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INFLUENCE OF DIAGENETIC DEPOSITS ON THE POROSITY OF SANDSTONES FROM IBOREPI FORMATION, LAVRAS DA MANGABEIRA BASIN

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Abstract

The study of diagenetic processes is essential to evaluate the potential of sandstones as good reservoirs of oil, gas, and water. Nonetheless, the diagenesis of the Iborepi Formation sandstones (Lavras da Mangabeira Basin) is little known, mainly regarding its effect on the original porosity of these rocks, which can be studied as analogs of oil basin reservoirs. Aiming to evaluate the diagenetic process that affected the Iborepi sandstones, as well as their potential for fluid storage, nine thin sections were analyzed. The study revealed that the processes that most affected the primary porosity of these rocks and their quality as reservoirs include compaction, cementation, and clay infiltration, with compaction prevailing. These processes have damaged the porosity and permeability of these rocks by reducing pore space and clogging pore throats. The detritic composition has also affected the original porosity, favoring some diagenetic processes. Although these rocks have a reasonable porosity for fluid storage (14% average), their diagenetic heterogeneities have impacted their quality as reservoirs.

Keywords: Sandstones Diagenesis; Porosity; Reservoir.

INFLUÊNCIA DOS PROCESSOS DIAGENÉTICOS NA POROSIDADE DOS ARENITOS DA FORMAÇÃO IBOREPI, BACIA DE LAVRAS DA MANGABEIRA, ESTADO DO CEARÁ

Resumo

O estudo diagenético é essencial para avaliar o potencial de arenitos como bons reservatórios de petróleo, gás e água. A diagênese dos arenitos da Formação Iborepi (Bacia de Lavras da Magabeira) é pouco conhecida, principalmente quanto a seu impacto sobre a porosidade original dessas rochas, que podem ser estudadas como análogos de reservatórios de bacias petrolíferas e aquíferos. A fim de conhecer os processos diagenéticos que afetaram os arenitos Iborepi, bem como seu potencial para armazenamento de fluidos, foram analisadas nove lâmenas delgadas. Esse estudo revelou que os processos diagenéticos que mais afetaram a porosidade primária desses arenitos e sua qualidade como reservatórios foram a compactação, cimentaço e a infiltração de argila, sendo a compactação predominante. Esses processos foram responsáveis pelo dano na porosidade e permeabilidade dessas rochas, face à redução do espaço poroso e obliteração da garganta de poros. A composição detrítica também influenciou na alteração da porosidade original, facilitaando a atuação de alguns processos diagnéticos. Embora essas rochas tenham uma porosidade razoável para armazenamento de fluidos (média de 14%), suas heterogeneidades diagenéticas impactaram sua qualidade como reservatório.

Palavras-chave: Diagênese de Arenitos; Porosidade; Reservatório.

INFLUENCIA DE LOS PROCESOS DIAGENÉTICOS EN LA POROSIDAD DE LAS ARENAS DE LA FORMACIÓN IBOREPI, CUENCA LAVRAS DA MANGABEIRA, ESTADO DE CEARÁ

Resumen

El estudio diagenético es fundamental para evaluar el potencial de las areniscas como buen indicador de reservorio petrolíferos. La diagénesis de las areniscas de la Formación Iborepi (Cuenca Lavras da Mangabeira) es poco conocida, especialmente en lo que respecta a su impacto en la porosidad original de estas rocas, que pueden ser estudiadas como análogas de los reservorios en cuencas petrolíferas y acuíferas. Para conocer los procesos diagenéticos que afectaron a las areniscas de Iborepi, así como el potencial de estas rocas para el almacenamiento de fluidos, se analizaron nueve laminas delgadas. Este estudio reveló que los procesos diagenéticos que más afectaron la porosidad primaria de estas areniscas y su calidad como reservorios fueron la compactación, cementación e infiltración de arcilla, siendo la compactación predominante. Estos procesos fueron responsables del daño a la porosidad y permeabilidad debido a la reducción del espacio poroso y la obliteración de la garganta de los poros. La composición detrítica también influyó en la alteración de la porosidad original, facilitando la realización de algunos procesos diagnósticos. Aunque estas rocas tienen una porosidad razonable para el almacenamiento de fluidos (promedio de 14%), sus heterogeneidades diagenéticas impactaron su calidad como reservorio.

Palabras claves: Diagénesis Areniscas; Porosidad; Reservorio.

1. INTRODUCTION

To know the diagenesis and its processes is essential to evaluate the quality of sandstones as oil, gas, and water reservoirs since diagenesis affects the rock porosity and permeability, and thus, their capacity to store hydrocarbons (ROSSI et al., 2001; AL-RAMADAN ET al., 2005) and groundwater.

Several diagenetic processes affect hydrocarbon reservoirs (MORAES and SURDAM, 1993). That is why their study has become a fundamental tool to understand their impact on the quality of reservoirs. The diagenetic constituents can either increase, preserve, or clog the porosity, damaging the permeability of the reservoirs through a complex combination of interrelated parameters (POSAMENTIER and ALLEN, 1999; MORAD et al., 2012).

According to Worden et al. (2018), to establish the dominant controls on reservoir quality, it is essential to define the constituents, texture, mineralogy, framework, cement morphology, and pore type.

The Iborepi Formation, the scope of this study, is part of Lavras da Mangabeira Basin, located in the southeast of the Ceará state. It consists predominantly of sandstones and, subordinately, siltstones, associated with alluvial fans and braided fluvial systems (BATISTA, 2015). Recent studies (Queiroz et al., 2017; Batista et al., 2018) have shown the composition of the sandstones of this formation. The petrography and petrology of this unit, however, are little known, mainly regarding the diagenetic processes that affected the sandstones.

Thus, this work aimed to identify and evaluate, through petrographic data, the diagenetic processes that impacted the original porosity of the Iborepi Formation sandstones. Understanding these processes is important to assess the potential of these rocks for fluid storage, especially as groundwater reservoirs of the Lavras da Mangabeira Aquifer, which includes the Rosário Dam, the Várzea-Alegre Drainage Basins, the Salgado Drainage Sub-Basin, and others.

2. GEOLOGICAL CONTEXT

The Lavras da Mangabeira Basin covers a total area of approximately 60.27 km² and is formed by a set of three small basins or sub-basins: Riacho do Meio (33.2 km^2 area), Riacho do Rosário (24.8 km^2), and the small Iborepi Basin (2.2 km^2) (GRANJEIRO et al., 2008). Along with the Iguatu, Lima Campos, Rio do Peixe, Araripe, São José do Belmonte, Jatobá, and other basins, the Lavras da Mangabeira Basin constitutes the set of interior basins of Northeast Brazil, which is aligned with the Cariri-Potiguar trend (Figura 1). The origin and evolution of these basins are associated with the tectonic events that caused the Gondwana rift and the opening of the South Atlantic (MATOS, 1992, 1999).

The breakup of Gondwana reactivated pre-existing faults of the Precambrian basement, which conditioned the formation and development of small and large sedimentary basins along with the Atlantic margins of Africa and South America (MATOS, 1992, 1999).

Among the tectonic models proposed to explain the evolution of the interior basins, the NW distention stands out (MATOS, 1992, 1999). The proposed model shows that the Patos Shear Zone would have its west end terminated in a series of curved faults, forming a sigmoidal geometry. During the Neocomian, a general NW-SE distension reversed the originally transpressional faults to normal faults, which reactivated small segments of the Patos Shear Zone, thus originating the interior basins of Northeast Brazil.

In the Transversal Zone of the Borborema Province, E-W structural lineaments predominate, which tend towards a NE-SW direction. The sedimentary basins of Lavras da Mangabeira are located in this region of structural bending (VERÍSSIMO and AGUIAR, 2005).

