PETROGRAPHIC CHARACTERIZATION AND DIAGENESIS IN SANDSTONES OUTCROPS OF THE NORTHERN MACEIÓ FORMATION: IMPLICATIONS IN RESERVOIR QUALITY

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ABSTRACT
The acquisition of geological data is of fundamental importance for the study of areas potentially relevant to the occurrence of petroleum systems. In this context, the development of research in outcropping rock formations has proven to be a potential method to investigate the geology of the geological unit studied in subsurface. One of several examples found in Brazil are the outcrops Barreiras do Boqueirão and Praia de Japaratinga, belonging to the Maceió Formation, located in the northern coast of Alagoas State. The Maceió Formation has the lowest cretaceous sedimentation record within the Alagoas Basin. This sedimentation, present almost in the entire basin, is located mainly in its subsurface. This geological unit is composed of several lithologies, including a turbiditic sequence predominantly formed by shales, sandstones and conglomerates. This environment makes it possible the occurrence of a petroleum system. Our research group chose to investigate this environment because turbiditic sandstones are excellent petroleum reservoirs, and they have a great economic relevance in the Brazilian petroleum scenario. To develop this research, a petrographic characterization of the Maceió Formation sandstones was conducted to help determine the compositional and diagenetic aspects of these rocks and infer the influence of diagenetic processes on the quality of these sandstones as reservoirs. The petrographic analysis showed that the studied sandstones can be classified as arkose and quartzenite, present moderate porosity and good permeability, observed through the predominant presence of floating contacts between the grains. The porosity is predominantly primary intergranular, averaging 15%, but secondary porosity by fracture and dissolution of primary grains also occurs. The sandstones of the Maceió Formation are poorly and moderately selected, with angular, sub-angular and sub-rounded grains, showing low to medium textural maturity, which may also influence the quality of the reservoir, impairing the primary porosity in the samples. The three diagenetic stages were identified as: eodiagenesis, mesodiagenesis, and telodiagenesis. The diagenetic processes found were: mechanical compaction, beginning of chemical compaction, clay infiltration, pyrite cementation, grain dissolution, chlorite cementation, quartz sintaxial growth, and mineral alteration and replacement. Mineral replacement was a phenomenon observed quite expressively in the samples analyzed. This event was evidenced, particularly, by the substitution of muscovite and feldspar for kaolinite, the alteration of biotite was also identified in the samples. Therefore, one can infer that the diagenetic processes had little influence on the reduction of the original porosity in the samples studied. In general, considering all the analyses performed in this research, one can see that the sandstones of the Maceió Formation (northern portion) present a good reservoir quality.

KEYWORDS
petrographic characterization; diagenetic aspects; reservoir quality
1. INTRODUCTION

Petrographic and petrological characterizations are essential tools for analyzing reservoir quality, since they identify the composition of the rock and complex diagenetic changes that have occurred therein, whether these changes are mechanical, physical or chemical. These techniques can be regarded as relatively precise instruments that, associated with other, more specific tools, provide predictive elements for exploration of hydrocarbon reservoirs in sedimentary basins.

The diagenesis constitutes a wide variety of physical, chemical, and biological processes that occur after the deposition of sediments, driven by increased temperature and pressure, directly related to the progressive burial, and by the water’s chemistry found in the interstitial pores, causing rock lithification (Worden & Burley, 2003). This phenomenon controls the quality of reservoirs, influencing the porosity and permeability of the rock and, therefore, the storage and production of hydrocarbons (Rossi et al., 2001).

The acquisition of geological data is essential for the study of areas potentially relevant to the occurrence of petroleum systems. The Maceió Formation, which belongs to the Alagoas Sedimentary Basin, is one of the relevant areas for the study of petroleum systems with potential oil accumulation. This geological unit is composed by different lithologies, among them conglomerates, sandstones, shales and evaporites, which compose part of its turbiditic sequence.

