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TÍTULO DO TRABALHO:

A REVIEW OF THE MAIN FACIES CLASSIFICATION OF PRE-SALT CARBONATES

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Title of Work

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Abstract

A província pré-sal brasileira é uma importante feição geológica localizada nas águas profundas do Atlântico Sul, principalmente nas bacias de Santos e Campos. Esta região, localizada sob espessas camadas de sal, estende-se ao longo da margem continental brasileira. A sua formação remonta aos períodos Jurássico Superior e Cretácico Inferior, coincidindo com uma fase de rifteamento que levou à separação das placas tectónicas Sul-Americana e Africana, seguida de uma fase de afundamento. Esta atividade tectónica criou extensas bacias de rifte que foram eventualmente preenchidas com xistos lacustres ricos em matéria orgânica, seguidos pela deposição de plataformas carbonáticas e evaporitos durante o período Aptiano. Os reservatórios do pré-sal, compostos predominantemente por rochas lacustres não marinhas com coquinas, carbonatos microbianos, carbonatos abióticos e carbonatos influenciados hidrotermicamente, tornaram-se algumas das reservas de hidrocarbonetos mais prolíficas do mundo, atraindo um interesse substancial da indústria do petróleo e do gás Diferentes facies carbonáticas, por vezes com influências siliciclasticas e hidrotermais, criam desafios a classificação de tais litologias, conforme as propostas mais tradicionais cf. Dunham (1962), Folk (1962) e Embry e klovan (1971). Este estudo apresenta um compilado das principais classificações de fácies para a de classificação de fácies para a sequência carbonática do pré-sal, baseado do pré-sal, baseado trabalhos mais relevantes para a região, identificando fácies, identificando fácies e bióticas com morfologias de microbialítos, e abióticas com, cristais de calcita fascicular, semelhantes a arbustos (i.e. Shrubs). Tais classificações categorizam as fácies sedimentares *in situ* em grupos como, shrubstones e mudstones com base na sua composição. Além disso, as fácies retrabalhadas, tais como packstones, grainstones e rudstones, são classificadas para melhorar a compreensão dos padrões das fácies em pequena escala e o seu impacto nas variações verticais de maior escala dentro e entre sequências ligadas a inconformidades. A identificação das principais classificações e a análise dos pontos positivos e negativos de cada sistema de classificação discutido auxiliarão trabalhos futuros na seleção do melhor sistema de classificação de rochas carbonáticas para o pré-sal, de acordo com o ambiente deposicional estudado Esta estrutura orientada para o processo facilitará futuras análises geológicas e sedimentológicas.

Palavras-chave:, Carbonatos, retrabalhados, *in situ.*

Abstract

The Brazilian pre-salt province is an important geological feature located in the deep waters of the South Atlantic, mainly in the Santos and Campos basins. This region, located under thick layers of salt, extends along the Brazilian continental margin. Its formation dates back to the Upper Jurassic and Lower Cretaceous periods, coinciding with a rifting phase that led to the separation of the South American and African tectonic plates, followed by a sinking phase. This tectonic activity created extensive rift basins that were eventually filled with lacustrine shales rich in organic matter, followed by the deposition of carbonate platforms and evaporites during the Aptian period The pre-salt reservoirs, composed predominantly of non-marine lacustrine rocks with coquinas, microbial carbonates, abiotic carbonates and hydrothermally influenced carbonates, have become some of the most prolific hydrocarbon reserves in the world, attracting substantial interest from the oil and gas industry Different carbonate facies, sometimes with siliciclastic and hydrothermal influences, create challenges for the classification of such lithologies, according to the more traditional proposals. Dunham (1962), Folk (1962) and Embry and Klovan (1971). This study presents a compilation of the main facies classifications for the pre-salt carbonate sequence, based on the most relevant work for the region, identifying facies and biotic facies with microbialite morphologies, and abiotic facies with fascicular, shrub-like calcite crystals (i.e. Shrubs). These classifications categorize in situ sedimentary facies into groups such as shrubstones and mudstones based on their composition. In addition, reworked facies, such as packstones, grainstones, and rudstones, are classified to improve understanding of small-scale facies patterns and their impact on larger-scale vertical variations within and between sequences linked to unconformities. The identification of the main classifications and the analysis of the positive and negative points of each classification system discussed will help future work in selecting the best classification system for pre-salt carbonate rocks, according to the depositional environment studied This process-oriented framework will facilitate future geological and sedimentological analyses..

Keywords:, Carbonates, reworked, *in situ*.