The Lavras da Mangabeira Basin is located on the Precambrian basement of the Rio Piranhas Domain and Seridó Belt Rio Grande do Norte Domain, in both inserted in the Rio Grande do Norte domain of the Borborema Province (BRITO NEVES et al., 2000), north of the Central Domain - on the Rio Piranhas - on the Seridó. The sedimentary record of the Lavras da Mangabeira Basin includes three stratigraphic units belonging to the Lavras da Mangabeira Group: the Iborepi Formation (basal unit); Serrote do Limoeiro (upper unit); and basaltic rocks (Lavras da Mangabeira basalt).

The Iborepi Formation comprises poorly selected medium to coarse-grained sandstones, siltstones, and conglomeratic and massive sandstones with angular to sub-rounded grains and planar crossbedding (Figura 2A and 2B). Batista (2015) associated this formation with alluvial and intertwined fluvial fan systems.

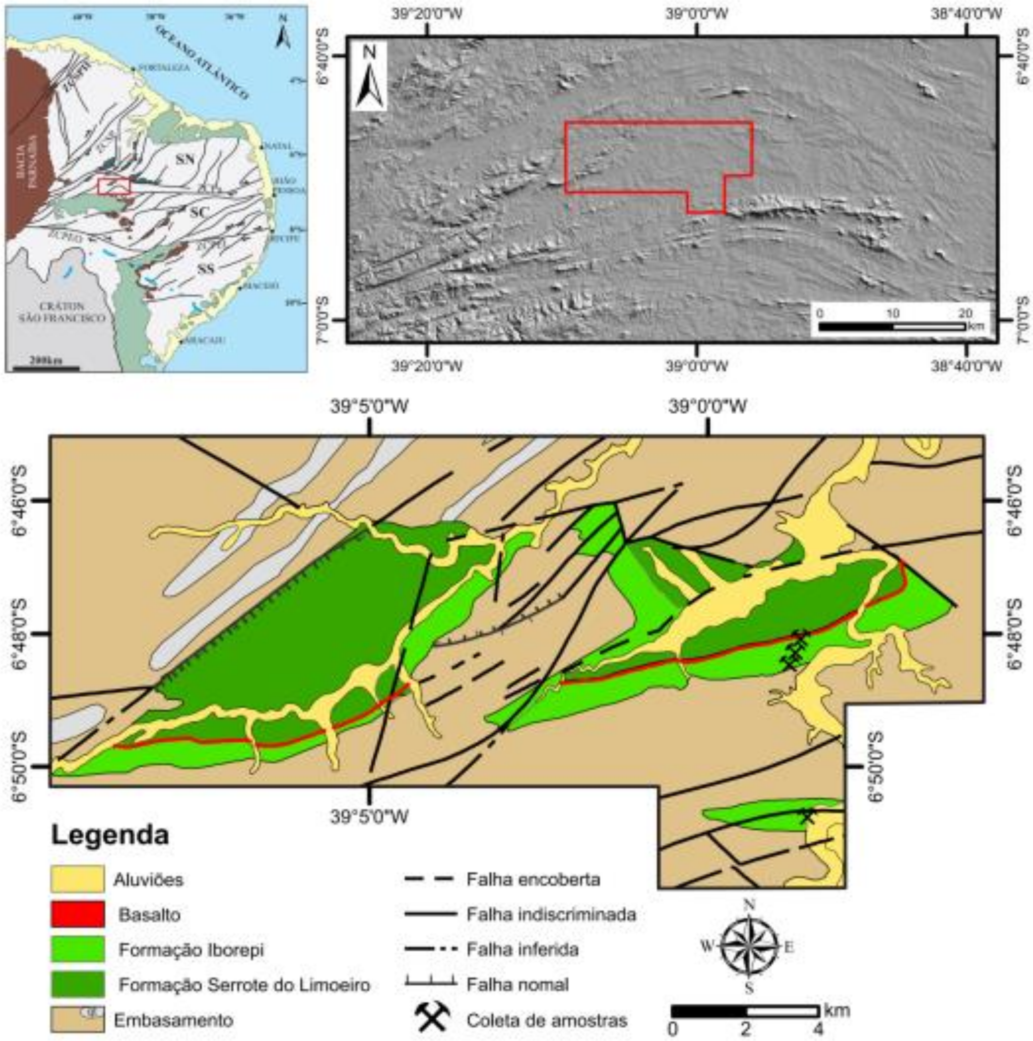

Figura 1 - A) Map of the interior sedimentary basins of Northeast Brazil, outlining (red rectangule) the Lavras da Mangabeira Basin (LMB)); B) Relevo sombreado (Modelo Digital de Terreno) da BLM; e C) Location of the Lavras da Mangabeira basins and of points where samples were colected. 1: Riacho do Rosário sub-basin; 2: Riacho do Meio sub-basin; 3: Iborepi sub-basin. *Modified after Assine (1992) and Veríssimo & Aguiar (2005).*

The Serrote do Limoeiro Formation comprises medium to fine-grained sandstones and well-selected siltstones, in addition to massive and planar cross-bedded claystones. The Lavras da Maangabeira basalts occur interspersed between the Iborepi and Serrote do Limoeiro formations (Figura 3).

3. MATERIAL AND METHODS

Nine thin sections were made for petrographic characterization of samples collected in three outcrops of the Iborepi Formation located in the south of the Lavras da Mangabeira Basin. These sections were vacuum-impregnated with blue epoxy resin according to the technique of Cesero et al. (1989), in order to better define and characterize the pores under the microscope.

Quantitative and qualitative descriptions were performed using a petrographic microscopy model O600P Opticam, with a transmitted and reflected light source and a digital camera attached. Three samples were analyzed using a scanning electron microscope coupled to an X-ray Dispersive Energy Detection System (EDS) and Wavelength Dispersion (WDS), Model SSX-550 SHIMADZU (voltage: 20kV), the samples were previously metalized with gold and carbon.

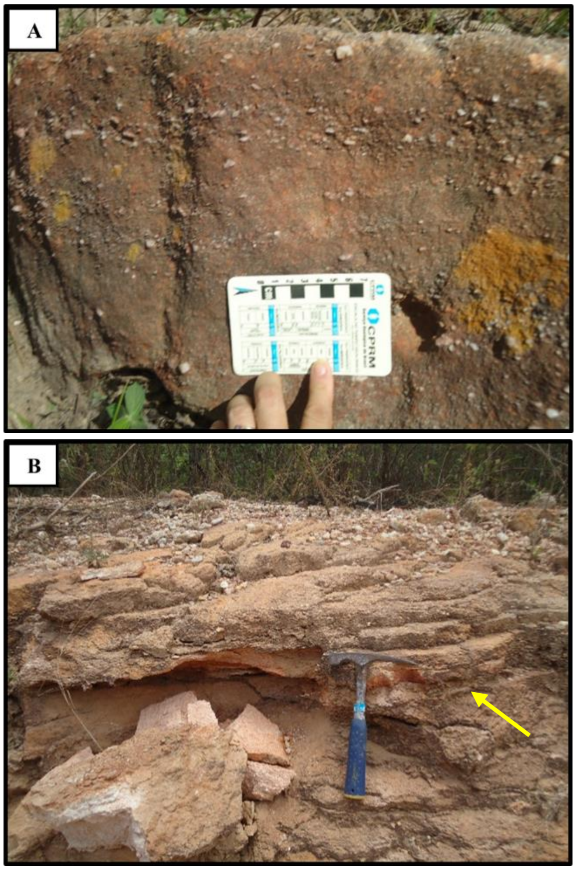

Figura 2 - Rocks from the Iborepi Formation: A) Massive conglomeratic sandstone with pebble levels; B) Coarse sandstone with planar cross-bedding (arrow).

Optical microscopy was carried out to determine the mineralogical composition and to describe aspects such as granulometry, roundness, sphericity, selection, matrix, cement, grain contacts, and porosity. 300 points per thin section were counted (framework, matrix, cement, and porosity) as suggested by Gazzi-Dickinson (cf. ZUFFA, 1985).