The turbidite sandstones are economically relevant in the Brazilian oil industry for being excellent oil reservoirs. An example of this are the turbidite sandstones in the Namorado Field, the best reservoirs in the Campos Basin. The Upper Cretaceous and Lower Tertiary turbidites are the main hydrocarbon reservoirs in the Espírito Santo Basin, East Brazilian coast. In 2004, these rocks accounted for more than 88.6% of total oil reserves in Brazil (Lima, 2004), until the pre-salt hydrocarbon accumulations were discovered.

Some authors have developed relevant work in the region studied over time. Among them, Abreu and Potter (1990), who calculated the average percentage of the different lithologies that compose it. Lira (2004) developed her research in three outcrops in the northern and southern portions of the Maceió Formation, describing and analyzing selected sedimentary deposits. The author identified heterogeneities in the rock formation studied at micro, meso, and macroscopic levels, regarding the depositional architecture and the internal framework. Nascimento and Lima Filho (2006) presented an analysis of petrographic and paleontological data in the Maceió Formation deposits. Almeida et al. (2017) performed lithogeochemical and petrographic analysis applied to the study of provenance of the sediments that compose the Maceió Formation.

Thus, the objective of this work is to deepen the petrographic knowledge of the sandstones studied in the outcrops Barreiras de Boqueirão and Praia de Japaratinga, to identify the diagenetic processes that impact the porous system of these rocks. The target area presents excellent preservation and exposure of turbiditic rocks. Thus, the results of this research may serve as basis for future exploration work of oil reservoirs in turbiditic sandstones of other sedimentary basins.

1.1 Study area location

This research was developed at the outcrops Barreiras do Boqueirão and Praia de Japaratinga (09°07’34.25 "S and 35°16’50.14 "W), that are adjacent to each other and belong to the Maceió Formation, located in the northern part of the Alagoas Basin. These outcrops are located in Japaratinga county, Alagoas State, as shown in Figure 1.

1.2 Geological context of Alagoas Basin and Maceió Formation

Among the Brazilian sedimentary basins, the Alagoas Basin, together with the Sergipe Basin, has stood out in terms of geological records. It has the most complete stratigraphic succession in the context of the Brazilian sedimentary basins, including remnants of a Paleozoic sedimentation, a widely developed Jurassic to Eocretaceous pre-rift package, and the classic Mesocenozoic rift and passive margin sequences (Feijó, 1994; Milani et al., 2000), as shown in Figure 2.
This is a marginal basin, located in the northeast of Brazil, occupying a coastal strip corresponding to 220 km of extension, and has 40 km of average width. Its northern and southern limits are: the Maragogi High, where it borders the Pernambuco-Paraiba Basin and the Jaopoatã-Penedo High, bordering the Sergipe Basin (Santos et al., 2003). The Alagoas Basin has a total of twenty-one formations, among them, the Maceió Formation (Feijó, 1994).

The Maceió Formation, object of study of this research, is part of the Rift Supersequence and of the third tectonic pulse of the rift of the Alagoas Basin (Souza-Lima et al., 2002), being represented by alluvial fans and turbiditic lacustrine systems of Neoaaptian age (Campos Neto et al., 2007). This geological unit represents the record of Lower Cretaceous sedimentation, which occurs in almost the entire basin under study, predominantly in the subsurface, having a sedimentary sequence of 5,000 meters thick in submerged areas (Abreu & Potter, 1990).

Its sedimentation took place from Mesoaptian to Eoalbian (Falkenheim, 1984). During the Neoaaptian and Eoalbian, the sedimentation environment became marine, probably because faults reactivated, making this basin much deeper. At this time, a carbonate-siliciclastic platform developed in front of the fandelts, providing the opportunity for alluvial fans to overtop and form turbiditic deposits (Lira, 2004).

