysis evaluates rock and fluid properties, emphasizing the integration of seismic data in these assessments. This is complemented by the **Geological Modeling** section, which discusses the development of predictive models for reservoir behavior, synthesizing insights from

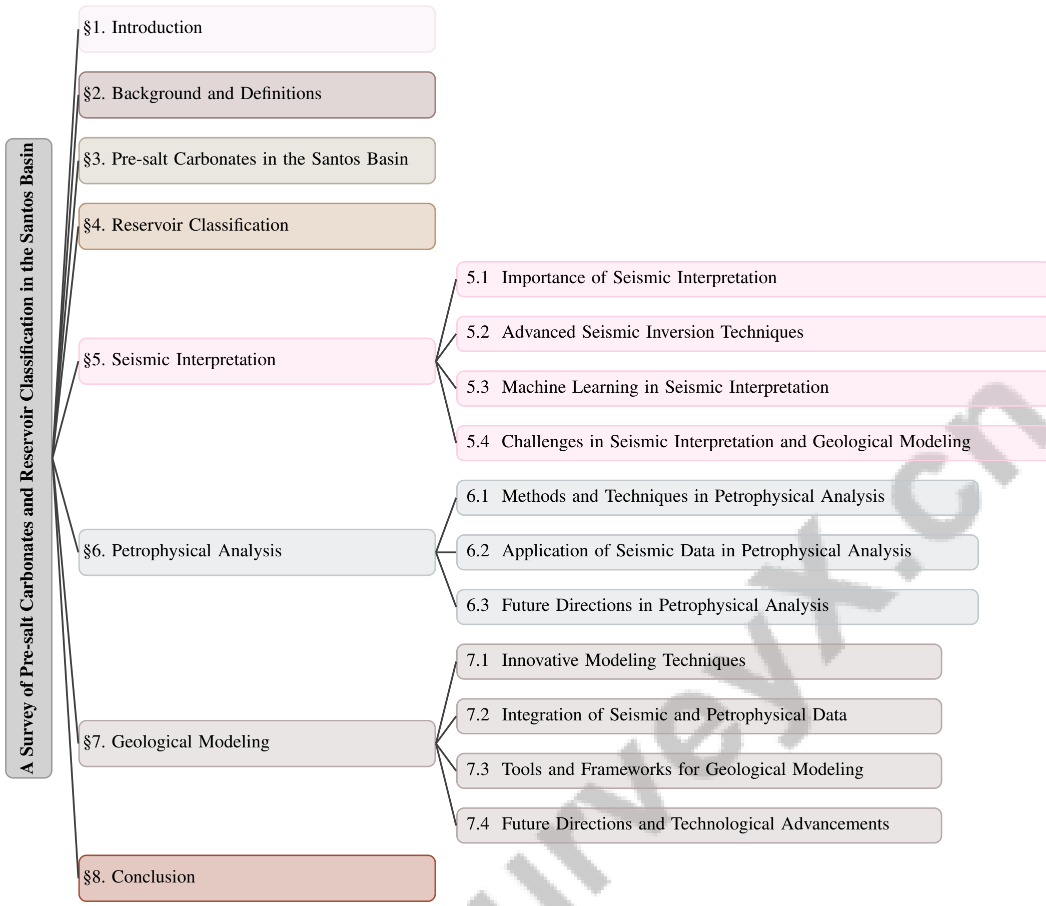

Figure 1: chapter structure

seismic and petrophysical data. The survey concludes with a **Conclusion** that synthesizes key findings and suggests future research directions and technological advancements in the Santos Basin.

The significance of data harmonization in geological modeling is underscored, particularly through the development of the GeoFault ontology [1], which enhances interoperability among diverse computer-based applications in multidisciplinary geological projects. This structured approach ensures a logical flow of information, guiding the reader through the complexities of pre-salt carbonate exploration and reservoir classification while spotlighting the latest methodologies and technologies in the field.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Overview of the Santos Basin

The Santos Basin, located offshore southeastern Brazil, is a prominent hydrocarbon province known for its extensive pre-salt carbonate reservoirs. Covering approximately 352,000 square kilometers, it is one of the largest sedimentary basins along the Brazilian continental margin. The basin's heterogeneous reservoir quality is shaped by diverse geological factors, playing a crucial role in the regional petroleum system, especially concerning its Aptian pre-salt carbonate reservoirs [2, 3, 4]. The basin's complex geological history has significantly influenced its hydrocarbon exploration potential.

The Santos Basin's sedimentary layers have developed over millions of years, with a particular emphasis on the pre-salt layer, which consists of heterogeneous Aptian carbonate rocks. Reservoir quality in this layer is affected by depositional and diagenetic processes, structural configurations, and climatic conditions. The Barra Velha Formation, notably, presents distinct facies compositions, such

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as magnesium-rich clays in lower structural areas and diverse grainstone types across depositional settings. A comprehensive understanding of these geological features is crucial for effective reservoir evaluation and management in this key offshore region [2, 5, 4]. The pre-salt sequence, positioned beneath a thick salt layer, acts as a hydrocarbon seal, a formation process linked to the breakup of Gondwana.

The Santos Basin's hydrocarbon exploration significance is highlighted by substantial reserves estimated to contain billions of barrels of recoverable oil and gas. The Aptian pre-salt carbonate reservoirs of the Barra Velha Formation exhibit heterogeneous reservoir qualities due to various depositional and diagenetic factors, enhancing the basin's potential for significant hydrocarbon production and its critical role in the global energy landscape [2, 3, 4, 6]. These discoveries have positioned Brazil as a key player in the global energy market, with the Santos Basin substantially boosting the country's oil production capacity. Advanced exploration and production technologies further amplify the basin's hydrocarbon potential, facilitating efficient extraction from challenging deepwater environments.