The granulometry, roundness, and grain selection were analyzed according to WENTWORTH (1922), TEIXEIRA et al. (2003), POWERS (1953), and LONGIARU (1987). For textural and mineralogical maturity, the criteria of Folk (1974) and Pettijohn (1975), respectively, were used. The mineralogical composition of detritic grains was determined after Folk (1968), which uses the total content of quartz, feldspar, and lithic fragments. The porosity volume (%) was determined through point-counting and visual estimation.

CRONO-ESTRATIGRAFIA	LITOESTRATIGRAFIA: Grupo	LITOESTRATIGRAFIA: Formação	SISTEMAS DEPOSICIONAIS	DESCRIÇÕES LITOLÓGICAS	ESPESSURA (M)
Quaternário	Sem denominação		Aluvial	Depósitos incosolidados: areias, siltes e argilas	0 a 5
Eo a Meso - Jurássico?	Grupo Lavras da Mangabeira	Fm. Serrote do Limoeiro	Fluvial meandrante, Planície fluvial, Lacustre raso	Arenito vemelhos e roxos finos a médios, friáveis, bem selecionados, caulínicos, estratificados em acamamento médio, intercalados com siltitos e argilitos vermelhos e folhelhos verdes, localmente fossilíferos.	em torno de 300
		Basalto Lavras da Mangabeira	Vulcânica	Basalto de textura subofítica, contendo palgioclásio, augita, hermatita e magnetita.	em torno de 10
		Fm. Iborepi	Leques aluviais coalescentes	Arenitos brancos, grossos a conglomeráticos, mas classificados, friáveis, com acamamento espesso e irregular, com estratificações cruzada.	60 a 80
Eo-Proterozoico	Grupo Ceará	Complexo Lavras da Mangabeira		Rochas metamóficas: filitos, micaxistos, intercaldos com quatizito e mármore; gnaisse.	

Figura 3 - Stratigraphy of the Lavras da Mangabeira Basin. Modified after Ponte et al. (1990); Veríssimo & Aguiar (2005).

X-ray diffraction analyses (XRD) were carried out on three rock samples to determine clay mineral assemblages. This technique allows the qualitative and semiquantitative identification of mineralogy in the fraction < 2μm, where clay minerals are concentrated. The XRD analyzes were performed at the X-Ray Laboratory of the Pernambuco Institute of Technology (ITEP). The rock samples were previously sprayed with a pestle on an agate mortar and then sieved using an ABNT 200 mesh sieve (0.75 mm opening). A Rigaku X-ray diffraction equipment, model Ultima, was used, operating at a 20 mA current and 40 kV voltage, using copper Kalfa radiation, with a goniometer speed of 2º per minute. Scans were performed between $2\theta = 2º$ and $2\theta = 100º$ for the analysis of in natura samples and in natura samples heated at 500ºC for 12 hours. Samples with glycosylation treatment were also analyzed by scanning between $2\theta = 2º$ and $2\theta = 15º$. Heating and glycosylation were performed to identify clay minerals from the 12Å to 15Å group (montmorillonite, chlorite, and vermiculite) and palygorskite, according to the criteria of WARSHAW and ROY (1961).

The rock porosity is calculated from the ratio between the volume of voids (pores) and the total volume, with its quantification in thin section obtained through modal and visual analysis and presented as percentages. The average porosity of the Iborepi sandstones was determined by the arithmetic mean of the porosities of each thin section (GESICKI et al., 2009).

The packing of the rocks was determined using the Kahn index (1956), which classifies the packing as loose, normal, and closed. This index refers to the arrangement of the grains with each other, with a more closed or more open framework, depending on the rock burial history, and is represented as a percentage.

4. RESULTS AND DISCUSSION

4.1. Mineralogy and Textures

The sandstones of the Iborepi Formation are composed of quartz (≤ 64%), feldspars (≤ 5%), lithic fragments (≤ 2%), and accessory minerals (<1%). Quartz occurs monocrystalline (Figura 4A) and polycrystalline, the latter being more frequent in coarse-grained sandstones. Feldspar occurs as microcline, orthoclase, plagioclase, and perthite (Figura 4B), frequently altered by diagenetic processes. The lithic fragments are metamorphic (gneiss and schist) and sedimentary (chert, Gig. 5A).

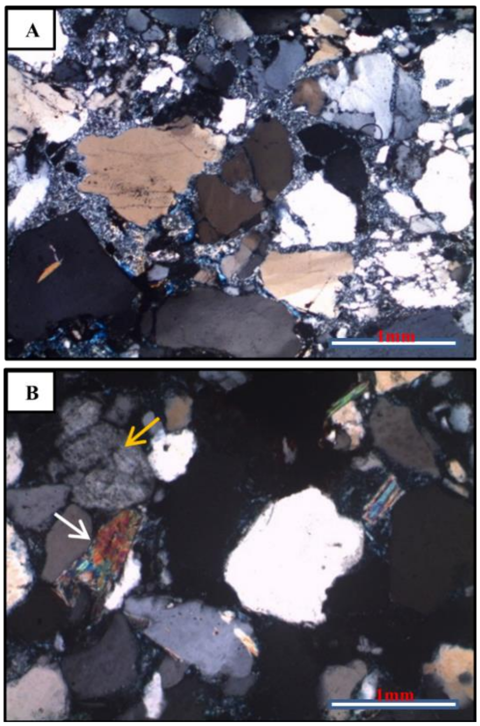

Figura 4 - Constituintes primários dos arenitos da Formação Iborepi: A) Grãos de quartzo monocristalino (PX); B) Feldspato microclínio fraturado e parcialmente alterado (seta laranja) e muscovita entre grãos (seta branca, PX).

The accessory minerals include muscovite (Figura 4B), opaque minerals, biotite, zircon, tourmaline, and rutile. Muscovite and biotite are commonly altered and replaced by kaolinite and chlorite, respectively; tourmaline and rutile are less common. The clay minerals comprise smectite, illite, kaolinite, interstratified illite-smectite, and traces of authigenic chlorite (Figura 5B), with the first two predominating.

The Iborepi Formation sandstones are poorly selected, with grains ranging from angular to sub-rounded, and of low sphericity. They present less than 5% of depositional matrix and, to a greater extent, infiltrated clayey matrix (>5%). They are texturally immature (Folk, 1974) and mineralogically mature (PETTIJOHN, 1975).

These rocks present a matrix-supported framework, with a normal and closed packing (Kanh index, 1956) of P = 42 and P = 56, respectively. The contacts are punctual, straight, concave-convex, and sutured; the punctual ones indicate shallow depths and low compaction (as depth increases, there is a progressive burial of the grains and a gradual change of contacts from long to concave-convex, and then sutured (BHUIYAN and HOSSAIN, 2020)).

According to Folk (1968), the sandstones of the Iborepi Formation were classified as quartzarenites and subarkoses (Figura 6).

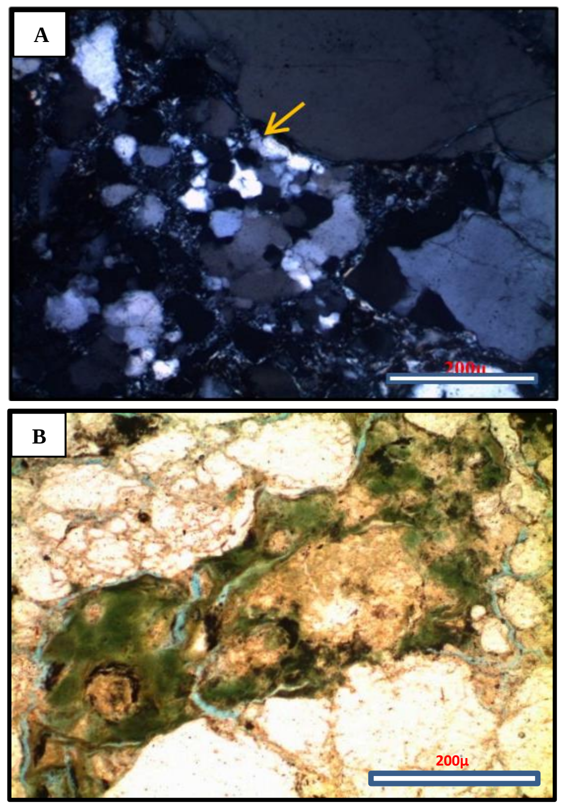

Figura 5 - Constituents of the Iborepi sandstones: A) Chert lithic fragment (arrow; XP); B) Authigenic chlorite (arrow, PP).