The depositional environment of the Maceió Formation during the Mesoaptian is thought to be fandelts, which developed between areas of intense evaporation at the low rim. To the north, fluvo-deltaic eolic sediments were deposited, being later uplifted by geologic faults, serving as source area (Abreu, 1989; Feijó, 1994). The Maceió Formation is composed of several lithologies, among them are sandstones, shales, argillites, evaporites, and conglomerates. These materials compose the turbidite sequence of the basin which is formed predominate by conglomerates and sandstones, but also shales in considerable proportions, that can characterize the occurrence of an oil system.

Figure 1. Location of the outcrops Barreiras do Boqueirão and Praia de Japaratinga (adapted from Almeida, 2016).
Figure 2. Stratigraphic chart of Alagoas Basin with emphasis on the corresponding sequence in the Maceió Formation (adapted from Feijó, 1994).

2. METHODOLOGY

From the samples collected in outcrops for this study, ten thin petrographic slides were made in laboratory, without coverslip and vacuum impregnated with blue epoxy resin (aiming a better definition and characterization of the rocks porosity), according to the technique developed by
Cesero et al. (1989). The slides were read in a conventional Opticam Model O600P optical microscope, with a transmitted and reflected light source and an attached digital camera.

Quantitative petrographic analysis was carried out by counting the points (grains of the framework, matrix, and porosity) per slide. Quantification (modal analysis) was performed by counting 300 points on each slide, according to Gazzi-Dicknson (Zuffa, 1985), using three crossings perpendicular to the main orientation of the rock. The percentage of monocrystalline quartz (Qm), polycrystalline quartz (Qt), potassium feldspar (Fk), plagioclase (Fp), and lithic fragment (L), accessory minerals, matrix, and porosity were counted on each slide. The results of grain quantification of each slide were plotted on triangular QFL diagrams (Folk, 1968) to classify the sandstones.

The packing index was also determined according to Kahn (1956), which classified the packing as loose, normal, and closed. The calculation of this index corresponds to the arrangement of grains among themselves, among more closed or more open frameworks, according to the history of burial of the rocks (Batista, 2015).

Based on the analysis of the samples made by means of conventional optical microscope, three samples were selected to be analyzed using a Scanning Electron Microscope (SEM) coupled to an X-ray Energy Dispersive Detection System (EDS) and Wavelength Dispersion (WDS), Model SSX-550 (voltage: 20kV) Shimadzu, to identify constituents and some diagenetic characteristics, and to understand the influence of diagenesis on the quality of the rocks studied as oil reservoirs. Prior to the analysis, the samples were metallized using gold.

The analyses of the petrographic slides in a conventional optical microscope and the rock samples in SEM also enabled the visual quantification of the porous characteristics, allowing us to infer the permeability of the rocks through grain contacts and their average porosity. Porosity, in a rock, is determined by the ratio between the volume of empty spaces and the total volume of the rock. In this case, it was possible to estimate the porosity by counting the empty points on the slides of the analyzed samples.

3. RESULTS AND DISCUSSIONS

3.1 Petrographic characterization

The definition of grain types, mineralogy, grain-grain contacts, intergranular volume, matrix types and quantity, cement mineralogy and morphology, pore types, pore genesis and proportions, is vital to establishing the prevailing controls on reservoir quality (Worden et al., 2018a).

Thus, from the petrology, it has been identified that the sandstones in the northern portion of the Maceió Formation exhibit a grain size range from very coarse to medium sand, with a predominance of coarse sand. Compositionally, these sandstones are composed of monocrystalline quartz (average of 39%, and 82% Figure 3 A), predominantly plutonic, with few polycrystalline crystals (around 2% and 0.4%, of plutonic origin).

The feldspars add up to an average of 26% and 0.5%, being essentially of the microlite type (Figure 3 B) and, in subordinated quantities, orthoclase, plagioclase, and traces of perite occur. Lithic fragments make up about 2% and 0.2%, and include granitic, gneissic rocks and clay fragments (Figure 3 C), with the former predominating.

Accessory minerals add up to more than 6% and 7%, and are represented by muscovite (Figure 3 D), biotite, opaques, zircon, and other heavies. The argilliminerals found were smectite, illite, kaolinite, and traces of authigenic chlorite, with predominance of the former and the latter.

