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TÍTULO DO TRABALHO:

PETROGRAPHY AND DIAGENESIS OF THE SANDSTONES OF THE MACEIÓ FORMATION, ALAGOAS BASIN, BRAZIL

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Abstract

The Alagoas Basin belongs to the group of passive marginal basins of the Brazilian coast, developed in part as an asymmetrical rift after the Gondwana breakup. The Maceió Formation, focus of this work, was deposited at the end of the rift stage during the late Aptian and consists of fan delta systems, eventually reworked by aeolian agents, and subaqueous gravity flows. The sandstones of the Maceió Formation are still poorly investigated in terms of petrography and diagenetic processes. They consist of poorly-to-moderately sorted, fine- to coarse-grained sandstones. This study aims to achieve a detailed petrographic analysis, identifying the diagenetic processes involved to provide new data that can enhance the interpretation of the sedimentary provenance, as well as evaluate their potential as an analog to other hydrocarbon reservoirs. Petrographic data from the Maceió Formation, obtained from Porto Calvo, Barreiras do Boqueirão, and Morro do Camaragibe outcrops, indicated subarkose and arkose composition, with a mineralogical arrangement rich in monocrystalline quartz, some polycrystalline quartz, and poor in feldspars and lithic fragments. Grains are angular to subrounded and poorly-to moderately sorted. Diagenetic processes occurred during eodiagenesis, mesodiagenesis, and telodiagenesis stages. Eodiagenesis is marked by mechanical compaction with grains deformations, clay infiltration, alteration of muscovite and feldspar, and iron oxide cementation. Mesodiagenesis features include chemical compaction, quartz cementation, clay minerals and chlorite, and replacement of feldspar and muscovite by clay minerals. The telodiagenetic stage is characterized by oxidation processes (cementation by iron oxide/hydroxide) and partial dissolution of feldspar grains. Regarding provenance, the mineralogical composition suggests a predominantly continental block origin, with a stable craton source area. Primary intergranular porosity predominates, followed by secondary porosity resulting from the rotation and dissolution of grains, as well as the contraction of expansive clay. Porosity was produced and modified during different diagenetic phases, as petrographic analysis shows that primary porosity was reduced during eodiagenesis by clay infiltration and during telodiagenesis by iron oxide/hydroxide cementation. The mechanical and chemical compaction during eodiagenesis and mesodiagenesis, as well as the secondary growth of quartz in mesodiagenesis, impact potential reservoir condition indicators and predictions based on the analog model.

Keywords: Aptian, quartz-rich, subarkose, arkose.

Introduction

The exposure of the studied succession crops out at the northern area of the Alagoas Basin. The Alagoas Basin is located on the northeastern margin of Brazil (Figure 1) and is associated with the opening processes of the South Atlantic formation (Schaller 1969, Assine 2007, Campos Neto et al. 2007). Campos Neto et al. (2007) divided its tectono-stratigraphic evolution into five depositional stages: syneclise, pre-rift, rift, post-rift, and drift. Its northern and southern boundaries are the Maragogi High and the Jaopoatã-Penedo High (Santos et al., 2004), respectively. The present-day configuration of the basin shows a NE-oriented, elongated shape, with an onshore area of approximately 13,000 km² and an offshore area of 40,000 km². The basin has the most complete stratigraphic record among all Brazilian and African marginal basins.