2.2 Defining Pre-salt Carbonates

Pre-salt carbonates are distinctive geological formations beneath thick evaporite layers, primarily salt, in the Santos Basin. Deposited during the Aptian stage of the Early Cretaceous period, these carbonates exhibit heterogeneous reservoir qualities shaped by diverse geological and structural factors. Their complexity stems from varied depositional environments, significant diagenetic alterations, and diverse facies, all impacting their petrophysical properties, such as porosity and permeability, which are crucial for assessing hydrocarbon potential. Similar complexities are observed in the South Gharib Formation of the Gulf of Suez, where structural features and sedimentary processes create a heterogeneous reservoir characterized by laminated dolomitic limestones and variable oil saturations. Advanced modeling techniques, including generative adversarial networks (GANs), are employed to develop realistic 3D facies models that enhance understanding of subsurface architecture and connectivity, essential for effective reservoir management [5, 4, 7, 6, 2].

The role of pre-salt carbonates within the Santos Basin's geological framework is substantial, serving as major hydrocarbon reservoirs that significantly contribute to Brazil's oil and gas output. The Aptian carbonate rocks display variable reservoir qualities influenced by porosity, permeability, and the presence of fractures and faults [2]. Integrating geological and petrophysical analyses is vital for evaluating these reservoirs, as demonstrated by the complexities in formations like the South Gharib Formation [4].

Moreover, the development and application of advanced technologies, such as full waveform inversion (FWI), have improved understanding of these subsurface structures. Tools like the O PEN FWI provide large-scale multi-structural benchmark datasets that enhance the reproducibility and rigor of seismic interpretation efforts [8]. These technologies are crucial in addressing the challenges posed by the heterogeneous nature of pre-salt carbonates, enabling more precise geological modeling and exploration strategies.

In recent studies of the Santos Basin, the pre-salt carbonates have garnered significant attention due to their geological characteristics and their importance as hydrocarbon reservoirs. Understanding these complex systems requires a thorough examination of their formation processes, geological features, and the technological integration involved in their analysis. Figure 2 illustrates the hierarchical organization of key concepts related to the pre-salt carbonates, effectively highlighting not only their geological significance but also the challenges and innovative methodologies employed in hydrocarbon extraction. This visual representation serves to enhance our comprehension of the intricate relationships among the various factors influencing the development and exploitation of these resources, thereby contributing to a more nuanced understanding of the subject matter.

3 Pre-salt Carbonates in the Santos Basin

3.1 Geological Characteristics and Formation

The pre-salt carbonates of the Santos Basin, primarily deposited during the Aptian stage of the Early Cretaceous, are characterized by complex geological features and formation processes that are essential for their function as hydrocarbon reservoirs. These carbonates are influenced by a multitude

