PALEOALTERATIONS IN HYDROCARBON RESERVOIR ROCKS: THE SERGI FORMATION CASE (RECÔNCAVO BASIN, NE BRAZIL)

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Resumo –A Formação Sergi é o principal reservatório de hidrocarboneto da Bacia do Recôncavo e suas paleoalterações foram estudadas com o objetivo de determinar a gênese e a relação com a evolução estratigráfica da unidade. Esta Formação faz parte da seqüência pré-rift da Bacia do Recôncavo (NE Brasil) e é composta por uma complexa justaposição de arenitos eólicos e fluviais e pelitos lacustres. A unidade pode ser subdividida em três seqüências deposicionais, limitadas por discordâncias regionais. As paleoalterações da Formação Sergi foram classificadas, de acordo com suas características macroscópicas, em quatro tipos diferentes: (1) Marmoreado Textural, (2) Marmoreado Não-Textural, (3) Concentrações Carbonáticas e (4) Carbonatos Bandados. O padrão de cores do marmoreado, bem como as acumulações de carbonatos não são, na sua maioria, produtos de processos pedogênicos, mas refletem predominantemente a atividade de águas subterrâneas e de variações do nível freático. Apenas as paleoalterações do tipo 3 e 4 têm sua gênese relacionada a processos pedogênicos em sentido estrito, no entanto, não formando solos. Como resultado da associação dessas feições com as condições deposicionais e pós-deposicionais, os horizontes de paleoalterações geralmente não são contínuos em escala de bacia ou mesmo, de reservatório. Essa afirmação implica que as paleoalterações da Formação Sergi não constituem heterogeneidades importantes em termos de compartimentação de reservatórios.

Palavras-Chave: Paleoalterações; Calcretes; Heterogeneidades; Reservatório; Jurássico-Cretáceo

Abstract – Paleoalterations in the reservoir rocks of the Sergi Formation have been analyzed in order to ascertain their origin and relationship with stratigraphic evolution of the unit. The Sergi Formation belongs to the pre-rift sequence of the Recôncavo basin (Northeastern Brazil) and comprises a complex association of eolian and fluvial sandstones and lacustrine mudstones. This formation can be subdivided into three depositional sequences, bounded by regional unconformities. Four paleoalteration types, each one related to a distinct origin, have been discriminated in the Sergi Formation: (1) textural mottling, (2) non-textural mottling, (3) carbonate concentrations and (4) banded carbonates. Both mottling color motifs and carbonate accumulation usually represent the product of phreatic level oscillations, rather than of pedogenesis. Only type 3 and 4 paleoalterations may have their origin ascribed to pedogenesis stricto sensu, although not directly related to soil-forming processes. As a result of the close association of these features with local depositional and post-depositional conditions, paleoalteration horizons are usually discontinuous at basin- or even oilfield-scale. This implies that the Sergi Formation paleoalterations do not constitute important heterogeneities in terms of sandstone reservoir compartmentation.

Keywords: Paleoalterations; Calcretes; Heterogeneities; Reservoir; Jurassic-Cretaceous.

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1. Introduction

Continental terrigenous successions are commonly heterogeneous, mostly in terms of facies space distribution, at different scales. This feature is usually a result of frequent energy fluctuations that produce grain size changes in the deposits. Furthermore, these energy changes affect rock porosity and permeability, influencing a more or less intense circulation of post-depositional fluids, hence the chemical precipitation of several minerals (carbonates, oxides, and clay minerals) and several types of paleoalterations.

The presence of carbonate nodules, or carbonate nodule intervals, has a singular effect on the petrophysical characteristics of hydrocarbon reservoirs within terrigenous successions (Hanneman *et al*., 1994), such as the herein-presented Sergi Formation. However, former studies on the Sergi Formation have not dealt with important points related to these carbonate nodules such as: distinct processes concerning their origin; discrimination between subaerial, subaqueous or groundwater-related origin as well as the importance of their distinct paleogeographical settings.