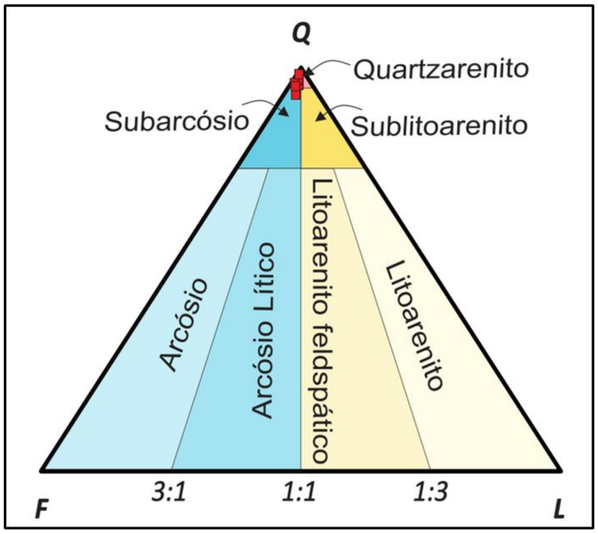

Figura 6 - Compositional classification of the Iborepi Formation sandstones, according to Folk (1968).

4.2. Porosity and Compaction

Most of the studied sandstones present a closed packing indicating strong compaction, mainly mechanical. Some samples, however, present a normal packing, with greater porosity, due to the lesser influence of compaction. The average porosity of these sandstones is 14% (Frame 1), with the intergranular primary porosity predominating (Figura 7A). Subordinately, a secondary intragranular porosity occurs, caused by dissolution and primary grain fractures (Figura 7B and C).

Frame 1 - Frame showing the porosity percentages of each sample analyzed.

Sample	Porosity (%)
1	20
2	13
3	11
4	14
5	13
6	15
7	15
8	9
9	18
Mean: 14,2%	

The dissolved constituents are primary, represented by orthoclase and plagioclase feldspar, monocrystalline quartz, and other unidentified grains (Figura 8A). Porosity by fractures is common in monocrystalline quartz (Figura 7C) and microcline and plagioclase (Figura 8B) but also occurs in lithic fragments. Secondary porosity due to shrinkage of smectite clay was also identified.

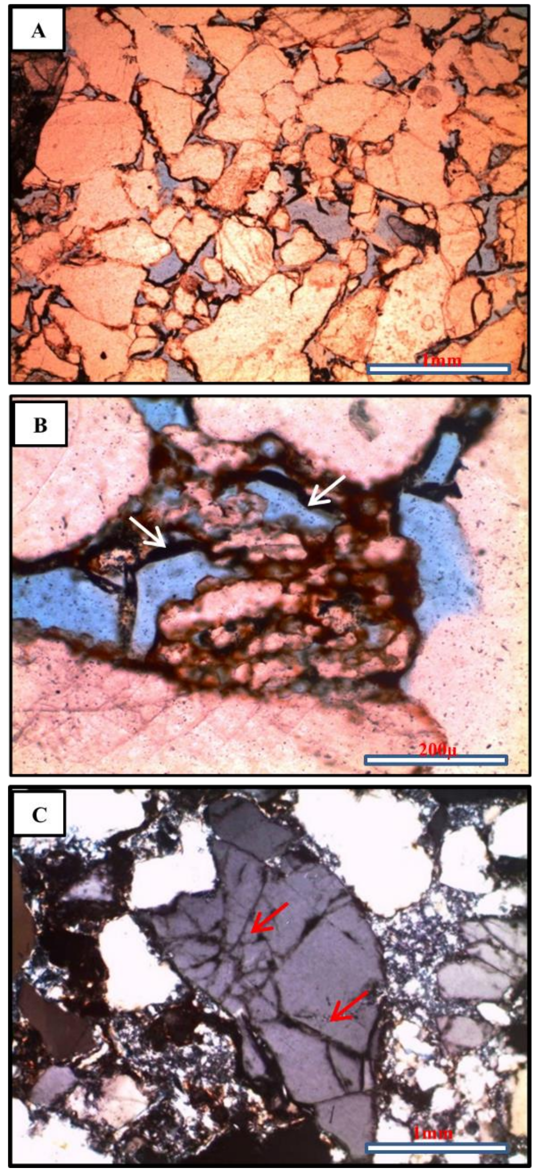

Figura 7 - Types of porosity: A) Intergranular primary porosity (blue; PP); B) Secondary porosity by partial dissolution of feldspar (arrows; PP); and C) Secondary porosity by the fracturing of a quartz grain (arrows, XP).

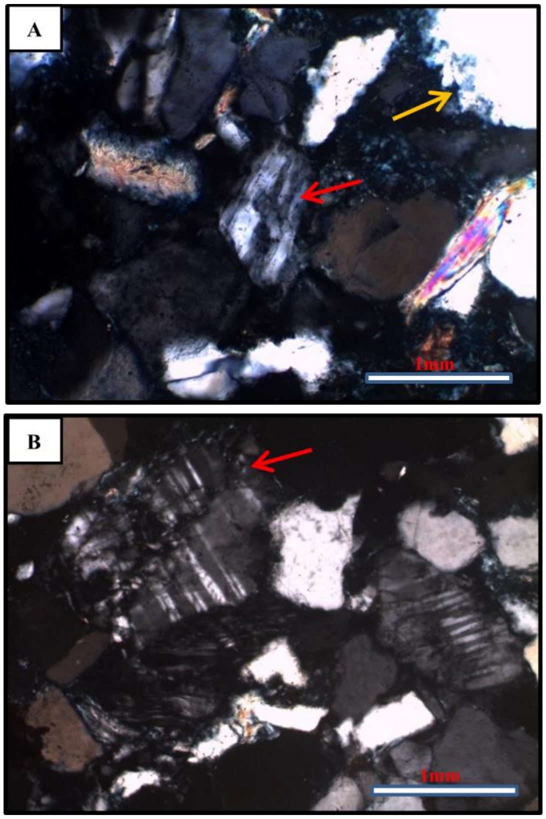

Figura 8 - Dissolved and fractured primary constituents: A) orthoclase and quartz grain undergoing dissolution (red and yellow arrows, respectively, XP); B) Fractured plagioclase grain (arrow, XP).

4.3. Diagenetic Processes

4.3.1. Mechanical Clay Infiltration

Infiltrated clay, an eodiagenesis process, occurs in the form of cuticles involving continuous and discontinuous grains, as interstitial microcrystalline aggregates obstructing much of the primary porosity (Figura 9A and B), and shrunken, originating secondary porosity.

They originate from waters of episodic river floods after long periods of drought. With the lowered water table, floods loaded with suspended cargo pass over the sediments, and large volumes of water infiltrate these deposits, thanks to the high permoporosity of the sands, supplying the water table (CAETANO-CHANG AND WU, 2003).

SEM analyzes along with WDS and X-ray diffractometry revealed that the clay minerals present in these sandstones are essentially smectite and, subordinately, kaolinite, illite (Figura 10 A and B), interstratified illite-smectite (Figura 9B)), and chlorite traces.

The in natura XRD analysis detected smectite by reflections of 16.08 Å (> peak) and 2.25 Å (< peak); reflections of 7.4 Å (> peak) and 2.56 Å (< peak) indicate kaolinite traces. After the glycosylation treatment the smectite, it presented a small displacement, with reflections of 17.0 Å. It was also possible to observe the presence of illite with a reflection of 9.88 Å, which did not appear in the in natura treatment.