According to the proportions of quartz, feldspars, and lithic fragments, the sandstones studied can be classified as arkose and quartzarenite (Figure 4). The arkose from Barreiras do Boqueirão outcrop and the quartzarenites from Praia de Japaratinga outcrop.

The sandstones from the Maceió Formation are either poorly or moderately selected, with angular, subangular, and subrounded grains, revealing low and medium textural maturity. It presents a sandy and clayey matrix, with predominantly ferruginous cement, occurring subordinately kaolinite and siliceous cement (by authigenic growth of quartz). The packing of these rocks varies from loose ($P_o = 21$), to normal ($P_o = 44$), and closed ($P_o = 61$), predominantly normal packing, suggesting low
compaction and preservation of primary porosity, with point contacts, followed by floating and rare concave-convex and sutured contacts, which indicates good permeability in the samples analyzed. As the depth increases, progressive burial of the grains and gradual change of the contacts to concave-convex and sutured occur, however, in smaller proportion (Bhuiyan & Hossain, 2020).

The average porosity in these sandstones, based on the slides analyzed, is 15%, which is considered a moderate for the percolation of fluids in a reservoir rock (Thomas, 2001; Rosa et al., 2006). This porosity is essentially primary (Figure 5 A), followed by secondary intragranular porosity by fracturing and grain dissolution (Figure 5 B).

3.2 Diagenetic processes

Diagenesis comprehends a variety of physical, chemical, and biological processes that occur after a sediment deposition, due to the increase of temperature and pressure. It has a direct relation to progressive burial, and to the chemistry of water found in the interstitial pores, causing rock lithification (Worden & Burley, 2003). Diagenetic constituents can increase, preserve or destroy the porosity and permeability of reservoirs from a complex arrangement of interrelated parameters (Posamentier & Allen, 1999; Morad et al, 2012).

The sandstones of the Maceió Formation were subjected to the following diagenetic processes: mechanical and chemical compaction; mechanical infiltration of clay; quartz sintaxial growth; alteration and replacement of minerals; dissolution of grains; formation of pyrite cement, chlorite, and iron oxide/hydroxide, as shown in some images obtained from the optical microscope of the slides analyzed, making it possible for us to identify some of the diagenetic processes observed.
The mechanical compaction process is associated with the burial of the sediments and is responsible for reducing the volume of porosity and permeability in the rock. The mechanical processes in the rocks analyzed involve deformation of interclasts and lamellar minerals, such as micas, in addition to fracturing of quartz and feldspar grains (Figure 6 A and B) and grain rotation (Caetano-Chang & Wu, 2003). Mechanical compaction is responsible for the expulsion of interstitial water from the pores and the rearrangement of the grains (Wolela & Gierlowski-Kordesch, 2007).

**Figure 4.** Compositional classification of the Maceió Formation sandstones (northern portion), according to Folk’s diagram (Folk, 1968). The yellow circles represent samples from the Praia de Japaratinga outcrop, and the blue triangles correspond to samples from the Barreira do Boqueirão outcrop.

**Figure 5.** Photomicrograph indicating: A) Primary intergranular porosity (arrows, parallel niche); B) Secondary grain fracture type porosity (arrow, crossed niche).

**3.2.1 Mechanical and chemical compaction**
The chemical compaction is characterized by the dissolution of grains of the framework at their points of contact, occurring due to the pressure from the sedimentary overload (Caetano-Chang & Wu, 2003; Lima & De Ros, 2002), where the stress concentration is maximum (Bocardi, 2009). Chemical compaction marks the end of eodiagenesis and the beginning of mesodiagenesis, producing sutured and concave-convex contacts between grains as a result of increased depth of burial (Bocardi, 2009; Batista, 2015).