The main goals of this study include the definition of the mesoscopic typology of the paleoalterations, analysis of the genetic processes involved and correspondent development stages, as well as to establish their role in the production of heterogeneities and reservoir compartmentation in the Sergi Formation. Firstly, some basic concepts on paleoalteration, particularly about calcretes, are presented. Then, it is shown how the use of these fundaments has enabled the distinction of four main types and nine subtypes of paleoalterations in the Sergi Formation, whose origins and depositional settings are later discussed.

2. Geological Setting

The Recôncavo Basin (NE Brazil – Fig. 1) covers an area larger than 10,000 Km^2 and is related to the crustal stretching process that culminated with the Gondwana breakup and consequent Africa and South America formation. Related rifting produced several asymmetrical grabens that constitute the NE-SW trending intracontinental rift that encloses this basin (Santos & Braga, 1990). The Jurassic-Cretaceous Sergi Formation is included in the pre-rift sequence. This sequence represents a long-lasting subsidence stage and consequent formation of an intracratonic basin in which the continental sediments of the Brotas Group accumulated. The Sergi Formation is part of the last sedimentation stage of the Brotas Group and represents a continental depositional system characterized by alternating fluvial-eolian sandstones and red lacustrine mudstones. It can be subdivided into three depositional sequences bounded by regional unconformities (Scherer *et al*., 2004), as follows:

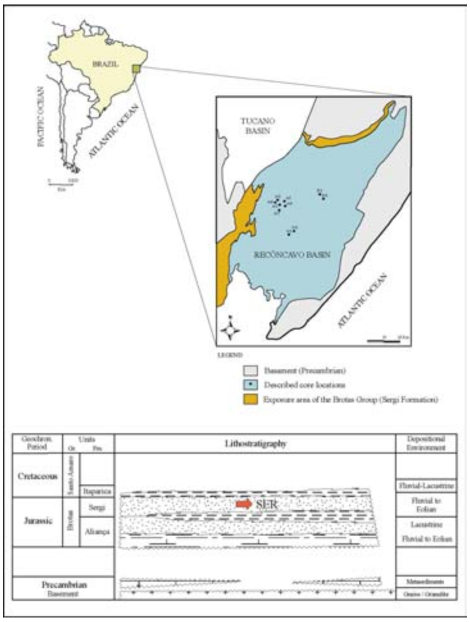

Figure 1: Recôncavo Basin setting presenting its exposure área, described core locations and crono-lithostratigraphic table, emphasizing the Sergi Formation position (adapted from Caixeta *et al*., 1994).

Sequence I comprises a complex juxtaposition of eolian and fluvial sandstones and lacustrine mudstones. Eolian sandstone, composed of horizontally laminated sand sheet and cross-bedded sand dune deposits, is truncated by either massive or plane-bedded /incipient cross-bedded sandstone deposited by ephemeral streams. Facies associations indicate a semi-arid climate characterized by periods of eolian dune and sand sheet formation often interrupted by an increment of fluvial activity. Sequence II is mostly composed of coarse-grained to conglomeratic sandstone displaying trough and planar cross-bedding and organized as 1- to 5-meter thick, fining upward cycles interpreted as braided river deposits. The coarser-grained nature of the deposits relative to Sequence I suggests an increase in the fluvial system capacity and competence, and indicates a discharge increase due to wetter climate and/or an increase in the declivity of the river equilibrium profile caused by a source area uplift. Sequence III is characterized by fine- to medium-grained sandstone displaying low-angle lamination related to climbing translatent strata (eolian sand sheets deposits). This sequence records the return of similar depositional conditions to those related to sequence I, although dominated by eolian processes relative to rare fluvial and nonexistent lacustrine deposits.