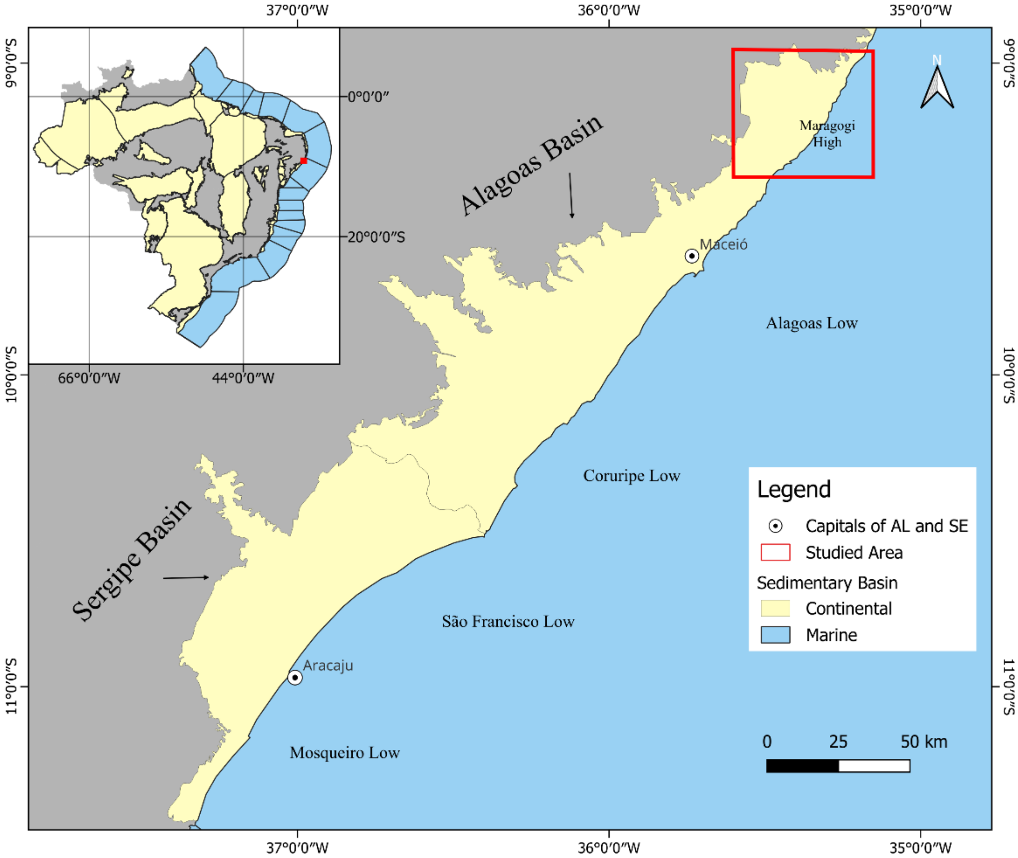

Figure 1. Location map of the Sergipe-Alagoas Basin with the study area highlighted in red.

The Maceió Formation, focus of this study, represents the fourth supersequence corresponding to the five tectonostratigraphic phases, encompassing the end of the rift phase during the Late Aptian (Campos Neto et al. 2007). It comprises conglomerates, sandstones, calcilutites, evaporites and shales, forming a lacustrine to transitional environments. Its deposits consist of fan deltas and associated prodelta deposits (often ascribed to turbidite systems in the literature; Arienti 2006; D'Ávila et al. 2008). The Maceió Formation shows a thick, wedge-shaped geometry, extending over 2,100 meters from the coast. The sedimentary stacking was largely influenced by a wet-to-dry climate, leading the deposition of fan deltas and "turbidites" during humid phases, and organic-rich shales during arid phases (Azambuja Filho, 2020). According to Arienti (1996), the formation encompasses three distinct depositional systems: transverse delta fans, axial delta fans, and subaqueous fans.

In terms of the petrographic and diagenetic characterization of sandstones, it is crucial to emphasize basic petrophysical properties, such as porosity and permeability, which are vital for evaluating the quality of hydrocarbon reservoirs. Petrographic studies on sandstones enable the identification of depositional and diagenetic components. Diagenesis, in turn, directly affects the distribution of porosity and permeability in rocks due to its ability to cause significant modifications. According to Daudt (2009), diagenesis is a key factor that significantly impacts the quality of many reservoirs.

Thus, this study aims to achieve a petrographic and diagenetic description and interpretation of the sandstones of the Maceió Formation (northern part of the Alagoas Basin). The goal is to analyze and identify the compositional aspects and diagenetic processes that have altered the original porosity and permeability of these sandstones.

Metodology

In this studied, twelve samples were collected for petrographic descriptions. Quantitative petrographic analysis involved counting 300 points (framework grains, matrix, and porosity) on each examined thin section. The Gazzi-Dickinson quantification method was employed (cf. Zuffa, 1985) to determine percentages of monocrystalline quartz (Qm), polycrystalline quartz (Qp), potassium feldspar (Fk), plagioclase (Fp), lithic fragments (L), matrix and porosity. This approach led to assess reservoir rock properties, including permeability, and evaluate its diagenetic and textural characteristics, as well as mineralogical and textural maturity. Thus, the data were compiled and classified according to Folk (1968).