The primary mineralogy of the shrunken clay probably comprises smectite, as it has shrinkage and detachment features, common in hydrated clay minerals such as smectite.

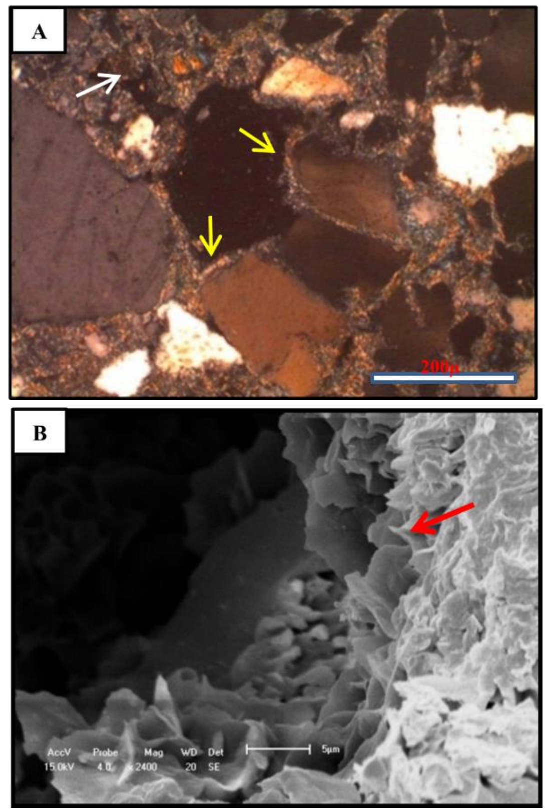

Figura 9 - Infiltrated clay: smectite/illite cuticle recovering grains (yellow arrows) and as microcrystalline aggregate (white arrow) (XP); and B) SEM image showing smectite recovering a grain (arrow), with evidence of illitization.

4.4. Compaction

Mechanical compaction in the analyzed sandstones was very active, causing the fracturing of rigid grains (quartz and feldspars), deformation of ductile grains forming a pseudomatrix, folding of micas between framework grains (Figura 11A), in addition to the close packing in some samples. This process occurs during eodiagenesis and, according to Worden et al. (2000a), the result of strong mechanical compaction depends mainly on the proportion of rigid and ductile grains.

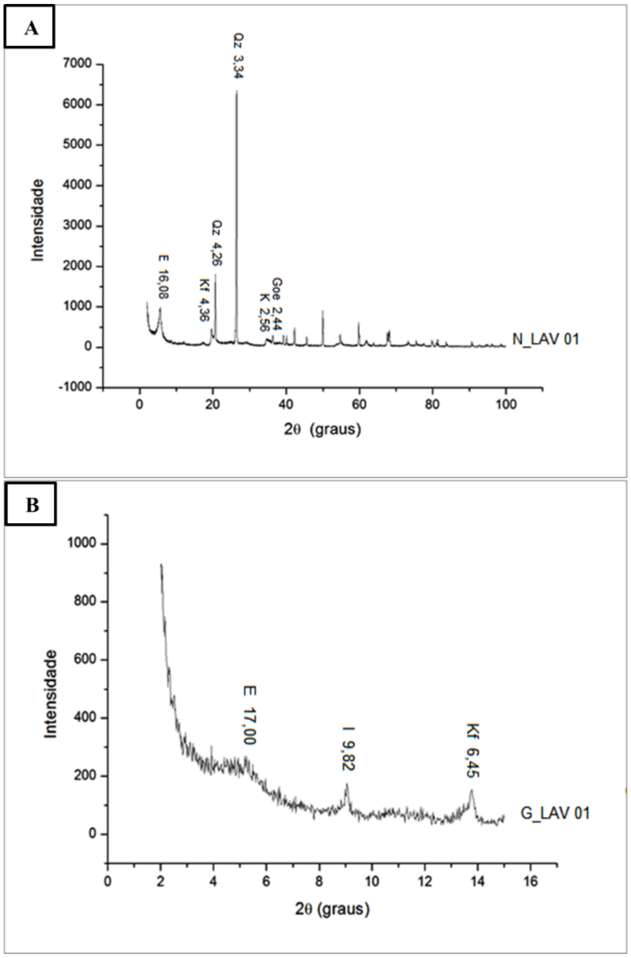

Figura 10 - Clay minerals: A) XRD without treatment (in natura); B) XRD with glycosylation *treatment.* ***Legend****: Qz – quartz; Kf – feldspar; E – smectite; I – illite; K – kaolinite; Goe – goethite.*

Chemical compaction, a process of mesodiagenesis that occurs with great burial, was less intense than mechanical compaction, causing the partial dissolution of feldspar and quartz in the center and edges of these grains and generating secondary porosity and concave-convex and sutured contacts.

4.5. Cementation

4.5.1. Iron Oxyde/hydroxide

This cement occurs as thin cuticles (coatings) surrounding the grains and constitutes the dominant cement. Subordinately, it occurs filling intergranular pores in most samples and is typical of telodyagenesis. These features indicate two phases of ferruginous cementation: cuticles covering quartz grains at the beginning of eodiagenesis (1); precipitation of this cement filling the intergranular pores in telodiagenesis (2).

X-ray diffraction (Figura 10A) revealed that this cement is made of goethite, which usually forms under oxidizing conditions as an alteration product of iron minerals such as hematite and biotite.

4.5.2. Authigenic Silicon

In most of the analyzed sandstones, cementation by authigenic silica occurs with secondary quartz growth (overgrowths) around quartz grains (Figura 11B), and as prismatic projections (outgrowths) (Figura 11C). This growth occurs continuously and discontinuously, suggesting two cementation phases: one before intense compaction, still in eodiagenesis (probably at the end); and another after intense compaction, during mesodiagenesis (greater sediment burial).

4.5.3. Kaolinite, Smectite, and Chlorite Precipitation

Kaolinite was identified in some samples and shows a lamellar habit, in the form of aggregates and as booklets, filling integral pores. Its precipitation is associated with the dissolution of unstable silicate grains due to the circulation of interstitial fluids (in eodiagenesis). It also occurs replacing minerals such as muscovite and feldspar (KETZER et al., 2003).

Smectite precipitation occurs continuously and discontinuously as fringes surrounding grains and may be related to alkaline fluids and the presence of feldspar, muscovite and heavy minerals, minerals suitable for alteration to clay minerals during continental eodiagenesis in arid climate conditions (KETZER et al., 2003; MCKINLEY et al., 2003; WORDEN and MORAD, 2003).

Chlorite cementation occurs in some samples filling pores, not very expressively, and as a product of alteration and biotite replacement. This cement is associated with the alteration of ferromagnesian minerals, and its precipitation is common in mesodiagenesis (KETZER et al., 2003).

4.6. Grain Dissolution

Dissolution, the main generator of secondary porosity, is a process in which a mineral is destroyed by interaction with fluid, leaving behind a cavity (WOLDEN and BURLEY, 2003).

In the analyzed sandstones, dissolution was relatively significant, occurring mainly in the primary constituents (feldspar (Figura 12A), quartz, micas, and other unidentified constituents). Feldspar was the most affected by dissolution, which is more frequent along with the cleavage and in the center of grains. In general, dissolution was predominantly partial and more effective in the center of the grains (Figura 12A), generating intragranular secondary porosity and pore widening.

4.7. Generation of Secondary Porosity

Secondary porosity can be generated by several factors, such as: partial or total dissolution of unstable grains in the rock framework, such as feldspars and lithic fragments; fracturing of rigid grains, when subjected to great pressures related to sediment burial; and shrinkage of clay minerals, when they undergo dehydration, resulting in loss of original volume.

In these sandstones, secondary porosity varies from small pores originated from the fracturing of rigid grains, such as quartz and feldspar (Figura 13B), to partial dissolution of feldspar (Figura 124A), in addition to clay shrinkage (Figura 13C).