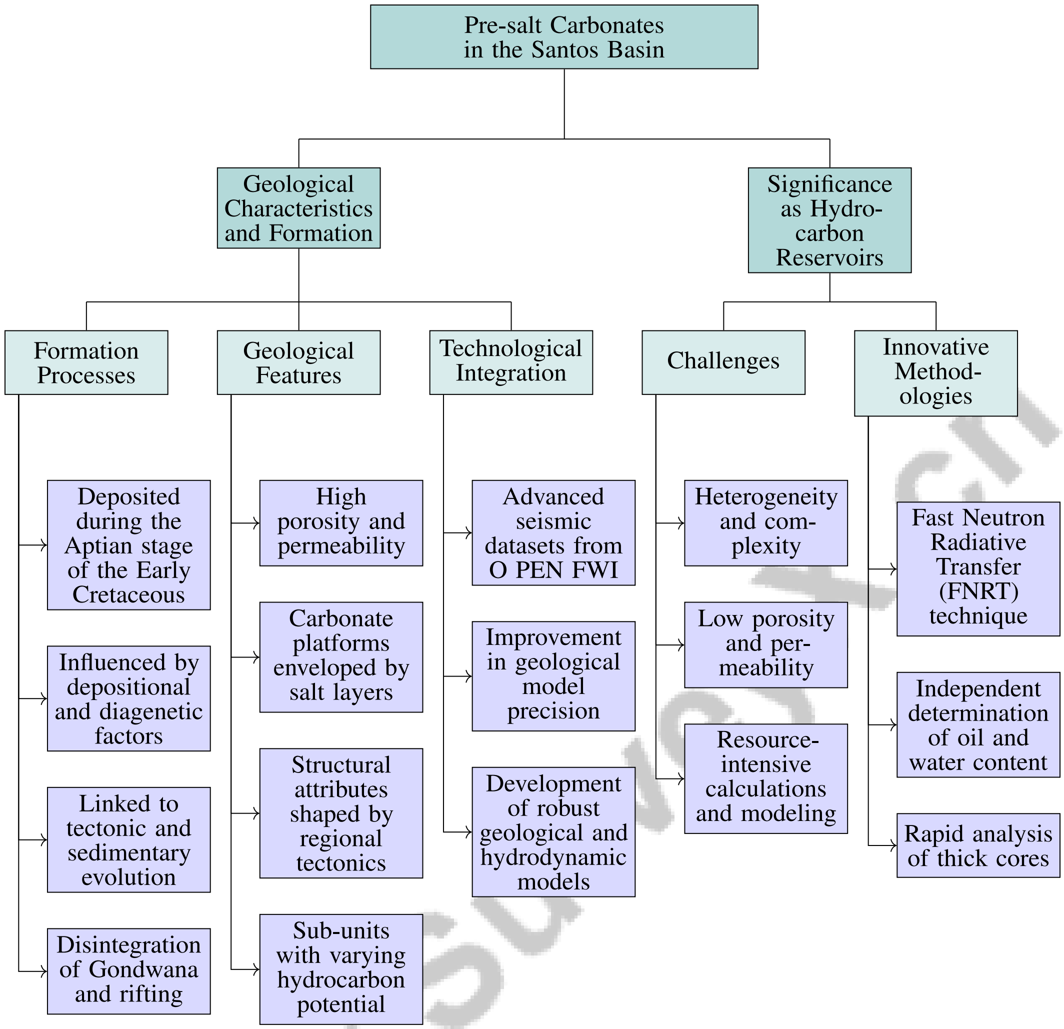


Figure 2: This figure illustrates the hierarchical organization of key concepts related to the pre-salt carbonates in the Santos Basin, focusing on their geological characteristics and significance as hydrocarbon reservoirs. It highlights the formation processes, geological features, and technological integration necessary for understanding these complex systems, as well as the challenges and innovative methodologies employed in hydrocarbon extraction.

of depositional and diagenetic factors, which critically impact reservoir quality [2]. The spatial and temporal distribution of these factors, especially in formations like Barra Velha, is crucial for understanding reservoir heterogeneity and potential.

The formation of these carbonates is intrinsically linked to the tectonic and sedimentary evolution of the Santos Basin. The disintegration of the Gondwana supercontinent and subsequent rifting led to the creation of extensive carbonate platforms, later enveloped by thick evaporite layers, predominantly salt. This unique geological setting, characterized by high porosity and permeability, facilitates effective hydrocarbon entrapment and preservation beneath the protective salt layers. The structural attributes, shaped by regional tectonics, enhance the reservoir's capacity to retain oil and gas, significantly contributing to regional hydrocarbon production [4, 3, 9, 6, 2].

The geological intricacy of pre-salt carbonates is further illustrated by formations like the SADI Formation, which comprises multiple sub-units with varying hydrocarbon potential [6]. This variability necessitates comprehensive geological and petrophysical analyses for precise evaluation of reservoir quality and distribution.

To visually encapsulate these complex geological characteristics and formation processes, Figure 3 illustrates the Santos Basin's pre-salt carbonates, highlighting the intricate interplay of geological features, the tectonic and sedimentary evolution, and the critical role of advanced seismic data in enhancing the precision of geological models.

Advanced seismic datasets, such as those provided by O PEN FWI, offer valuable insights into the subsurface structures of the Santos Basin. These datasets, which include seismic data and velocity maps outlining interfaces, faults, and geological structures, improve the precision of geological models [8]. Integrating such data is crucial for developing robust geological and hydrodynamic models, especially in low-permeability reservoirs where conventional methods may be insufficient [10].

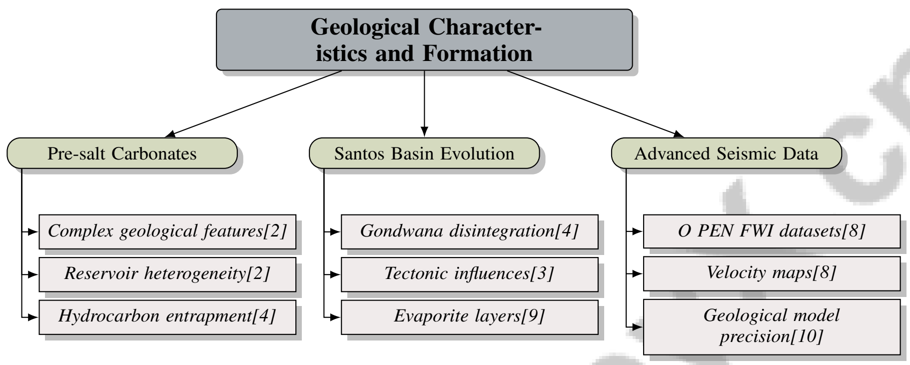


Figure 3: This figure illustrates the geological characteristics and formation processes of the Santos Basin's pre-salt carbonates, highlighting the complexity of geological features, the tectonic and sedimentary evolution, and the role of advanced seismic data in enhancing geological model precision.

3.2 Significance as Hydrocarbon Reservoirs

The pre-salt carbonates in the Santos Basin are pivotal hydrocarbon reservoirs, significantly bolstering Brazil's oil and gas output. Reservoirs within formations like Barra Velha exhibit notable heterogeneity and complexity, posing unique challenges for exploration and production [2]. The intricate depositional and diagenetic processes that have shaped these carbonates result in variable reservoir properties, such as porosity and permeability, which directly impact hydrocarbon recovery potential [6].

A primary challenge associated with pre-salt carbonates is their generally low porosity and permeability, as observed in formations like the SADI Formation in the Halfaya oil field. These characteristics require advanced recovery techniques for efficient hydrocarbon extraction [6]. The complexity of these geological formations also demands resource-intensive calculations and sophisticated modeling approaches to accurately predict reservoir behavior and optimize production strategies [10].

Innovative methodologies, such as the Fast Neutron Radiative Transfer (FNRT) technique, offer significant advantages in evaluating these reservoirs. The FNRT method allows for the independent determination of oil and water content without correlation issues, enabling rapid analysis of thick cores and providing critical insights into reservoir characteristics [11]. These technological advancements are crucial for addressing the challenges posed by the heterogeneity and complexity of pre-salt carbonates, thereby enhancing exploration and production efforts.

4 Reservoir Classification

4.1 Methods for Reservoir Classification

Reservoir classification within the Santos Basin involves an intricate integration of geological, petrophysical, and geophysical analyses to characterize hydrocarbon reservoirs effectively. Key methodologies include comprehensive quantitative approaches that utilize petrographic, mineralogical, and geochemical analyses. These analyses are crucial for understanding the depositional and diagenetic features of formations like Barra Velha, elucidating reservoir heterogeneity and quality [2].