Results and Discussion

Petrographic Characterization

The sandstones of the Maceió Formation show grain-size ranging from very coarse to fine-grained, with a coarse-grained dominated fraction. These sandstones are primarily composed of monocrystalline quartz grains (average 41%; Figure 2A), mostly of plutonic origin, with a small proportion of polycrystalline quartz (approximately 3%, also plutonic). Feldspars constitute around 26%, predominantly microcline (Figure 2B), with lesser amounts of orthoclase, traces of plagioclase and perthite. Lithic fragments account for about 3%, including granite, gneiss and mud fragments. Accessory minerals exceed 6%, including opaque minerals and other heavy minerals. Muscovite and biotite are present, the latter showing some oxidized fragments (see Figure 5A).

The analyzed thin sections exhibit angular to subangular grains and are poorly sorted, indicating low textural maturity (Figure 2A). Overall, the grains have angular to subangular contacts, predominantly point and floating, followed by straight contacts, with occasional concavo-convex and sutured contacts. There are no visible signs of compaction, but the disseminated matrix and lack of grain contact suggest minimal compaction in the rock. Some coarse grains of quartz and feldspars show fractures. The detrital matrix is widely dispersed throughout the section, comprising more than 5%, thus showing an immature texture. Compositional analysis, based on Pettijohn's (1975) Quartz/Feldspar ratio, classifies the rock as immature.

Based on petrographic thin section analysis and Folk's classification (1968), these sandstones are classified as subarkoses and arkoses (Figure 3A), with feldspars comprising 5-25%. The mineralogical composition suggests a predominantly continental block origin, with a stable craton source area and transitional continental tectonic environments (Figure 3B). They exhibit a sandy and clayey matrix, predominantly ferruginous cement, with subordinate occurrences of kaolinite and siliceous cement (due to secondary quartz growth).

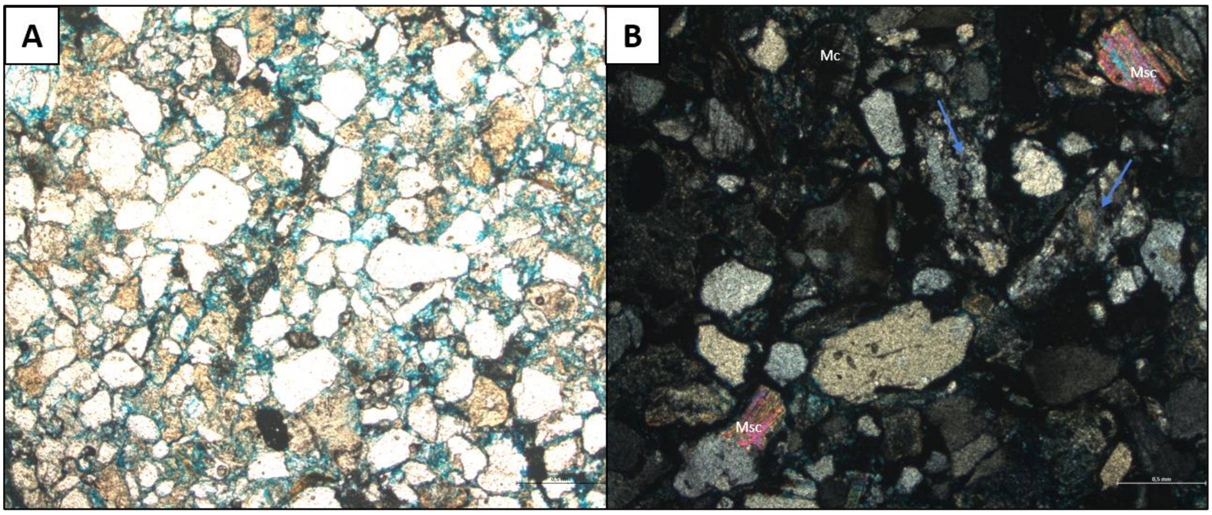

Figure 2. Photomicrographs of the Barreiras do Boqueirão outcrop showing compositional aspects under cross-polarized light. A) Angular and subangular monocrystalline quartz grains. B) Altered feldspar grains (blue arrow).