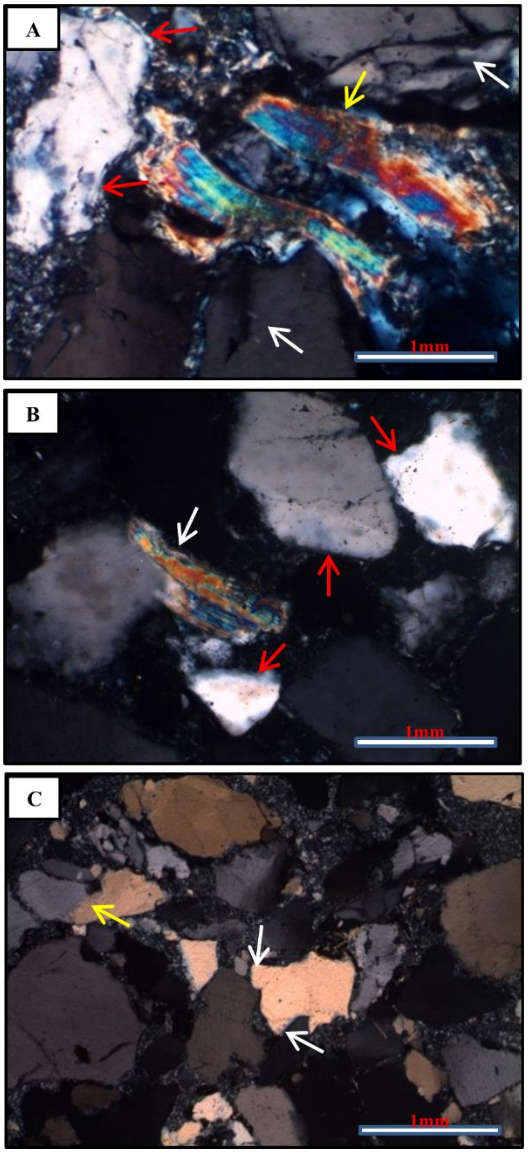

Figura 11 - Diagenetic Products: A) Muscovite folded between quartz grains (yellow arrow), fractured quartz grains (white arrows), with dissolution and secondary growth (red arrows) (PX); B) Secondary growth of quartz (red arrows) and inter-grain muscovite (white arrow) (PX); and C) Prismatic quartz projections (white arrows), and sutured contact between quartz grains (yellow arrow) (PX).

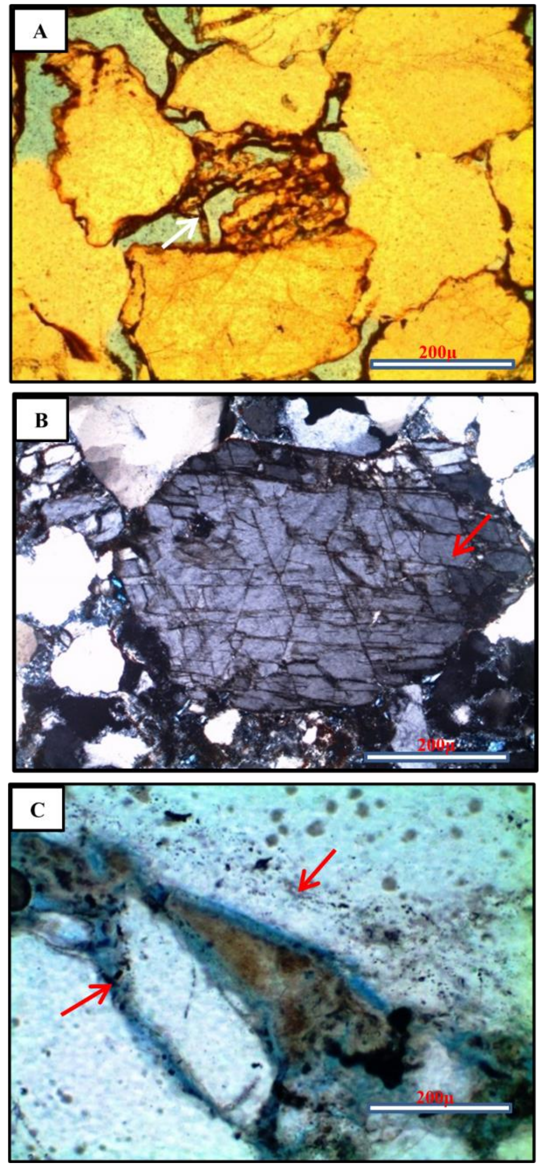

Figura 12 - Diagenetic products: A) partially dissolved feldspar generating secondary porosity (arrow, PP); B) Fracture of feldspar generating secondary porosity (arrow, PX); and C) Clay shrinkage (arrows) generating secondary porosity (PP).

4.8. Grain Alteration and Replacement

Grain alteration and replacement features affect potassium feldspar and muscovite. These minerals often occur altered and replaced by kaolinite and illite (Figura 13A and B), which appear in the expanded form, as lamellae, and as fringes and cuticles surrounding quartz grains.

There is also alteration and replacement of biotite to chlorite, due to the increase in clay mineral instability with increasing depth (COSTA ET al., 2014).

The exposure of feldspars to the eodiagenesis and mesodiagenesis stages likely caused its alteration, causing its partial or total dissolution, and/or its total kaolinization. The kaolinization of muscovite was recognized by the morphology of the open ends, similar to fans, in addition to separate lamellae.

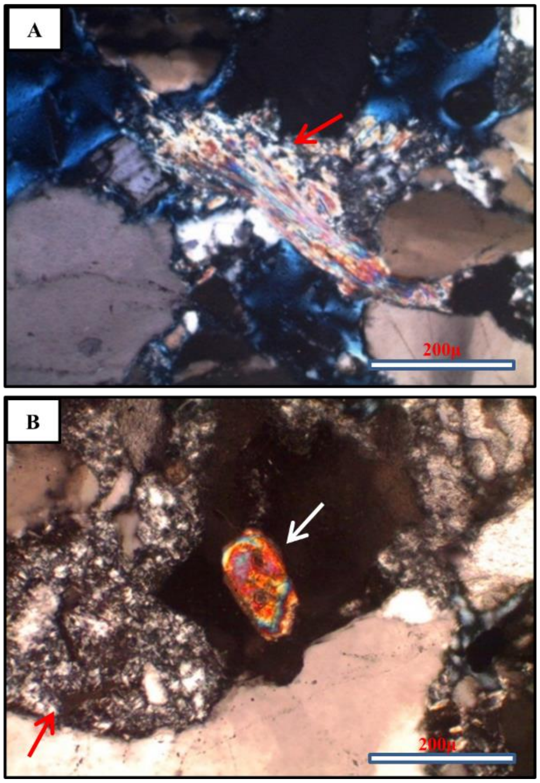

Figura 13 - Diagenetic products: A) partially dissolved feldspar, generating secondary porosity (arrow, PP); B) Fracture of feldspar generating secondary porosity (arrow, PX); and C) Clay shrinkage (arrows) generating secondary porosity (PP).

4.4. Discussion

The mineral composition of the Iborepi Formation sandstones is quartz-rich and poor in feldspar and heavy minerals, probably due to diagenetic processes (alteration and dissolution of unstable primary grains, and replacement by clay minerals), which modified their original composition (causing the predominance of quartzarenites).

The most active diagenetic processes and that most reduced the primary porosity of these sandstones are mechanical and chemical compaction, cementation, infiltrated clay, and grain replacement.

Compaction was the most active process and negatively impacted the primary porosity of these sandstones. Very fractured rigid grains, deformation of ductile grains, close packing, and concave-convex and sutured contacts suggest strong burial and intense mechanical and chemical compaction, causing reducing the original porosity of these rocks and their potential as a fluid reservoir.

According to Worden et al. (2018), compaction processes in mesodiagenesis are influenced by the burial rate, pressure, and the thermal history of the basin.

Cementation by iron oxide/hydroxide and authigenic silica constitutes the second diagenetic process that most impacted the primary porosity of the Iborepi sandstones. To a lesser extent, the loss of porosity was also due to cementation by kaolinite, smectite, and chlorite.