Advanced seismic attributes play a significant role in this process. The SalSi attribute, for example, employs a saliency-based method to delineate salt dome boundaries, thereby clarifying structural features that impact reservoir distribution and connectivity [12]. When integrated with traditional geological analyses, these seismic attributes enhance the precision of reservoir classification by providing a nuanced understanding of subsurface structures.

Data-driven methods have gained prominence, as demonstrated by the ATLAS approach, which optimizes training data selection by focusing on regions of high disagreement, often highlighting geologically significant areas. This method improves data analysis efficiency and enhances reservoir classification accuracy by concentrating efforts on the most relevant geological features [13].

Moreover, the DSI method presents a novel classification approach by generating forecasts conditioned on flow-based observations. This method efficiently samples the posterior probability distribution of data variables, integrating dynamic reservoir data into classification efforts, thus enhancing the robustness and reliability of reservoir classification in the complex geological settings of the Santos Basin [14].

The integration of sophisticated analytical techniques and innovative methodologies is crucial for enhancing reservoir classification in the Santos Basin. This comprehensive approach includes evaluating petrographic, mineralogical, and geochemical data to assess the heterogeneous quality of Aptian pre-salt carbonate reservoirs, along with analyzing petrophysical properties such as porosity, permeability, and water saturation. By examining the spatial and temporal distribution of diagenetic processes and utilizing well log data and core samples, researchers can identify factors influencing reservoir performance and optimize extraction strategies [4, 3, 6, 2, 10]. The ongoing development and application of these methods are vital for optimizing exploration and production strategies in this prolific hydrocarbon province.

4.2 Role of Reservoir Classification

Reservoir classification is pivotal in understanding the potential of hydrocarbon reservoirs and guiding exploration strategies within the Santos Basin. By integrating geological, petrophysical, and geophysical data, accurate reservoir characterization facilitates informed decision-making in hydrocarbon exploration and production, enhancing the understanding of reservoir characteristics and heterogeneity [4].

This classification process aids in identifying reservoir potential and informs the development of tailored exploration strategies. By delineating structural and petrophysical properties, classification optimizes drilling locations, improves resource estimation, and enhances recovery techniques. Advanced methodologies, such as the ATLAS approach, further refine reservoir classification by improving data selection and analysis. ATLAS consistently surpasses traditional active learning frameworks, achieving significant advancements in data interpretation, which is crucial for accurate reservoir characterization and strategic planning [13].

5 Seismic Interpretation

The significance of seismic interpretation in the context of hydrocarbon exploration cannot be overstated. This process serves as the foundation for understanding subsurface geology, enabling geoscientists to make informed decisions regarding resource extraction. As we delve into the specifics of seismic interpretation, it is essential to acknowledge the various methodologies employed to enhance our understanding of geological formations. The following subsection will explore the importance of seismic interpretation, highlighting its critical role in identifying hydrocarbon reservoirs and elucidating the intricacies of subsurface structures.

5.1 Importance of Seismic Interpretation

Seismic interpretation is a pivotal component in hydrocarbon exploration and reservoir identification, providing critical insights into subsurface structures and stratigraphic features. This process is essential for mapping geological formations, identifying potential hydrocarbon traps, and delineating reservoir boundaries, all of which are crucial for successful exploration and production activities. The complexity inherent in modern seismic datasets, which are characterized by their increasing size and intricacy, necessitates the adoption of advanced analytical techniques to enhance interpretation accuracy and efficiency [15].

The integration of deep neural networks (DNNs) into seismic interpretation has marked a significant advancement in the field, improving both the accuracy and efficiency of interpretation processes. DNNs enable the automatic classification of geological units by leveraging a partial loss function that allows training with a limited subset of labeled pixels, thus addressing the challenge of sparse labeling in seismic datasets [16]. Additionally, the necessity for high-quality labeled datasets is underscored by the challenges of accurately describing subsurface geology, which is critical for hydrocarbon exploitation [17].

Recent innovations, such as the directional coherence attribute, significantly enhance the clarity of seismic interpretation by effectively highlighting subtle subsurface features like channels, faults, and fractures [18]. Furthermore, the utilization of waveform curvature analysis, which leverages the dynamic aspects of seismic waveforms, has been shown to improve the accuracy of seismic interpretation [19]. These methods complement traditional approaches by providing a more detailed characterization of subsurface structures within seismic volumes [20].

The application of advanced computational techniques, including the example forgetting method, enhances the interpretability and performance of DNNs in seismic interpretation, addressing issues related to mispredictions and improving overall interpretative outcomes [21]. These innovations are crucial in supporting the identification and development of hydrocarbon resources, ultimately contributing to more informed and strategic exploration efforts.

5.2 Advanced Seismic Inversion Techniques

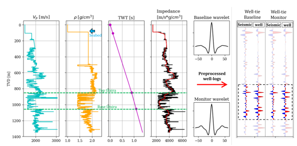
Advanced seismic inversion techniques play a crucial role in enhancing the interpretation of intricate subsurface structures, particularly in hydrocarbon-rich regions such as the Santos Basin. These techniques enable the simultaneous estimation of subsurface properties, like acoustic impedance, and the segmentation of geological features, which is essential for effective reservoir mapping and characterization. By integrating prior geological knowledge with actual seismic measurements, these methods improve the accuracy of identifying geological frameworks and understanding the spatial distribution of facies and diagenetic processes, ultimately facilitating more successful exploration and management of underground resources. [2, 22, 23]. These techniques employ sophisticated computational models to convert seismic reflection data into quantitative estimates of rock properties, offering detailed insights into the geological characteristics of hydrocarbon reservoirs.