3. Paleoalteration Description and Origin

At first the differentiation of the Sergi formation paleoalterations was based on macroscopic features, such as their relationships with the original rock texture, presence of carbonation and structures, among others. After their formation, the paleoalterations underwent diagenetic processes that will not be discussed herein. Therefore, the following four types of paleoalterations, with distinct genetic interpretations, were identified:

3.1 Textural Mottling (Type 1)

Mottling is characterized by the occurrence of diverse colors in the rock as a result of iron oxide mobilization within mineral phases caused by alternating oxidation (yellow, brownish and red) and reduction (gray and green) phases. This kind of paleoalteration presents discoloration following the original texture of the rock and producing the following subtypes:

Textural mottling with preserved lamination (Subtype 1a): characterized by alternating colors and preservation of the primary sedimentary structures of the rock;

Textural mottling with deformed lamination (Subtype 1b): distinguished by alternating colors without preservation of the original sedimentary structures. This subtype occurs associated with heterogeneous beds in which post-depositional deformations (e.g. conturbation, bioturbation or clastic dykes formation) took place.

Textural heterogeneities are the main cause of the discoloration that typifies this type of paleoalteration. The alternation of millimeter- to centimeter-scale strata of porous sandstone and mudstone controlled the percolation of reducing fluids containing some carbonate. As a result, the fine-grained strata maintained their primary oxidized color (red) whereas the sandy, primarily porous horizons were reduced and cemented by a small volume of carbonate.

3.2 Non-Textural Mottling (Type 2)

This type of paleoalteration presents a discoloration trend that is independent of the rock original texture:

Non-textural mottling with reduced spots (Subtype 2a): differentiated by alternating colors, produced by iron oxide mobilization within intermittent oxidant and reducing phases, which form irregular and isolated spots in the rock;

Non-textural mottling with diffusive carbonation (Subtype 2b): similar to the previous subtype although it includes an important carbonation phase that appears as spots in the rock.

Discoloration is also present in this kind of paleoalteration although it is independent of the original rock texture. This fact indicates that percolation of both reducing and carbonate-rich fluids obeyed an irregular trend through a relatively porous rock promoting reduction and carbonation along diffuse areas (Fig. 2a).

3.3 Carbonate Concentration (Type 3)

This kind of paleoalteration is usually linked to carbonate nodule formation. Nodules present a commonly massive or laminated internal structure, hence indicating a development related to a continuous growth or crystallization (Retallack, 2001). Two sub-types were differentiated:

Carbonate concentration forming venules (Subtype 3a): differentiated by calcium carbonate ($CaCO_3$) accumulations forming an intricate network of thin veins (1 to 4 mm thick) that may contain pink or gray siliceous masses. The dominantly horizontal and planar, but not linear arrangement of these calcium carbonate ($CaCO_3$) accumulations suggests an origin connected to phreatic processes. Therefore, groundwater oscillations within the vadose zone are supposed to have produced successive $CaCO_3$ precipitations generating horizons characterized by a network of millimeter-scale ribbons;

Carbonate concentration forming isolated nodules (Subtype 3b): distinguished by the occurrence of small isolated nodules that result from the infiltration of carbonate solutions into the rock and subsequent calcite precipitation around grains or within pores. Their clear delineation as well as the lack of other pedogenic or biogenic marks suggest carbonate precipitation from phreatic fluids along restricted areas of the rock;

Carbonate concentration forming carbonate intraclasts (Subtype 3c): originated from the accumulation of poorly- to sub-rounded white carbonate clasts (1 to 10 cm long) within a sandy matrix. Intraclasts correspond to fragments of palustrine calcretes scoured from ephemeral lakes formed on floodplains by strongly erosive, channelized streams (Fig. 2b).

Although calcrete profiles can be easily preserved in the geological record (Watts, 1980; Warren, 1983; Sancho *et al*., 1992) sometimes, usually when poorly developed, they can be entirely reworked. In this case, calcrete clasts can be included in the channel or even flood plain deposits. Reworked clasts are composed of carbonate or mud aggregate and are usually transported as fluvial bedload. Within ancient successions, however, compactation might lead to the loss of the original calcrete texture, hence making it difficult to determine their origin (Ékes, 1993; Marriott and Wright, 1993; Khadkikar *et al.*, 1998).