Introduction

The lacustrine deposits from the Santos Basin after the breakup of Gondwana in the age of the early cretaceous highlight an assemblage of information about the environmental conditions that were unknown before. Unique and uncommon deposition properties, early digenesis, and the quality present in the reservoir differentiate the lacustrine carbonate oil fields from the other classic lake reservoirs (Gomes et al., 2020).

A facies classification scheme has multiple functions providing the characteristics of a sediment/sedimentary rock, finding facts to provide information about the depositional environment,

providing a platform for the comparison, and contributing observations. Besides these, the main reason for using a classification is to communicate details regarding the features of rocks and the name of the rock. The provided names from a classification may be unpredictable or in common with an existing classification but will define the characterization and interpretation more than the existing one. Following these principles, several classifications for carbonate rocks have been proposed. In the previous decades, the geological study of carbonate facies has been improved, especially in the understanding of the biological and digenetic processes and their products Walker, (1992).

Folk (1959, 1962) introduced the genetic classification of limestone based on the presence or absence of matrix (micrite) versus cement (sparite). Also, it indicated the dominant grains present, to provide a simple descriptive name for limestone. Dunham (1962) proposed a more texturally based classification, which used lime-mud amount and the abundance of the grains, presenting grainstone, packstone, wackestone, and mudstone which shows the energy levels in the environment. Embry and Klovan (1971) put forward the terms framestone, bafflestone, and boundstone to provide more information about the reefal rocks to identify particular types of boundstone. Similarly, Riding (2000) identified and categorized four distinct types of microbialite: stromatolite, thrombolite, dendrite, and leiolite. In a study related to this, Wright (1992) presented the term 'cement stone' to describe limestone predominantly composed of cement." From the discoveries of the early 2000s, the interest in the classification increased on pre-salt rocks

However, few works have synthesized the main characteristics of the sedimentary facies of this reservoir and developed carbonate sedimentary facies classification systems specific to the depositional context of the pre-salt. Terra et al. (2010) were pioneers in presenting a facies classification system for the pre-salt, introducing a broad set of abiotic and biotic facies, with different morphological variations of microbiolites. The description of shrub-like calcite crystals exclusively as various classes of stromatolites contrasts with most current facies classification systems Such classifications discussed above are based on the work by Erthal et al. (2017), which extensively outlines the features and primarily presents a physicochemical genesis for the various shrubs-morphologies described in the pre-salt. Rocks characterized by spherulites have been classified in various ways: as spherulite-dominated lithologies Wright and Barnett (2015), as Mg-clay with spherulites facies and spherulitite (Farias et al., 2019), and as stevensitic claystone containing calcite spherulites (Lima and De Ros, 2019). In contrast, the predominantly fine-grained facies are commonly referred to as laminites (Lima and De Ros, 2019); Muniz and Bosence (2015), Gomes et al. (2020) discard the broad biotic influence on the development of sedimentary facies, categorizing them into depositional or in situ facies, such as spherulitestones, shrubstones, mudstones, and their variations according to the proportions of shrubs, spherulites, and

mud. They also classify reworked facies composed predominantly of rock fragments, such as packstones, grainstones, and rudstones.

This study aims to conduct a comprehensive bibliographical review of the main cited and uncited classification systems, highlighting each system's strengths and most sensitive points, based on available literature. Also, this work will provide a detailed understanding of the above classifications and their respective implementations and services in geological research.

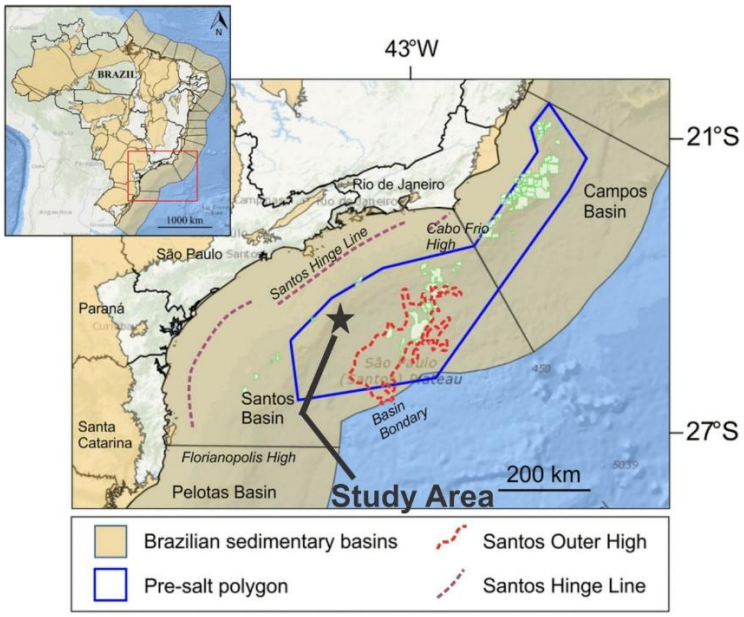

Figure 1: Location map of the Santos Basin, offshore Brazil from Basso et al. 2020.