Clay minerals fill the pore spaces; illite replaces feldspar grains; and kaolinite occurs as lamellae replacing muscovite and biotite grains, as well as feldspar grains (Figure 4). It is noteworthy that smectite is commonly found in arid and semi-arid environments, while kaolinite, according to Morad (1991), may originate from the dissolution of potassium feldspar like microcline.

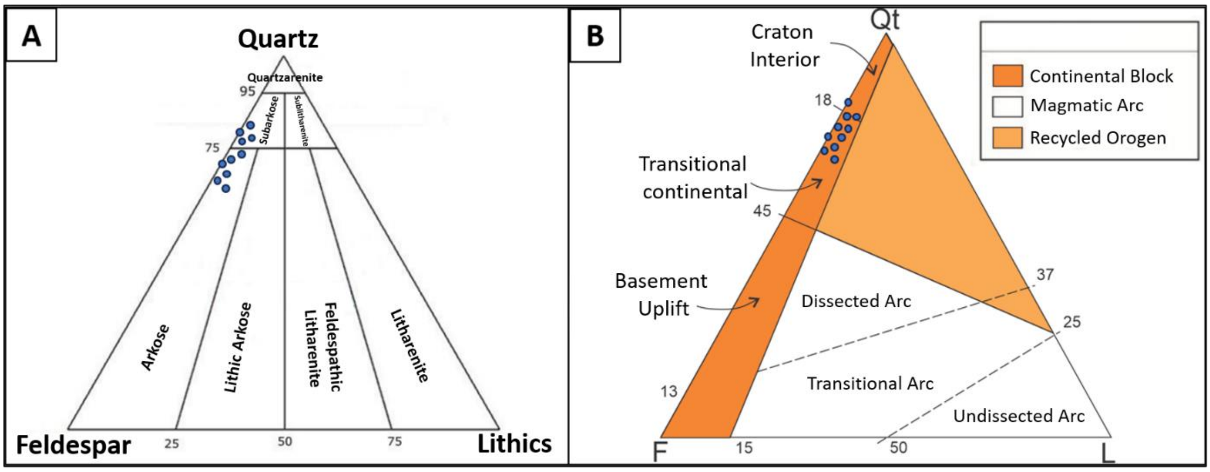

Figure 3. A) Compositional classification of the sandstones of the Maceió Formation (northern portion), according to Folk's diagram (Folk, 1968). B) Provenance diagrams for these sandstones, indicating a stable craton source area and transitional continental tectonic environments. Modified from Dickinson (1985).

The average porosity in these sandstones is 16%, characterized by typical intergranular primary porosity (Figure 5A) and intragranular/secondary porosity resulting from the dissolution of feldspars and highly fractured quartz grains. (Figure 5B).