The main iron source of these sandstones may be associated with the dissolution of ferromagnesian minerals, such as biotite and hematite.

Quartz cement is the feature that most destroys the porosity of heavily buried sandstones (Worden & Morad 2000; Chudi et al., 2016) and it increases steadily as depth increases (CHUDI et al., 2016). This type of cement tends to crystallize with time, temperature, and grain size (WORDEN et al., 2018).

The infiltrated clay occurs predominantly as microcrystalline aggregates, destroying much of the original porosity of these sands and thus decreasing their potential as fluid reservoirs (oil, gas, and groundwater).

In the Iborepi sandstones, feldspar and muscovite replacement by kaolinite is common. Kaolinized muscovite occurs mainly expanded and as lamellae, indicating that its expansion occurred before significant compaction (KETZER et al., 2003; MORAD et al., 2010). The replacement of micaceous grains caused an increase in their volume, obstructing and reducing the primary porosity of the rock.

The scarcity of lithic fragments, feldspars, and unstable minerals such as amphibole, pyroxene, among others, suggests that these grains were dissolved by the percolation of under-saturated meteoric water (Morad, et al., 2000) in telodyagenesis.

The reaction of potassium feldspar with meteoric water may have generated, in addition to dissolution, its replacement by kaolinite. According to Morad et al. (2000), in proximal river sediments, the percolation of under-saturated meteoric waters causes the dissolution of detrital silicates, mainly lithic grains, feldspars, and micas, besides kaolinite precipitation.

Among the studied components, feldspar grains were the most susceptible to partial dissolution (BHUIYAN and HOSSAIN, 2020).

The petrographic analysis showed that the porosity of the Iborepi sandstones was more affected by compaction processes than by cementation. On the other hand, the porosity was more affected by cementation than by clay infiltration.

It is noteworthy that the reduction of porosity by compaction has an irreversible aspect, both upon the pore size and the pore geometry. In its turn, the cementation can act to preserve the framework during burial and, subsequently, favor porosity gain by dissolution.

The detrital composition of the studied sandstones also influenced the reduction of its porosity (Rodrigues & Goldberg, 2014), since sandstones with micaceous grains show greater porosity reduction due to mechanical compaction. In addition, many are replaced by kaolinite, obliterating porosity (RODRIGUES and GOLDBERG, 2014).

5. FINAL CONSIDERATIONS

The original composition of the Iborepi sandstones was significantly modified by diagenetic processes, resulting in quartz-rich rocks.

The diagenetic processes that most affected the primary porosity of these sandstones and, consequently, their quality as oil, gas, and groundwater reservoirs include mechanical and chemical compaction; ferruginous cementation; authigenic silica; cementation by kaolinite and smectite fringes (which, in pore throats, may have diminished the connection between them); and clay infiltration. The porosity of these rocks, however, was mainly destroyed by compaction.

These processes were responsible for damaging both porosity and permeability, due to the reduction of the pore space and obliteration of the pore throat. Furthermore, the loss of intergranular porosity also occurred due to the replacement of grains such as feldspar and micas.

The petrographic analysis revealed that the detrital composition also influenced the change in the original porosity of the Iborepi sandstones, as some unstable primary constituents were dissolved, generating cement, while others were replaced.

Despite having a reasonable porosity for fluid storage (average of 14%), the diagenetic processes upon the Iborepi sandstones impacted its quality as a reservoir.

6. REFERENCES

AL-RAMADAN, K; MORAD, S.; PROUST, J.N.; AL-AASM, I.S. Distribution of diagenetic alterations within the sequence stratigraphic framework of shoreface siliciclastic deposits: evidence from Jurassic deposits of ne France. *Journal of Sedimentary Research*, v. 75, p. 943-959, 2005.

ASSINE, M.L. Análise Estratigráfica da Bacia do Araripe, Nordeste do Brasil. *Revista Brasileira de Geociências*. v. 22, n. 3, p.298-300, 1992.

BATISTA, Z.V.; QUEIROZ, L.F.; AGOSTINHO, S.M.O. *Petrofácies Deposicionais dos Arenitos da Formação Iborepi, Bacia de Lavras da Mangabeiras*. In: CONGRESSO TÉCNICO CIENTÍFICO DA ENGENHARIA E DA AGRONOMIA (CONTECC) E 75ª SEMANA OFICIAL DA ENGENHARIA E DA AGRONOMIA (SOEA), 2018, Maceió - AL. Ciência, Inovação e Tecnologia. Campina Grande - PB: epgraf, 2018.

BATISTA, Z.V. *Caracterização faciológica, petrográfica e diagenética das sequências basais das bacias do Parnaíba, Araripe, São José do Belmonte e Lavras da Mangabeira*: contribuição às possíveis correlações dos arenitos basais e suas implicações geotectônicas. 2015. 236f. Tese (Doutorado em Geociências). Programa de Pós-Graduação em Geociências, Universidade Federal de Pernambuco, Recife-PE, 2015.

BHUIYAN, A.H.; HOSSAIN, S. 2020. Petrographic characterization and diagenetic evolution of reservoir sandstones from Smørbukk and Heidrun fields, offshore Norway. *Journal of Natural Gas Geosciences*, 5, 11-20. Online 27 January 2020. https://www.keaipublishing.com/jnggs.

BRITO NEVES, B.B., SANTOS, E.J., AND VAN SCHMUS, W.R. Tectonic history of the Borborema province, northeastern Brazil, in Cordani, U. G. et al., eds., *Tectonic evolution of South America*, 31ST INTERNATIONAL GEOLOGICAL CONGRESS. p. 151–182, 2000.

CAETANO-CHANG, M.R., WU, F.T. Diagênese de arenitos da Formação Pirambóia no Centro-Leste Paulista. UNESP, *Revista Geociências*, v. 22, n. especial. São Paulo. p. 33-39, 2003.

CHUDI, O.K.; LEWIS, H.; STOW, D.A.V. & BUCKMAN, J.O. Reservoir quality prediction of deep-water Oligocene sandstones from the west Niger Delta by integrated petrological, petrophyscial and basin modelling. *In*: Armitage, P.J., Butcher, A. et al. (eds) *Reservoir Quality of Clastic and Carbonate Rocks: Analysis, Modelling and Prediction*. Geological Society, London, Special Publications, 435. First published online December 14, 2016, https://doi.org/10.1144/ SP435.8.

CESERO, P.; MAURO, L.M.; DE ROS, L.F. Técnicas de preparação de lâminas petrográficas e de moldes de poros na Petrobrás. *Boletim de Geociências da Petrobrás*, n.3, p. 105-116, 1989.

COSTA, A.B.S.; CÓRDOBA, V.C.; JARDIM DE SÁ, E.F.; SHERER, C.M. Diagênese dos arenitos da tectonossequência rifte na Bacia do Araripe, NE do Brasil. *Brazilian Journal of Geology*, v. 44, n. 3, p. 457-470, 2014.

FOLK, R.L. *Petrology of sedimentary rocks*. Hemphill Publishing Company, Austin, TX, USA. 1974. 182p.

FOLK, R.L. *Petrology of sedimentary rocks*. Austin, Texas, Hemphill's, Pub., 1968. 107p.

FOLK, R. L. Stages of Textural Natury in Sedimentary Rocks. 1951. *Journal of Sedimentary Petrology*, 21, 127-130.

GESICKI, A. L. D., SAYEG, I. J., CURTI, D. K, BOGGIANI, P. C., GIANNINI, P. C. F. Determinação quantitativa de parâmetros texturais de arenitos eólicos através de análise de imagens digitais de seções delgadas. 2009. *Revista Brasileira de Geociências,* 39 (2): 267-275.

GRANJEIRO M.L.; SANTIAGO, M.M.F.; FRISCHKORN, H.; VIDAL SILVA, C.M.S.; MENDES FILHO, J. *Influência do Ambiente Sedimentar na Qualidade das Águas Subterrâneas da Bacia Sedimentar no Município de Lavras da Mangabeira, Ceará*. In: XV CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS. Natal. 2008.