Methodology

In this work, a literature review was carried out through bibliographical research in the Science Direct databases, in the Periodicals Portal of the Coordination for the Improvement of Higher Education Personnel – Capes, and Google Scholar®, using the following keywords: Facies classification and Pattern, Geochemical and Mineralogical Analysis, Depositional, and digenetic processes of pre-salt carbonates.

The methodology employed for the facies classification of pre-salt carbonates in the Santos Basin by the researchers in the past involved a comprehensive approach to understanding the study area's geological characteristics and depositional history. Extensive field surveys were conducted to establish the geographic and geological context, pinpointing key locations for subsequent data collection. Core samples collected from different wells were subjected to detailed logging and log interpretation, focusing mainly on composition and lithology such as grain size, minerals, sedimentary structures, and

fossil contents. The samples collected were studied under a petrographic microscope to identify microfacies and their textural relationships. Entirely, the study or the methodology here gives detailed information and a systematic approach to the complex history of pre-salt carbonates present in Santos Basin. It provides valuable insights into their geological history, paleoenvironmental conditions, hydrocarbon reservoir, and also geological setting.

Results and Discussions

The results and discussion of the facies categorization of pre-salt carbonates in the Santos Basin highlight several important findings and interpretations based on the thorough investigation and methods described by several researchers and experts. According to the study, the Barra Velha Formation has a wide variety of sedimentary facies, each with its unique lithological units and depositional settings. Numerous facies types, including mudstone-claystone-laminate sequences characterized by organic-rich shales and talc-stevensite ooids typical of lacustrine environments, have been found by core sample and thin section investigations Dias, (2005); Wright and Barnett, (2015). Micrometer-diameter spherulites and shrub-like calcite crystals frequently punctuate these facies, indicating periods of shifting depositional energy and environmental dynamics (Muniz and Bosence, 2015; Arienti et al., 2018). The used classification schemes incorporate biotic and abiotic elements, improving upon earlier models to better capture the unique facies associations observed in the Santos Basin (Lima and De Ros, 2019; Gomes et al., 2020)

The classification by Terra et al. (2010) for carbonate rocks is structured around both depositional textures and diagenetic features. In terms of depositional textures, the classification distinguishes between grain-supported and mud-supported textures. Grain-supported textures include packstone, a carbonate rock where grains are the primary component with interstitial carbonate mud, and grainstone, a grain-supported carbonate rock without carbonate mud. Mud-supported textures, on the other hand, include mudstone, which contains less than 10% grains, and wackestone, which has more than 10% grains but remains mud-supported

Gomes et al. (2020) developed a facies classification system for the lacustrine carbonates of the Barra Velha Formation in the Santos Basin, Brazil. This scheme includes terms like spherulitic, shrubstone with mud, spherulitic rudstone, and shrub-grainstone. These terms classified rocks based on the relative abundance of mud, calcite spherulites, and calcite shrubs, integrating petrographic, core, and chemical data. The classification aids in recognizing facies cycles, diagenetic variations, and provides models for interpreting depositional processes, thus enhancing the understanding of depositional environments and

reservoir quality(Gomes et al. (2020). The findings further highlighted the importance of facies classification in predicting hydrocarbon accumulation and comprehending reservoir heterogeneity.

De Ros et al. (2024) recently presents an operational classification system which put in order to the unique characteristics of South Atlantic pre-salt lacustrine carbonate rocks. The system classifies in situ rocks based on the proportion of calcite spherulites, fascicular shrubs, and mud matrix, and resedimented rocks by the volume of particles larger than 2 mm, using terms like calcirudite, calcarenite, and calcilutite. This new system addresses the deficiencies of traditional and already present marine carbonate classification methods, providing a coherent, simple, and operational approach that enhances the understanding, exploration, and production of pre-salt petroleum reservoirs(De Ros et al. 2024).