Among the reworked calcretes of the Sergi Formation the preservation of some primary textures, which suggests vegetal colonization and episodic desiccation, allows to interpret them as palustrine calcretes eroded from areas close to channels and included as intraclasts into the river bedload. The extensive presence of the mottling pattern and desiccation cracks point to very shallow water bodies submitted to episodic desiccation and flooding events. These processes are typical of lacustrine environments (Pimentel, 2002).

3.4 Banded Carbonate (Silicified) (Type 4)

This kind of paleoalteration is related to the latest carbonation stages when the formation of uneven surfaces takes place:

Carbonate with discrete bands (Subtype 4a): appear as whitish horizontal bands displaying irregular borders and centimeter-scale thickness. These bands occur within clay-rich, greenish material and can be discrete or amalgamated, originating continuous, decimeter-scale horizons.

Carbonate with juxtaposed bands (Subtype 4b): form a very compact, whitish rock presenting only remains of its horizontal banding (white to pale green). These paleoalterations usually display a brecciated aspect formed by a network of nearly orthogonal fractures, filled by sparry calcite.

The banded structure is primary and corresponds to the chemical precipitation of carbonates within paludal environments (shallow lakes exposed to episodic subaerial exposure). Both uncomplete silicification and euhedral carbonate crystals suggest secondary features related to diagenesis reproducing the primary depositional texture.

4. Depositinal Setting and Its Significance

The Textural and Non-Textural Mottling types (1 and 2, respectively) comprise most paleoalterations present at the base of the Sequence I of the Sergi Formation. These types of discolorations are associated with meteoric, reducing fluids, whose percolation through the sediments was controlled by their original texture, hence explaining the differences between types 1 and 2. The origin of these types of paleoalterations is linked to high-frequency changes of the rate of the phreatic level oscillations (Fig. 2c). Whenever the phreatic level rose above the depositional surface a lake was formed (Pimentel, 2003). On the other hand, during its subsequent fall, lakes dried and meteoric fluid flowed through the vadose zone, hence bleaching sediments (Pimentel, 2003). Groundwater oscillations have also originated carbonation subtypes 3a and 3b (Venules and Isolated Nodules, in that order).

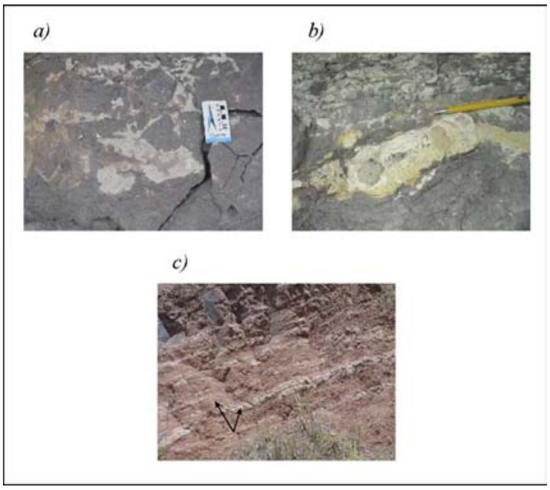

Figure 2: (A) Non-Textural Mottling with reduced spots within Sequence I fluvial sandstone. (B) Detail of a palustrine carbonate intraclast displaying millimeter-scale internal lamination (primary features). (C) Oxidation and reduction alternating events (arrows) within fine-grained lacustrine deposits of Sequence I produced by phreathic level oscillations.

The development of small, ephemeral lakes along the deposition of Sequence I has allowed the formation of palustrine calcretes. It is possible to find in the lacustrine claystone evidence of organic filaments, later wrapped by thin calcite coats, such as those discussed by Alonso-Zarza (2003). Subsequent erosion of these calcretes during events of larger fluvial discharge has controlled their reworking and concentration, thus producing subtype 3C paleoalterations (Carbonate Intraclasts).