Therefore, mechanical and chemical compactions were not so effective in the sandstones studied, since only a few products from these diagenetic processes were identified. Only a few fractured quartz and feldspar grains were recognized, besides rare folded muscovite (Figures 5B; 6 A and B). Concave-convex and sutured contacts between grains indicating chemical compaction were also rare. The contacts between grains were predominantly punctual, followed by floating, evidencing low compaction of these rocks, contributing to original porosity preservation. Very strong mechanical compaction belongs to the mesodiagenetic stage. However, in the Maceió Formation, sandstones mechanical compaction was little active, indicating low burial of sediments and a tendency towards the eodiagenetic stage. According to Worden et al. (2000), the result of a strong mechanical compaction depends mainly on the proportion of hard grains, such as quartz and feldspar; and ductile grains, such as micas and ductile lithic fragments.
3.2.2 Mechanical clay infiltration

The mechanical infiltration process of clay in the studied sandstones is not very significant, preserving their original porosity. The infiltrated clay found was of smectite type, which occurs in small quantities, filling the porous spaces and circulating grains in the samples analyzed (Figure 7A). It is important to highlight that the clay infiltration process occurs mainly in the eodiagenesis stage, indicating proximity to the depositional surface, and may also occur during telodiagenesis (Batista, 2015).

Smectite is a typical argillomineral of alkaline environments, with abundant iron and magnesium ions, from arid and semi-arid climate environments (Worden & Burley, 2003; Drozinski, 2004). Their deposition in the pores occurs through percolation of water from torrential and sporadic rainfall, infiltrating the rock by gravity and being deposited on the surfaces of detrital grains by mechanical processes (Silva, 2014).

The infiltrated clay process takes place because the diameter of suspended clay grains is much smaller than the pore "throat" and the infiltration flow rate of the meteoric water, which is initially quite high. Here, the injection flow is gravitationally propelled through the pore zone, promoting the decantation and adhesion of the clay onto the surface of the grains (Menezes, 1999).

The pore-lining habits (fringe and coatings around the grain) that clay minerals, such as smectites, causing a significant impact on reservoir quality, mainly regarding permeability. The disposition of clays on the grain’s surface can generate narrowing or even total congestion of the pore throats. In the second case, fluid flow is obstructed. However, the impact of this clay morphology on porosity is much less relevant than one may think (Drozinski, 2004).

In some cases, infiltrated clays can, to a certain extent, help preserve porosity by, for example, inhibiting the precipitation of quartz cement (Salah et al., 2016). In this case, this inhibition occurs when the clay surrounds the grains. If this material is deposited in the intergranular spaces, the primary porosity is reduced. Since the deposition of mechanically infiltrated clay was negligible, this phenomenon had little impact on the reservoir quality of the samples analyzed.

3.2.3 Autigenic quartz growth

In the turbiditic sandstones of the Maceió Formation, autigenic silica cement was also found in the form of syntaxial growth and prismatic projections at the endings (Figure 7 B). In these sandstones, this type of cement occurs discontinuously around the quartz grains and in small amounts, contributing little to the reduction of the original porosity. The quartz sintaxial growths present themselves in a discontinuous way suggesting that they were formed after intense dissolution of grains by pressure (chemical compaction), probably at the end of eodiagenesis and beginning of mesodiagenesis.

Some of the possible sources of this cement are: dissolution of ferromagnesian minerals, gravitational percolation of meteoric water rich in silicon ions (extra bacinal source), dissolution of feldspars (Suguio, 1980; Wolela & Gierlowski-Kordesch, 2007; Khoudja et al., 2020) into kaolinite and illite, releasing considerable amounts of silica (Souza, 2017; Xi et al., 2019; Bhuiyan & Hossain, 2020). Cementation of authigenic silica in the form of quartz syntaxial growth is commonly attributed to pressure dissolution processes, and may be associated with smectite illitization, feldspar kaolinization, decomposition of silica-rich particles, dissolution of quartz, biogenic silica, amphiboles, and pyroxenes (Tucker, 1991).

The process of quartz syntaxial growth is common in the mesodiagenesis stage (De Ros, 1998; Worden & Burley, 2003; Khoudja et al., 2020). However, since this diagenetic process occurred in a small amount, it can be inferred that it may have happened at the end of eodiagenesis and beginning of mesodiagenesis.