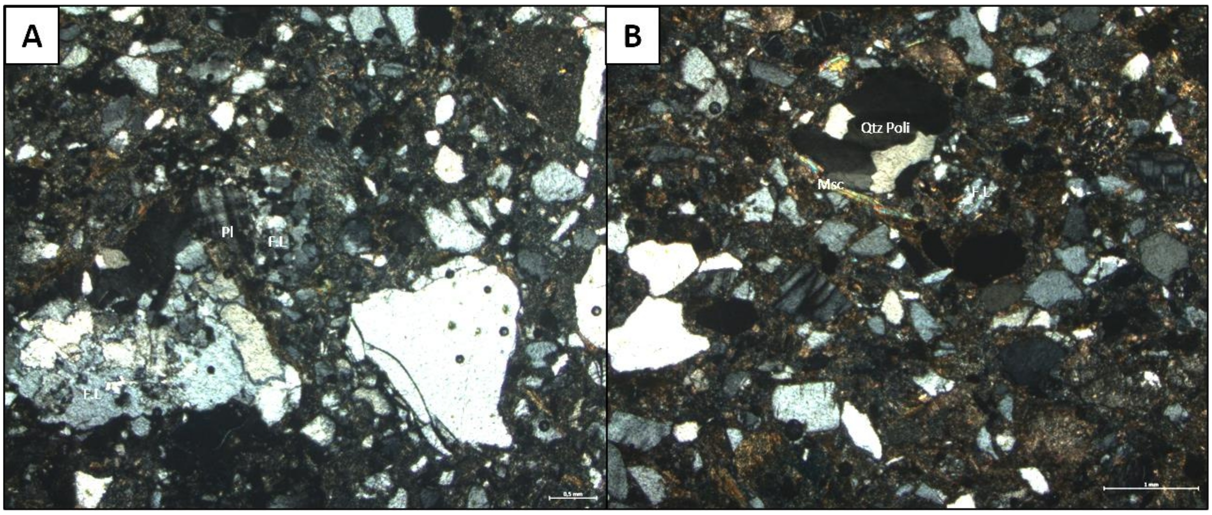

Figure 4. Photomicrographs of the Porto Calvo outcrop showing compositional aspects under cross-polarized light. A) Monocrystalline and polycrystalline quartz grains, plagioclase grains and granite rock fragment. B) compacted muscovite (cross-polarized light).

Diagenetic Processes

Diagenesis encompasses a range of physical, chemical, and biological processes that occur after sediment deposition, driven by increasing temperature and pressure. It is directly related to progressive burial and the chemistry of fluids within interstitial pores, leading to rock lithification (Worden & Burley, 2003). Diagenetic processes can enhance, preserve, or diminish the porosity and permeability of reservoirs through a complex interplay of interrelated factors (Posamentier & Allen, 1999; Morad et al., 2012).

Through images obtained from the optical microscope analysis, the sandstones of the Maceió Formation underwent several diagenetic processes, including mechanical and chemical compaction, mechanical infiltration of clay, quartz syntaxial growth, alteration and replacement of minerals, grain dissolution and the formation of opaques cement, chlorite, and iron oxide/hydroxide.

According to Martini (2010), mechanical compaction involves burial processes that reduce both pore spaces and the total volume of sediments. These mechanical processes include the deformation of intraclasts and lamellar minerals such as micas, as well as the fracturing and rotation of grains (Figure 5B) (Caetano-Chang & Fu Tai, 2003). The process of chemical compaction is characterized by the dissolution of framework grains at their contacts; this dissolution occurs due to the pressure from sedimentary overload.

In this scenario, it is clear that mechanical and chemical compaction had limited impact on these sandstones, as there were few indicators of these diagenetic processes. Only a few numbers of fractured quartz and feldspar grains, as well as occasional folded muscovite, were observed. Concavo-convex and sutured grain contacts, which suggest chemical compaction, were also scarce. The grain contacts are mainly point and floating, reflecting the low degree of compaction in these rocks, which helps preserve their original porosity.