KAHN, J.S. The analysis and distribuition of the proprerties of packing in sand size sediments. *Journal Geology*, v. 64, n.4, 385-395, 1956.

KETZER, J.M.; MORAD, S.; AMOROSI, A. *Predictive diagenetic clay-mineral distribution in siliciclastic rocks within a sequence stratigraphic framework*. In: Clay Mineral Cements in Sandstones, International Association of Sedimentologists Special Publication 34 (Ed. by R.H.

Worden and S. Morad), Blackwell Publishing, Oxford, p. 43–61, 2003.

LONGIARU, S. 1987. Visual Comparators for Estimating the Degree of Sortting from Plane and Thin Section. *Journal of Sedimentary Petrology*, 57, 791-794.

Matos, R.M.D. History of the Northeast Brazilian Rift System: Kinematic implications for the breakup Brazil and West Africa. In: Cameron, N.R., Bate, R.H., Clure, V.S. (eds.). *The oil and gas habitats of the South Atlantic*. Geological Society of London, Special Publications, London, v. 153, p.55-73, 1999.

Matos R.M.D. The Northest Brasilian Rift System. *Tectonics*, v. 11, p. 776-791, 1992.

MCKINLEY, J.M.; WORDEN, R.H.; RUFFELL, A.H. *Smectite in sandstones: A review of the controls on occurrence and behaviour during diagenesis*. in: Worden, R. H., Morad, S. (Eds.), Clay Cements in Sandstones. International Association of Sedimentologists Special Publications, Blackwell Scientific Publications, Oxford, UK, n. 34, p. 109–128, 2003.

MORAD, S.; KETZER, J.M.; DE ROS, L.F. Linking diagenesis to sequence stratigraphy: an integrated tool for understanding and predicting reservoir quality stribution. In: Morad, S.; Ketzer, J. M.; De Ros, L. F. *Linking Diagenesis to Sequence Stratigraphy*. IAS Special Publication 45. Chichester, UK: International Association of Sedimentologists. Wiley-Blackwell, p.1-36. 2012.

MORAD, S.; AL-RAMADAN K., KETZER, J.M. & DE ROS, L.F. The impact of diagenesis on the heterogeneity of sandstone reservoirs: a review of the role of depositional facies and sequence stratigraphy. *American Association of Petroleum Geologists Bulletin*, v. 94, 1267–1309, 2010. https://doi.org/10.1306/04211009178.

MORAD S., KETZER .J.M.; DE ROS L.F. Spatial and temporal distribution of diagenetic alterations in siliciclastic rocks: implications for mass transfer in sedimentary basins. *Sedimentology*, v. 47. 1-27, 2000.

MORAES, M.A.S.; SURDAM R.C. Diagenetic heterogeneity and reservoir quality: fluvial, deltaic, and turbiditic sandstone reservoirs, Potiguar and Reconcavo rift basins, Brazil: *AAPG Bulletin*, v. 77, p. 1142–1158, 1993.

PETTIJOHN, F.J. *Sedimentary Rocks*, 3rd Ed., 1975. 628p.

PONTE, F.C.; DINO, R.; ARAI, M. E SILVA-TELLES JR. A.C. DA. Geologia das bacias sedimentares de Lavras da Mangabeira e do remanescente sedimentar do Rio dos Bastiões, no Estado do Ceará, Petrópolis, RJ, 1990. *PETROBRAS-CENPES-DIVEX-SEBIPE*.

POSAMENTIER, H.W; ALLEN, G.P. 1999. *Siliciclastic sequence stratigraphy concepts and applications*. SEPM, 1999, n. 7, 216p.

POWERS, M. C. 1953. A new roundness scale for Sedimentary Particles. *Journal of Sedimentary Petrology*, 23, 117-119.

QUEIROZ, L.F.; BATISTA, Z.V.; LIMA FILHO, M.F. *Caracterização Petrográfica e Diagenética dos Arenitos da Formação Iborepi, Porção Sul da Bacia de Lavras da Mangabeira*. In: 9º CONGRESSO BRASILEIRO DE P&D EM PETRÓLEO E GÁS, 2017, Maceió-AL, 2017. v. 5. p. 222-229.

RODRIGUES, A.G.; GOLDBERG, K. Primary composition and diagenetic patterns of sandstones from Barra de Itiúba Formation in Atalaia High, Sergipe Sub-Basin. *Brazilian Journal of Geology*, v. 44, n. 4, p. 545-560, 2014.

ROSSI, C.; MARFIL, R.; RAMSEYER, K.; PERMANYER, A. Facies-related diagenesis and multiphase siderite cementation and dissolution in the reservoir sandstones of the khatatba formation, gypt's western desert. *Journal of Sedimentary Research*, v. 71, p. 459-472, 2001.

TEIXEIRA, W.; TOLEDO, M.C.M. DE; FAIRCHILD, T.R.; TAIOLO, F (Orgs.). *Decifrando a Terra*. Oficina de textos. São Paulo. 2003. 558p.

VERÍSSIMO, L. S. & AGUIAR, R. B. *Comportamento das bacias sedimentares da região semi-árida do Nordeste brasileiro. Hidrogeologia da bacia sedimentar de Lavras da Mangabeira*. Fortaleza: CPRM/FINEP, 2005. 36 p. il.

WARSHAW, C.; ROY, R. Classification and scheme for the identification of layer silicates. *Geological Society of America Bulletin*, v. 72, 1455–1492, 1961.

WENTWORTH, C. K. 1922. A scale of grade and class terms for clastic sediments. *Journal Sedimentary Petrology*, 30, 377-392.

WORDEN, R.H.; ARMITAGE, P.J.; BUTCHER, A.R.; CHURCHILL, J.M.; CSOMA, A.E.; HOLLIS, C.; LANDER, R.H.;OMMA, J.E. 2018. Petroleum reservoir quality prediction: overview and contrasting approaches from sandstone and carbonate communities. In: ARMITAGE, P.J.; BUTCHER, A.R.; CHURCHILL, J.M.; CSOMA, A.E.; HOLLIS, C.; LANDER, R.H.; OMMA, J.E. & WORDEN, R.H. (eds.). *Reservoir Quality of Clastic and Carbonate Rocks: Analysis, Modelling and Prediction*. London: Geological Society, Special Publications, 435. First published online 01, 2018, http://doi.org/10.1144/SP435.21.

WORDEN, R. H. & MORAD, S. Clay minerals in sandstones: controls on formation distribution and evolution. In: Worden, R. H. & Morad, S. (Eds.). *Clay minerals cements in Sandstones*, International Association of Sedimentologists Special Publication 34 (Ed. by R.H. Worden and S. Morad), Blackwell Publishing, Oxford, p. 109–128, 2003.

WORDEN, R.H. & BURLEY, S.D. 2003. Sandstone diagenesis: the evolution from sand to stone. In: Burley, S.D. & Worden, R.H. (eds) *Sandstone Diagenesis, Recent and Ancient*.

International Association of Sedimentologists Reprint Series, Oxford, 3–44.

WORDEN, R.H., MAYALL, M.J. & EVANS, I.J. The effect of ductile–lithic sand grains and quartz cement on porosity and permeability in Oligocene and Lower Miocene clastics, South China Sea: prediction of reservoir quality. *American Association of Petroleum Geologists Bulletin*, 84, 345–359, 2000a.

WORDEN, R.H. & MORAD, S. 2000. Quartz cementation in sandstones: a review of the key controversies. *In*: Worden, R.H. & Morad, S. (eds) *Quartz Cementation in Sandstones*. International Association of Sedimentologists, Special Publications, oxford, 1–20.

ZUFFA, G.G. Optical analysis of arenites: influence of methodology on compositional results. In: Zuffa G.G. (ed.). *Provenance of Arenites*. Dordrecht, Germany, D. Reidel Pub. Co. 1985. p.165-189.

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