It is worth mentioning that the turbidite sandstones of the Maceió Formation were deposited during the rift phase of the Alagoas Basin. The type of sedimentary basin in which the sediments were deposited may also explain the little occurrence of syntaxial quatzro growth, since the type of basin controls the cementation process. Thus, sandstones that are formed in the rift phase of the basin, such as the arkose, have a small percentage of quartz authigenic cement (McBride, 1989). This is the case of the sandstones of the outcrops studied, which are classified as arkose (Figure 4), and, therefore, have a greater amount of feldspars in their composition. Another possible explanation for the low occurrence of cementation
by silica would be the presence of chlorite cement because this material hinders the secondary growth of quartz (Khoudja et al., 2020). Chlorite cement was also identified in the samples studied.

### 3.2.4 Mineral alteration and substitution

In many samples of the sandstones analyzed, the alteration and replacement processes of muscovite and potassium feldspar by kaolinite and illite argilminerals are frequent (Figure 8 A). The alteration and replacement of biotite by iron oxide cement and chlorite occur in smaller amounts (Figure 8 B).

The alteration and replacement of muscovite by kaolinite may have occurred due to percolation of leaching fluids at shallow depths, dissolving the muscovite (Batista, 2015). In the studied sandstones the kaolinized muscovite presents in the expanded and lamellae form, indicating that its expansion occurred before significant compaction (Ketzer et al., 2003; Morad et al., 2010). The dissolution of the feldspar grains influences the precipitation of kaolinite, which is deposited in the secondary pores due to the reaction between the unstable grains and in the presence of acidic interstitial water (Wolela & Gierlowski-Kordesch, 2007).

The precipitation of kaolinite is associated with the dissolution of unstable silicate grains due to interstitial fluid circulation during eodiagenesis, but it also occurs while replacing minerals such as muscovite (Ketzer et al., 2003) in mesodiagenesis, or due to feldspar dissolution (Khoudja et al., 2020). It is possible that the exposure of feldspar grains to mesodiagenetic processes and weathering intensifies their alteration, producing

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**Figure 8.** A) Expanded muscovite being replaced by kaolinite (arrow, crossed niches); B) Altered biotite generating iron oxide cement (arrow, crossed niches); C) Illite replacing feldspar grain (red arrow) and iron oxide/hydroxide (yellow arrow, crossed niches; B) Quartz grains being covered by illite (yellow arrow, image obtained by SEM).
partially or fully kaolinized feldspars. Thus, the feldspar may have originated the kaolinite found in the rocks studied.

In the sandstones analyzed, illite is found replacing microcline feldspar grains (feldspar illitization) and covering quartz grains (Figure 8 C and 8 D, respectively). The process of feldspar "illitization," as occurs in the analyzed sandstones, can result in the precipitation of this illite in the pore spaces. The illite is formed in mesodiagenesis by replacement of infiltrated clays and clayey intraclasts (Morad et al., 2000). In the outcrops studied, many clayey intraclasts, that may have originated this illite, were observed.

Bioclast alteration, in turn, is a diageneric process that can occur in both eodiagenesis and telodiagenesis. The iron released from bioclast alteration reactions can occur as ferric or ferrous ions, depending on the existing pH conditions: the ferrous ion (Fe2+) remains in solution or is incorporated into authigenic phases such as pyrite and smectite, while the ferric ion (Fe3+), which is not very soluble, precipitates as iron oxide or hydroxide (Walker, 1976). This process may have been responsible for the generation of a ferruginous cement in the rocks studied in this research, impairing their porosity.