A notable advancement in this domain is the use of deep convolutional neural networks (CNNs) for seismic data interpretation. The application of learnable Gabor convolutional kernels, where parameters are optimized during training, has demonstrated significant potential in enhancing seismic facies classification. This approach captures both spatial and frequency domain features, thereby improving the resolution and accuracy of subsurface imaging [24].

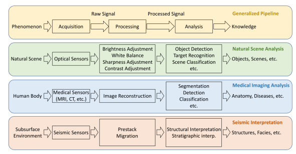
The integration of multiresolution analysis techniques, such as the Multiresolution Analysis for Seismic Interpretation (MRA-SI), further exemplifies the extraction of texture attributes from seismic images. This method facilitates the automatic segmentation and classification of subsurface structures, providing a robust framework for delineating complex geological features [25]. These techniques are complemented by the use of texture attributes, which have proven effective in various image analysis tasks, enhancing the interpretative capabilities of seismic data [20].

Moreover, the adoption of end-to-end semantic segmentation approaches, as seen in recent studies, enables the simultaneous tracking of multiple horizons, effectively addressing the limitations of traditional horizon tracking methods [26]. The development of deconvolutional neural networks, such as SpiNet, has revolutionized real-time seismic data processing and annotation, providing immediate feedback on subsurface structures and facilitating timely exploration decisions [27]. The implementation of reversible neural network architectures has also been crucial in managing the computational demands of processing large-scale 3D seismic datasets, maintaining low memory requirements while ensuring high accuracy [28].

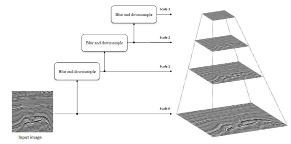
Furthermore, the example forgetting method has been shown to improve segmentation performance, particularly for underrepresented classes in seismic data, enhancing the overall interpretational outcomes [21]. The integration of these advanced seismic inversion techniques in the Santos Basin significantly enhances the understanding of its complex geological framework. By providing high-resolution images and accurate subsurface models, these techniques support the identification of potential hydrocarbon reservoirs and improve exploration strategies, ultimately contributing to more efficient resource management and extraction in this prolific hydrocarbon province.



(a) Seismic and Well-Tie Wavelet Analysis of Utsira Formation in the North Sea[29]



(b) Pipeline for Data Processing and Analysis in Various Fields[23]



(c) Image Processing: Blurring and Downsampling at Different Scales[25]

Figure 4: Examples of Advanced Seismic Inversion Techniques

As shown in Figure 4, The example on "Seismic Interpretation; Advanced Seismic Inversion Techniques" delves into the sophisticated methodologies employed in the realm of seismic data analysis, highlighting the intricate processes involved in interpreting subsurface structures. The first illustration focuses on the Utsira Formation in the North Sea, showcasing a meticulous comparison between seismic and well-tie wavelet data, emphasizing key parameters such as velocity, density, and impedance. This analysis is crucial for understanding the geological characteristics and potential resource deposits in the region. The second image provides a comprehensive overview of a data processing and analysis pipeline used across various domains, including natural scene analysis, medical imaging, and seismic interpretation, illustrating the versatility and applicability of these techniques. Lastly, the third image offers insights into image processing techniques like blurring and downsampling, which are essential for refining data resolution and enhancing interpretability. Together, these examples underscore the advanced techniques utilized in seismic inversion, reflecting the integration of diverse analytical approaches to yield more accurate and insightful geological interpretations. [**?**]romero2023seeingco2plumejoint,alregib2018subsurfacestructureanalysisusing,alfarraj2019multiresolutionanalysislearningcomp

5.3 Machine Learning in Seismic Interpretation

Machine learning has revolutionized seismic interpretation by offering sophisticated solutions to the challenges associated with analyzing large and complex seismic datasets. These techniques facilitate the automated analysis of geological structures, significantly enhancing the accuracy and efficiency of subsurface interpretations. A key advancement in this domain is the application of deep neural networks (DNNs) to tackle both forward and inverse problems in geophysics, thereby improving the interpretation of seismic data. Deep neural networks (DNNs) facilitate the automatic classification of seismic images into geological units, significantly minimizing the need for extensive manual annotation and enhancing the efficiency of the interpretation process. By leveraging advanced techniques such as image-to-image mapping and partial loss functions, DNNs can learn from partially annotated seismic images, requiring only a limited number of labeled pixels to generate high-quality interpretations. This capability not only accelerates the interpretation workflow but also allows for the analysis of large seismic datasets, making DNNs a practical and powerful tool for geophysicists in the field of seismic data interpretation. [16, 15]

The advancement of binary segmentation techniques utilizing deep neural networks (DNNs), exemplified by the Deep Neural Network for Facies Segmentation (DNFS) model, underscores the significant role of machine learning in enhancing the efficiency and accuracy of seismic facies classification. DNFS achieves state-of-the-art results by employing a combination of cross-entropy and Jaccard loss functions, enabling detailed predictions with fewer parameters compared to traditional models like StNet and U-Net. This innovation not only reduces the reliance on manual facies segmentation but also accelerates the interpretation of seismic data, making it a practical tool for geophysicists in the characterization of geological features. [30, 16, 15]. This model utilizes an encoder-decoder architecture inspired by networks like U-Net, which allows for effective segmentation with fewer parameters. Publicly available annotated datasets, such as the Netherlands dataset, are instrumental in advancing machine learning applications by providing a platform for benchmarking and comparing different models and techniques.

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Innovative methods, such as the use of learnable Gabor kernels in convolutional neural networks (CNNs), have shown substantial improvements in seismic facies classification, particularly under noisy conditions. Revised Sentence: "The incorporation of learnable Gabor kernels in convolutional neural networks (CNNs) effectively captures both spatial and frequency domain features of seismic data, significantly enhancing the interpretative capabilities by aligning the filters with the diverse wavelet textures and petrophysical parameters present in seismic facies, thus improving generalization, robustness to noise, and overall classification performance in seismic interpretation tasks." [25, 16, 24, 31]. Additionally, the integration of directional coherence attributes, which employ directional Gaussian preprocessing kernels and 3D rotational matrices, further refines seismic interpretation accuracy by highlighting subtle subsurface features.