The intervals of reworked palustrine calcretes of Sequence I are comparable to Gómez-Graz and Alonso-Zarza (2003) subtypes 1 and 3. According to these authors, reworked calcretes of type 1 comprise lenses that fill small erosional depressions related to small channels crosscutting flood plains. These channels are linked to ephemeral streams formed after sporadic, but heavy rainfalls that drain specific areas of the flood plain removing important amounts of sediments (Marriot and Wright, 1993). These reworked palustrine calcretes (type 1) are analogous to subtype 3c of the base of the Sequence I. In contrast, Gómez-Graz and Alonso-Zarza (2003) type 3 palustrine calcretes are linked to channels rather than flood plains and considered as channel lag deposits. Channel lateral migration or avulsion constitute the main causes for the reworking of these palustrine calcretes. In the Sergi Formation, this type is similar to the subtype 3c paleoalterations that occur at the top of Sequence I.

Sequence II paleoalterations were formed within an entirely distinct depositional setting and climate relative to Sequence I. This statement is reinforced by the presence, along the entire area of study, of an unconformity that bounds both sequences. Sequence II is mostly composed of fluvial deposits related to a perennial braided system with seasonal discharge fluctuation. Although almost always located below the depositional surface, this seasonal fluctuation on fluvial discharge controlled phreatic level oscillation in the channel surroundings. Therefore, phreatic level changes originated type 1 and 2 paleoalterations as well as subtypes 3a and 3b.

Although rare, it is possible that the phreatic level could eventually surpass the depositional surface, hence forming small temporary lakes on the flood plains and associated palustrine carbonates (Pimentel, 2003) classified as type 4 paleoalterations (banded carbonates). These carbonates are primarily banded as a result of carbonate chemical precipitation within paludal environments. Therefore, type 4 paleoalterations represent *in situ* palustrine carbonates.

A decline on the rate of accommodation space creation during the deposition of the Sequence II induced lateral migration of channels and consequent reworking of the flood plain and marginal lake deposits as well as soils. Although well-developed soil profiles could be formed in this stage (Plint et al., 2001) not one was found in the Sergi Formation, probably due to their low preservation potential.

4.1 The Role of The Paleoalterations on Heterogeneity Development in the Sergi Formation

The Sergi Formation presents a suite of post-depositional features essentially related to color changes and carbonate cementation that occur as isolated or amalgamated nodules (Scherer *et al*., 2004). These features, related to the depositional dynamics, are frequently restricted to fluvial channel base or fine-grained lacustrine deposits. As a result, paleoalteration horizons are usually not continuous at basin- or even oilfield-scale. This statement implies that the Sergi Formation paleoalterations do not constitute important heterogeneities in terms of sandstone reservoir compartmentation.

5. Conclusions

Mottling color configuration as well as carbonate accumulation does not represent pedogenic products. Although pedogenic processes have probably played a role their products have not been preserved due to the depositional system dynamics. The Sergi Formation paleoalterations mostly reflect groundwater activity and phreatic level changes, in a similar way to studies elsewhere (Pimentel *et al*., 1996; Pimentel, 2002). Only subtype 3c and type 4 paleoalterations owe their origin to pedogenic processes *strictu sensu*, although not forming soils. Therefore, it is natural that fluvial and meteoric waters constitute the essential factors controlling paleoalteration development and depositional trend as both are controlled by the same causes – chiefly climate, relief and sedimentation rate.

Despite its advanced exploration stage, the Recôncavo Basin still features good exploration perspectives (Santos and Braga, 1990). For that reason, it is important to improve the hydrocarbon migration/accumulation models through the study of heterogeneities.

The Sergi formation reservoirs hold depositional and diagenetic heterogeneities that control the distribution of the permeability-porosity space at distinct hierarchical scales (Scherer *et al*, 2004). Paleoalterations are restricted and do not represent heterogeneities at oil field- or basin-scale.

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