### 3.2.5 Grain dissolution

The dissolution is a process in which a mineral is destroyed by interaction with the fluid, resulting in a cavity (Worden & Burley, 2003), i.e. porosity. In the turbidite sandstones studied, partial dissolution of grains of the primary constituents, such as feldspars and quartz (edges), occurs generating secondary porosity. However, this process hardly occurred and affected the original porosity of these rocks. Among the constituents of sandstones, feldspar grains are more susceptible to total or partial dissolution (Bhuiyan & Hossain, 2020). Secondary porosity generated by grain dissolution, although common in the mesodiagenesis stage, can also still occur in eodiagenesis and telodiagenesis, since in these diageneric stages the sediments are still influenced by the surface.

The dissolution event of outcropping sedimentary rocks is most often referred to as resulting from the percolation of meteoric interstitial waters that interact with the grains of the framework and with the cement, promoting partial or full solubilization of this material. The generation of secondary porosity arises as an immediate consequence of this event (Menezes, 1999). The presence of secondary porosity does not necessarily imply an increase in total porosity (Bjørlykke et al., 1989). This means that the increase in secondary porosity may not contribute significantly to increase the quality of the reservoir, because part of the dissolved material may reprecipitate as diagenetic minerals, which basically represents a redistribution of porosity (Drozinsk, 2004), and this was observed in the samples analyzed.

#### 3.2.6 Cementation by pyrite, chlorite, and iron oxide/hydroxide

In the sandstones studied, precipitations of pyrite, chlorite, and iron oxide/hydroxide cement were found in small quantities. Pyrite corresponds to a very common sulfide in the form of primary or secondary mineral (Silva, 2014). It is common in sedimentary rocks and is associated usually with organic matter. Pyrite cement is formed at the redox interface of sediments, being restricted by the supply of degradable organic matter, dissolved sulfate, and detrital reactive iron minerals (Ding et al., 2014). Sulfate from alkaline fluids reacts with the iron from ferromagnesian minerals, resulting in pyrite, which precipitates in the pore. This process is more common in anoxic environments in which high concentration of anaerobic bacteria occurs (Drozinsk, 2004; Liu et al., 2020). Pyrite can also be formed from the combination of Fe+2 cations during the transformation of smectite to autigenic chlorite with the sulfate present in the formation water (Khoudja et al., 2020).

Pyrite cement can occur in eodiagenesis and also in subsequent phases. Pyrite cement tends to occupy the intergranular spaces, impairing the primary porosity of the rock. In the samples analyzed, however, little precipitation of this material in the pore spaces was observed, so this phenomenon did little damage to the original porosity of the sandstones studied.

According to Khoudja et al. (2020), the precipitation of chlorite is a phenomenon still poorly understood. Nevertheless, these authors explain that the precipitation of authigenic chlorite can occur through two sources: by chloritization of biotite, or else, through the transformation of
smectite into an intermediate mineral, the berthierine, and from this mineral into chlorite. This phenomenon occurs because the precipitation of chlorite involves large amounts of Fe, Mg and Al. Iron and magnesium ions are also released during the illitization process of unstable grains (Hower et al., 1976; Deer et al., 2013a) as a product of hydrothermal alteration of ferromagnesian minerals (Deer et al., 2013b; Batista, 2015). The formation of autigenic chlorite can comprise depths greater than 3 kilometers, thus, occurring during the beginning of mesodiagenesis (Wolden & Burley, 2003).

It is important to note that, in the samples analyzed, both biotite and smectite were found. This means that the identified autigenic chlorite may have occurred as an alteration product of these argillminerals. The cementation by autigenic chlorite was also not significant in the sandstones of the outcrops studied.

The autogenic chlorite is considered an important diagenetic constituent in sandstone reservoirs, since it helps to preserve porosity during the deeper stages of sediment burial (Khoudja et al., 2020). This is because autogenic chlorite can commonly occur in the form of fringe and coating (pore-lining) covering the quartz grains (Bahlis, 2015; Khoudja et al., 2020), consequently inhibiting silica cementation, which results in the preservation of primary porosity in deeply buried rocks (Ryan & Reynolds, 1996; Worden et al., 2018b; Worden et al. 2020; Khoudja et al.,2020). However, even though it assists in preserving the porosity of the reservoir, chlorite cement can impair the permeability of the rock, since it decreases the diameter of the voids in the case of interconnected pores (Khoudja et al., 2020). In the case of the studied sandstones, it is possible that the chlorite cementation, even if it is minor, may have contributed positively to reservoir quality by being able to inhibit the autogenic growth of quartz.