The application of texture attributes in seismic data analysis underscores the importance of hybrid methods that combine multiple attributes to improve interpretation workflows. While no single attribute is universally effective for all structures, GLCM attributes have demonstrated superior performance overall. The implementation of visual saliency techniques, particularly the SalSi attribute, significantly automates the detection and delineation of salt domes in seismic data. SalSi, which is rooted in the modeling of the human visual system, effectively identifies salient features and captures spatial correlations within seismic volumes. This innovative attribute not only highlights regions surrounding salt domes to aid interpreters but also employs a region growing method combined with post-processing to delineate these geological structures with high precision. Experimental evaluations on real seismic datasets from the North Sea's F3 block demonstrate that the SalSi-based workflow outperforms traditional salt dome delineation algorithms, offering enhanced efficiency and accuracy in seismic interpretation. [32, 12]

The introduction of the 'example forgetting' method offers a novel approach to improving model performance on underrepresented classes in seismic interpretation. By tracking forgotten samples and augmenting training data, this method enhances the robustness of machine learning models, ensuring more comprehensive and accurate seismic analyses [21]. These advancements in machine learning not only improve the interpretative capabilities of seismic data but also support more informed and strategic exploration efforts in hydrocarbon-rich regions like the Santos Basin.

5.4 Challenges in Seismic Interpretation and Geological Modeling

Seismic interpretation and geological modeling within the Santos Basin present numerous challenges, primarily due to the complexity and scale of seismic datasets. One core issue is the accurate localization and delineation of subsurface structures, such as salt domes, which are critical for understanding the geological framework. Traditional methods often struggle with the increasing size and complexity of seismic datasets, necessitating more efficient and precise approaches to address these limitations [16]. The requirement for fully annotated label images in standard implementations further complicates the training of models, as manual labeling is both time-consuming and labor-intensive [16].

The inadequacy of existing texture analysis techniques applied to seismic data is another significant challenge. Advanced texture attributes from image processing have not been fully utilized in seismic interpretation, highlighting a gap in current methodologies [20]. This limitation restricts the ability to fully characterize seismic volumes and capture the nuanced geological features necessary for accurate modeling.

The inherent uncertainties in seismic interpretation further complicate the process, often leading to variability in the assessment of fault geometry and other geological features. The proposed deep variational autoencoder (VAE) method offers a promising solution by efficiently sampling and inverting complex geological structures [33]. However, the computational demands of such advanced models can lead to performance degradation, particularly when processing large and complex datasets.

Noise and amplitude variations in seismic data impede the accurate detection of critical structures, and the computational expense associated with methods that adaptively combine saliency maps for detecting multiple salient structures within seismic data remains a challenge. Despite significant advancements in machine learning techniques, effectively suppressing ground roll noise while maintaining the integrity of seismic signals remains a complex challenge. Ground roll, characterized by low frequencies and high amplitudes, often overlaps with seismic signals in the same frequency ranges, leading to unintended signal suppression when traditional frequency-amplitude filtering methods are applied. Recent approaches utilizing convolutional neural networks (CNNs) and conditional generative adversarial networks (GANs) have shown promise in detecting and suppressing ground roll more effectively than conventional methods, yet the task continues to demand innovative solutions to ensure high-quality seismic data for reliable interpretation. [34, 13, 23, 25]

The overfitting of convolutional neural networks (CNNs) trained on limited data, especially in noisy environments, presents another hurdle. This challenge is exacerbated by class imbalance in datasets, which can affect model performance on smaller classes [21]. The proposed 'example forgetting' method offers a novel approach to improving model performance on underrepresented classes, enhancing the robustness of machine learning models in seismic interpretation [21].

Future research should prioritize the enhancement of existing seismic interpretation methodologies to accommodate more intricate geological scenarios. This includes the integration of diverse seismic data types, such as pre-stack data, which can significantly improve interpretative accuracy. Additionally, employing advanced data selection frameworks like ATLAS, which leverages interpretation disagreement and active learning, could further refine the training processes for machine learning algorithms in seismic analysis. By focusing on these areas, researchers can better address the uncertainties inherent in seismic interpretations and ultimately enhance the predictive capabilities related to subsurface structures, including fault patterns and hydrocarbon reservoirs. [7, 27, 23, 35, 13]. The application of innovative methods, such as the ATLAS approach, which enhances model performance by concentrating on geologically significant regions often overlooked by conventional techniques, represents a promising direction in addressing these challenges.

6 Petrophysical Analysis

6.1 Methods and Techniques in Petrophysical Analysis

Petrophysical analysis in the Santos Basin employs diverse methodologies to evaluate crucial reservoir properties for hydrocarbon exploration and production. A key approach involves well log data analysis to determine petrophysical attributes such as porosity, permeability, water saturation, and net-to-gross thickness in tight carbonate reservoirs, providing insights into reservoir quality [6]. Core analysis, combined with wire-line log interpretation, enhances reservoir characterization by addressing carbonate formation heterogeneity, essential for effective management [4]. Advanced techniques like the Fast Neutron Radiative Transfer (FNRT) method utilize energy-dependent neutron interactions for precise oil and water quantification in core samples, proving advantageous in complex reservoir assessments [11].