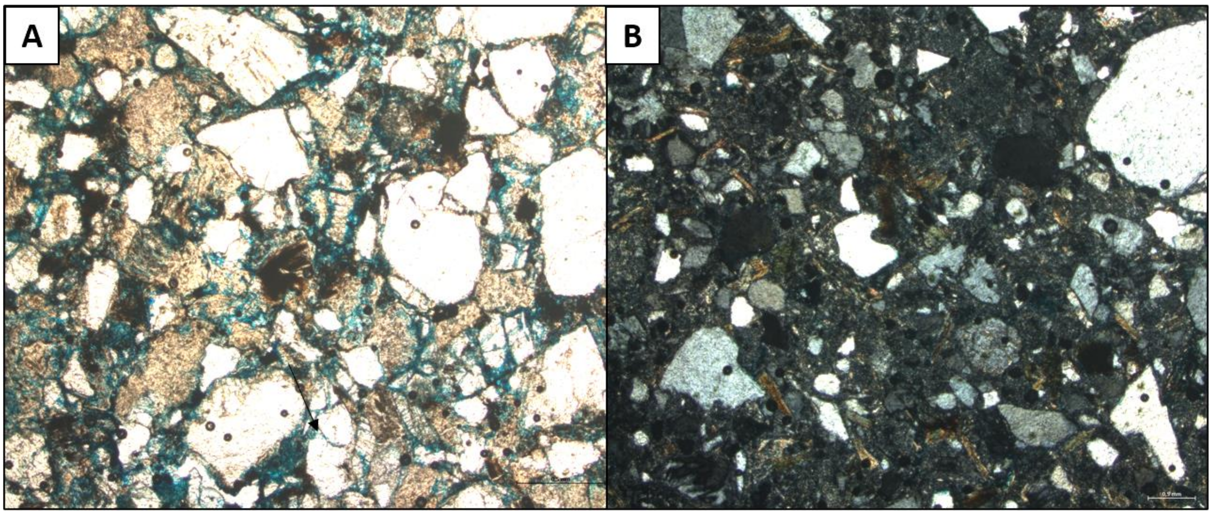

Figure 5. Photomicrographs of the Morro do Camaragibe outcrop under cross-polarized light indicating: A) Primary intergranular porosity; B) Secondary grain fracture porosity.

In arid and semi-arid climates, mechanically infiltrated detrital clay is mainly composed of smectite. However, with subsequent diagenesis, smectite gradually transitions into chlorite-smectite and illite-smectite interstratifications (Caetano-Chang & Wu, 2003). The mechanical infiltration of clay in the examined sandstones is minimal, allowing the preservation of their original porosity. Mechanical compaction and clay infiltration processes primarily occur during the eodiagenesis stage, indicating close proximity to the depositional surface. Strong mechanical compaction indicates the mesodiagenesis stage. Nevertheless, in the sandstones of the Maceió Formation, mechanical compaction was minimal, pointing to shallow burial of the sediments and a propensity to eodiagenetic stage.

In many of the analyzed sandstone samples, alteration and replacement processes of muscovite, biotite, and feldspars (undergoing kaolinization) are frequent. Altered biotite, resulting in iron oxide/hydroxide cement, is also present. Feldspar grains exposed to weathering processes may have experienced intensified alteration, resulting in partially or fully kaolinized feldspars. Consequently, feldspar may have contributed to the kaolin observed in the thin sections. The alteration of biotite is a diagenetic process that can occur during both eodiagenesis and telodiagenesis. Iron released from biotite alteration reactions can exist as ferric or ferrous ions, depending on the pH conditions: ferrous ion (Fe^{2+}) remains in solution or is incorporated into authigenic phases like pyrite and smectite, while ferric ion (Fe^{3+}), which is less soluble, precipitates as iron oxide or hydroxide (Walker, 1976). This process may have contributed to the formation of ferruginous cement in the studied samples.

Prodelta sandstones of the Morro do Camaragibe show partial grain dissolution, generating secondary porosity. This type of porosity, while common in the mesodiagenesis stage, can also occur during eodiagenesis, as sediments are still influenced by surface conditions during this stage. In the prodelta sandstones, authigenic quartz cement in the form of syntaxial overgrowth was also observed, which in turn affect porosity. According to De Ros (1998, *apud* Bocardi et al., 2006), the process of quartz syntaxial overgrowth is common in the mesodiagenesis stage.

Conclusions

Petrographic analysis of the sandstones of the Maceió Formation (northern portion of the Alagoas Basin), revealed that these rocks are primarily rich in monocrystalline quartz and feldspars (with microcline being the most frequent), classifying them as arkose, within a continental block origin. The rock fragments are predominantly plutonic, the matrix is sand- and clay-rich, and the most common cement is iron oxide/hydroxide, followed by clay minerals. The most common clay minerals are smectite and kaolinite.

The dominant porosity is intergranular, with secondary intragranular porosity and grain dissolution also observed, although less frequently. The packing is normal, mainly with point contacts, indicating low compaction of these rocks and preservation of the original porosity. These sandstones primarily underwent eodiagenesis, which included mechanical grain compaction, mechanical clay infiltration, ferruginous cementation (from biotite alteration), grain dissolution, and kaolinization of muscovite, biotite, and feldspars. The effects of compaction and clay infiltration had a minor impact on the reduction of the rock's original porosity. Conversely, partial grain dissolution contributed to an increase in porosity in some samples of these sandstones.

The diagenetic processes such as mechanical grain compaction, grain dissolution, clay infiltration, and cement generation in the sandstones of the Maceió Formation were not highly influential, which may have helped preserve intergranular porosity. The dissolution and fracturing of grains caused by diagenetic processes resulted in the formation of secondary porosity. The primary porosity observed was around 16%, which is considered good for reservoir rocks.

Acknowledgment

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