Iron oxide/hydroxide cementation was observed in some samples, in varying amounts, in the form of thin coatings surrounding the detrital grains and filling intergranular pores. In the samples presenting silica cementation in the form of quartz sintaxial growths, this type of cement was not identified, possibly because such coatings prevent the later diagenetic phases from acting. Thus, two phases of iron oxide/hydroxide cementation were identified: one represented by coatings covering quartz grains, prior to the secondary quartz growths, at the beginning of eodiagenesis; and the other phase from the precipitation of iron oxide/hydroxide filling the intergranular pores, in the telodiagenesis.

4. CONCLUSIONS

From the analyses performed on the outcropping units, it was possible to infer what may also occur in them at greater depths. The petrographic characterization revealed that the detrital composition of the sandstones studied is either immature or submature, with lots of feldspars and unstable minerals preserving their original Arcosian composition. These sandstones are mostly rich in quartz (mono and polycrystalline) and feldspars (microcline and orthoclase), being classified as arkose and quartzarenite. The lithic fragments are mainly from plutonic rocks, followed by metamorphic and sedimentary rocks.

The contact between grains is predominantly fluctuating, with few sutured and concave-convex contacts, revealing that these sandstones were poorly compacted. It also indicates good permeability in the samples analyzed. The detrital composition may have contributed to impairing the primary porosity of the rock, since in the samples analyzed the sandstones have low and medium textural maturity. The alteration and replacement of unstable minerals may have been the most active diagenetic process, with it being the process that most contributed to the reduction of the original porosity of the Maceió Formation sandstones.

In the sandstones studied, all diagenetic stages were identified: eodiagenesis, mesodiagenesis, and telodiagenesis. The eodiagenesis is evidenced in the samples analyzed through phenomena such as mechanical compaction, beginning of chemical compaction, mechanical infiltration of clay, and pyrite cementation. Nevertheless, these events acted in a minor way, not significantly damaging the primary porosity in the analyzed sandstones. Mesodiagenesis can be expressed by phenomena such as grain dissolution, an event that did not contribute significantly to the total porosity, but acted in the redistribution of porosity in the studied sandstones. The autogenic silica growth also
evidences mesodiagenesis, observed in a punctual way. Probably, the precipitation of siliceous cement was inhibited by autigenic chlorite, found in the studied samples, which occurs during the onset of mesodiagenesis.

Mineral alteration can occur in all three stages of diagenesis. However, this diagenetic process occurs mainly in mesodiagenesis, at greater depths if compared to eodiagenesis. Mineral substitution was a phenomenon observed in a very expressive way in the samples analyzed, and this event was evidenced, particularly, by the substitution of muscovite and feldspar for kaolinite. Biotite alteration may have occurred in both eodiagenesis and telodiagenesis.

The petrographic analysis also revealed that fracturing and dissolution of primary grains such as quartz and feldspars, respectively, were the main processes responsible for the generation of secondary intragranular porosity. In addition, the detrital composition also influenced the alteration of the original porosity of the Maceió Formation sandstones, because some unstable primary constituents were dissolved (generating cement), while others were replaced.

In general, the diagenetic processes observed did not generate fluid flow barriers in an expressive way, since there was preservation of the original porosity of the rock, essentially primary, followed by secondary intragranular porosity by fracturing and dissolution of grains. The average porosity of these sandstones, based on the slides analyzed, is 15%, classified as moderate for fluid percolation in a reservoir rock. In view of these analyses, one can observe that the sandstones of the northern portion of the Maceió Formation presents a good quality of reservoir, since diagenetic processes did had a limited negative impact the original porosity of the rock.

5. REFERENCES

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