Integrating data from multiple wells, petrographic analysis, and isotopic studies enriches petrophysical insights. For instance, data from 21 wells, including 1483 thin sections and isotopic analyses, provide critical information on rock properties and depositional environments [2]. This detailed examination is vital for understanding diagenetic history and reservoir quality. Petrophysical Seismic Inversion (PSI) advances reservoir characterization by integrating seismic and well log data, utilizing elastic properties and nonlinear optimization algorithms [36]. Moreover, CNN-PCA, which combines principal component analysis with convolutional neural networks, enhances geological model representation by capturing multipoint correlations, essential for modeling the complex geological scenarios typical of the Santos Basin [37].

6.2 Application of Seismic Data in Petrophysical Analysis

Seismic data significantly enhances petrophysical analysis by improving the assessment of rock and fluid properties within hydrocarbon reservoirs. This integration enhances the reliability of estimates for essential properties like porosity, permeability, and fluid saturation [6]. When combined with well logs and core samples, seismic data provides a comprehensive framework for reservoir evaluation, as demonstrated in formations like the Issaran Field in Egypt, which analyzes depositional and diagenetic features affecting reservoir quality [4]. Seismic elastic inversion techniques predict reservoir properties between wells by fitting nonlinear experimental relations for each lithofacies class, enhancing subsurface condition representation [36].

Integrating seismic data with advanced computational methods, such as CNN-PCA, refines rock and fluid property assessments by leveraging deep learning to capture complex spatial correlations often overlooked by traditional methods, providing a robust framework for petrophysical analysis in the

Santos Basin [37]. Publicly available datasets, like the Netherlands F3 block dataset, highlight the importance of high-quality labeled seismic data for training machine learning models. This dataset includes post-stack data, well logs from four wells, and nine interpreted horizons, with approximately 190,000 labeled images for inlines and crosslines. Such resources are pivotal for advancing machine learning applications in seismic interpretation, especially in the oil and gas sector, where data sharing is often limited due to confidentiality issues [35, 13, 38, 17]. These datasets facilitate the development of innovative techniques that enhance petrophysical evaluations, particularly in estimating critical parameters like water saturation.

6.3 Future Directions in Petrophysical Analysis

The future of petrophysical analysis in the Santos Basin is set to benefit from emerging trends and technological advancements aimed at improving reservoir characterization accuracy and efficiency. A key focus area is refining models through artificial intelligence, which can explore non-linear data relationships, addressing existing method limitations and leading to more sophisticated interpretations of complex geological formations [9]. Parallel computation techniques, as demonstrated by Liu et al., significantly enhance the efficiency of computing probability density functions (PDFs) for large spatial datasets, achieving speedups of up to 97

Addressing class imbalance in machine learning models remains a critical challenge, with future research potentially focusing on methods to mitigate this issue through additional data or improved model architectures [39]. Incorporating additional texture attributes into the labeling workflow, as suggested by Long et al., could enhance petrophysical model performance by providing more detailed subsurface characterizations [20]. Reducing dependency on large training sets, particularly for inversion methods, is another area of concern. Laloy et al. emphasize the need for localized representations that can improve inversion performance across multi-categorical and continuous variables, essential for advancing petrophysical analysis techniques [33]. Additionally, exploring passive seismic imaging techniques and extending current methodologies to a multivariate joint inversion framework could yield new insights into subsurface structures, enabling simultaneous predictions of multiple reservoir properties and providing a more comprehensive understanding of the subsurface [36].

7 Geological Modeling

7.1 Innovative Modeling Techniques

Advancements in modeling techniques have significantly enhanced our understanding of subsurface structures. Utilizing topological characteristics for model selection provides a robust framework for evaluating geological models' effectiveness in representing reservoirs, emphasizing their importance in accurately reflecting subsurface realities [40]. Deep learning integration, exemplified by the Recursive Convolutional Neural Network (RCNN), has transformed geological modeling by learning patterns from training images to simulate structures based on hard data, thereby enhancing predictive capabilities [37]. Conditional Generative Adversarial Networks (CGANs) further capture intricate geological patterns, generating realistic models consistent with physical measurements and geological facies, thus supporting uncertainty assessments and informed decision-making [41, 5, 37, 42, 33].

Implicit modeling techniques, such as Geo-Sketcher, use potential-field approaches for rapid 3-D model creation, efficiently integrating diverse geological data [43]. The DNFS architecture, combining U-Net and StNet, optimizes parameter usage while maintaining accuracy in seismic facies segmentation, reflecting a trend towards scalable modeling techniques for large datasets [39]. Integrating deep learning with geological parameterization enhances data assimilation in subsurface flow problems, streamlining the modeling process and improving predictive capabilities [41, 37, 43]. Deconvolution network architectures have improved seismic structure localization and classification, enhancing model resolution and interpretability [39]. The Bayesian inversion framework, Blockworlds, incorporates anti-aliasing techniques to enhance geophysical calculations, showcasing innovative advancements in geological modeling [44].

7.2 Integration of Seismic and Petrophysical Data

Integrating seismic and petrophysical data is vital for constructing comprehensive geological models that accurately depict subsurface structures, enhancing reservoir characterization and informing exploration strategies. The Joint Inversion and Segmentation (JIS) approach retrieves high-resolution acoustic impedance models, segmenting differences into user-defined classes for nuanced subsurface representations [45]. Topological data analysis, particularly through Persistent Homology Analysis (PHA), provides a framework for analyzing reservoir structures, enhancing understanding of connectivity and continuity [40]. Advanced machine learning techniques like RCNN improve geological simulations by leveraging previously simulated data [41]. CGANs and Info-WGAN exemplify the integration of seismic and petrophysical data, addressing challenges like mode collapse and ensuring diverse sample generation [46].