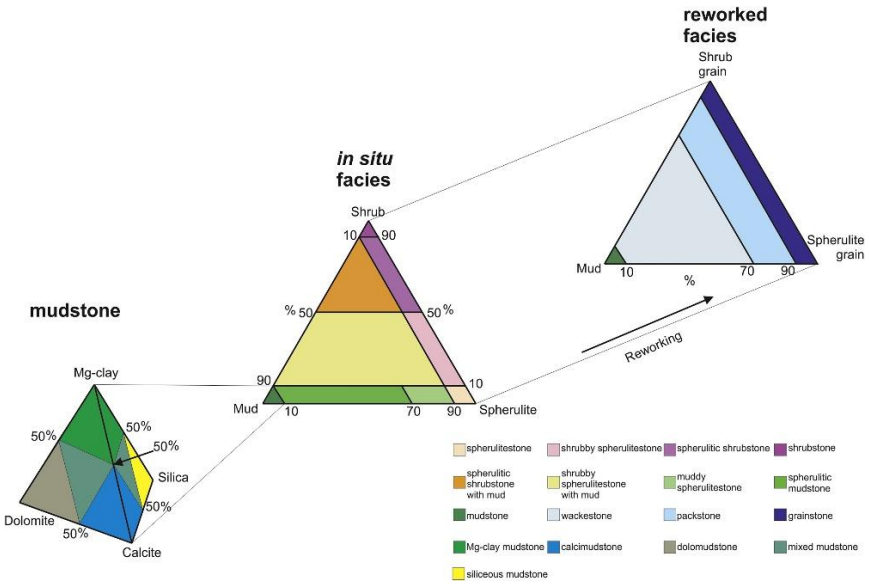

Figure 2: Gomes et al 2020 classification for the carbonates (*in situ* and reworked)

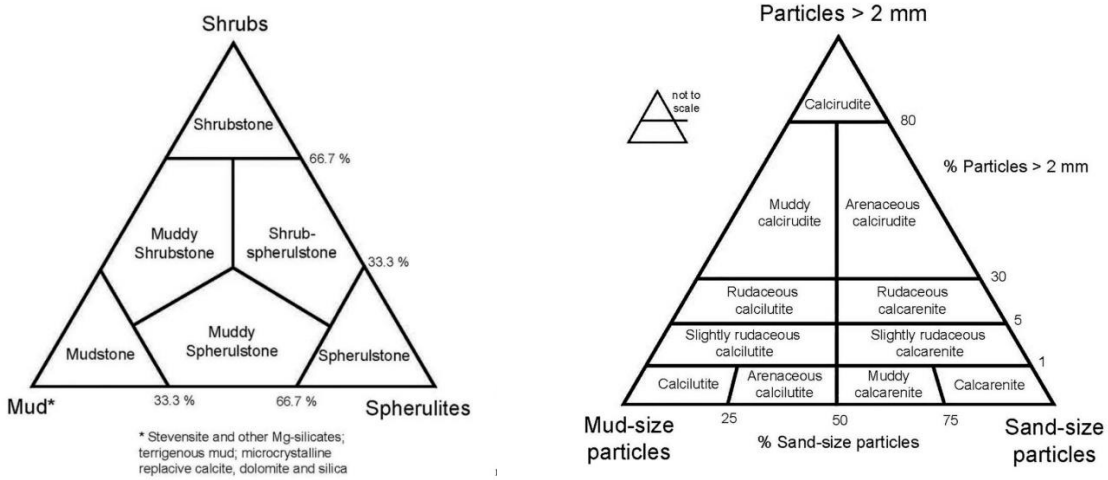

Figure 2: Proposed classification diagram for the in situ and reworked pre-salt sag deposits. De Ros et al 2024

Conclusions

Due to the complex Geological Settings of the pre-salt carbonates, limited data on the pre-salts, significant heterogeneity in terms of lithology, porosity, and permeability, changes occurring during and after sediment deposition shows a huge difficulty in choosing a classification system for pre-salt carbonates. The classification systems for pre-salt carbonates proposed by Terra et al. (2010), Gomes et al. (2020), and De Ros et al. (2024) each present distinct strengths and weaknesses. Terra et al. (2010) emphasized the differentiation between how rocks are formed and how they change over time. They came up with a way to help us understand the history of certain types of rocks better but sometimes they used names with an Mg-clay matrix for carbonate rocks that might not be quite right, creating some confusion. Gomes et al. (2020) provide a classification that integrates depositional and early diagenetic components, sediment mineralogy, and dissolution processes, which offers insights into depositional conditions and reservoir quality. Despite its usefulness, this classification often overlooks the variety of syngenetic or diagenetic constituents *in situ* sag deposits and has biases toward specific reservoir types. De Ros et al. (2024) propose a purely textural classification system, aiming to address the shortcomings of previous systems by focusing on depositional and reservoir-quality coherence. Their approach adapts the Folk (1968) textural classification for clastic deposits. While more consistent in addressing the unique characteristics of pre-salt rocks, the De Ros system is also complex. Each classification offers valuable insights and highlights the ongoing challenges in creating a universally applicable system for pre-salt carbonate rocks.

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