The GeoFault ontology by Qu et al. enhances the integration of seismic and petrophysical data by providing a reliable framework for representing geological features, addressing limitations in existing models like GeoSciML and RESQML [1]. The Bayesian framework employed by the DSI method quantifies uncertainty in subsurface flow predictions, further integrating seismic and petrophysical data for geological modeling [44]. New algorithms for 3D seismic interpretation, as suggested by Peters, highlight the potential for future advancements in integrating deep neural networks with traditional geophysical methods [15].

7.3 Tools and Frameworks for Geological Modeling

Developing tools and frameworks in geological modeling is crucial for supporting exploration and production decisions. Advanced tools facilitate integrating various datasets essential for accurately interpreting subsurface structures in applications like environmental monitoring and carbon sequestration. Sophisticated image processing and machine learning algorithms improve seismic data analysis, enhancing decision-making in geoscience. Specialized datasets, such as the Netherlands and Penobscot datasets, provide high-quality labeled data supporting deep learning model training, refining complex geological feature interpretation [35, 13, 23, 38].

The GeoFault ontology offers a well-founded representation of fault systems, addressing limitations in existing models [1]. Integrating machine learning techniques into geological modeling frameworks enhances the simulation of complex subsurface environments. The RCNN exemplifies this trend by generating realistic geological models consistent with observed data, leveraging previously simulated information [37]. CGANs and Info-WGAN generate detailed geological facies models, addressing challenges like mode collapse and ensuring diverse sample generation [46]. Implicit modeling techniques, such as Geo-Sketcher, facilitate rapid complex 3-D model generation using potential-field approaches [43]. The Bayesian framework, demonstrated by the DSI method, provides robust uncertainty quantification in subsurface flow predictions, integrating seismic and petrophysical data [44].

7.4 Future Directions and Technological Advancements

Future geological modeling will leverage computational advancements and novel approaches to enhance model accuracy and applicability. Exploring additional topological characteristics can improve model robustness against noise, enhancing predictive capabilities [40]. Expanding CGAN applications to integrate diverse geological data types presents a promising avenue for broadening their applicability. Developing user-friendly interfaces and enhancing integration with computational frameworks are critical for improving modeling tools' accessibility and functionality. Enhanced methodologies in uncertainty quantification, such as the DSI technique, can lead to more accurate subsurface flow prediction assessments [14, 7]. Advancements in seismic image quality analysis will impact fault interpretation, crucial for predicting hydrocarbon reservoir volumes [7]. Expanding frameworks like the GeoFault ontology to include ductile deformations could further enhance modeling comprehensiveness.

In seismic data interpretation, robust image quality assessment methods are essential for advancing accuracy, particularly in challenging environments. Future research should focus on developing these methods and examining their impact on interpretation accuracy [7]. Enhancing the robustness of seismic attributes, such as SalSi, against noise and exploring their application in detecting a broader range of features could yield significant benefits. Further advancements in computational techniques, such as refining RCNN training processes and exploring alternative architectures, could enhance simulation performance, particularly in handling conditioning data. Integrating anti-aliasing techniques into geophysical sensor analysis and applying sophisticated geological models holds potential for improving interpretation accuracy and realism [25, 19, 23, 44].

Optimizing data handling, particularly parallel computation methods for probability density functions (PDFs), could advance modeling efficiency and scalability, especially in processing large datasets. Advancements of CNN-PCA to incorporate three-dimensional models, alongside enhancements in training methodologies, represent vital research avenues. These developments promise to improve the accuracy and representation of intricate scenarios by leveraging new regularization techniques and spatial metrics from deep learning approaches [41, 16, 37].

Geological modeling is poised for significant advancements through integrating cutting-edge computational techniques, enhancing existing methodologies, and exploring innovative strategies. This evolution will utilize advanced image processing and computer vision algorithms, employ RCNNs for improved three-dimensional unit simulation, and apply deep learning methods like GANs for realistic 3D facies models. New sketch-based modeling approaches, such as Geo-Sketcher, will streamline model creation, addressing current accuracy and efficiency limitations. These advancements aim to enhance understanding and representation of complex formations, benefiting resource management and environmental monitoring [41, 5, 23, 43]. These developments will support more accurate and efficient modeling, facilitating improved exploration and production strategies in hydrocarbon-rich regions.

8 Conclusion

The exploration of pre-salt carbonates and reservoir classification in the Santos Basin underscores the intricate geological structures and significant hydrocarbon prospects inherent in this region. The confluence of seismic interpretation, petrophysical analysis, and geological modeling emerges as pivotal in refining exploration and production methodologies. The deployment of high-quality labeled datasets exemplifies the potential of deep learning models to enhance the precision and efficacy of hydrocarbon exploration endeavors.

Emerging techniques, such as the Fast Neutron Radiative Transfer method, present notable advancements by enabling the non-destructive quantification of fluid content in geological cores, surpassing traditional approaches. Similarly, the application of Info-WGAN for generating geological facies models addresses the limitations of conventional GANs by offering diverse and unbiased model outputs. These technological strides facilitate a deeper comprehension of reservoir characteristics, informing more strategic exploration and production decisions within the Santos Basin.

Machine learning approaches, such as those utilizing the SalSi-based workflow, advance the delineation of essential geological features, notably salt domes, thereby enhancing the accuracy and efficiency of seismic data analysis. The development of scalable solutions for large-scale machine learning applications, as demonstrated by DDPA, effectively reduces processing durations and resource demands, proving its utility in managing complex geological datasets.

Prospective research should focus on refining these methodologies and exploring novel technological innovations to address the challenges posed by the heterogeneity and complexity of pre-salt carbonates. The integration of advanced computational techniques and innovative modeling strategies will be crucial in unlocking the full potential of these hydrocarbon reservoirs, thereby supporting sustained exploration and production efforts in this resource-rich region. Additionally, examining the factors influencing reservoir properties and the evolution of carbonate formations will enhance the understanding of the Santos Basin's geological framework.

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