

Petrological meaning of ethnostratigraphic units: Laminated Limestone of the Crato Formation, Araripe Basin, NE Brazil

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Abstract. The Crato Formation, NE Brazil, consists of laminated limestones deposited in a lacustrine environment during the Early Cretaceous. The Nova Olinda Member, the lowest unit of the Crato Formation, is world-famous for their exceptionally well-preserved fossils. The Nova Olinda limestones have been economically exploited for centuries. Today, this commercial excavation still represents the main economic activity in the region. During the mining process, the quarry workers have developed an informal stratigraphic nomenclature to individualize the different beds in the quarries. The local workers recognize the succession as "lajão dos sete cortes", "matracão", "lajão branco", "pão de milho", "veio da paiba", "veio doidão", "lajão amarelo" and "veio do besouro". Here, we used principles of ethnostratigraphy to verify the origin and validity of these informal stratigraphic nomenclatures by classifying them as ethnostrata. For this, we applied a detailed petrographical analysis with thin sections and high-resolution X-ray techniques to characterize each ethnostratum. Our results suggest possible linkages between informal and formal stratigraphic nomenclatures in Nova Olinda Member. Finally, this study showed that ethnostratigraphy can be applied as an auxiliary tool in stratigraphic studies, in both, as an initial exploratory approach and as enhancing the relationship between the geologists and the local community.

Keywords. Araripe Basin, Ethnostratigraphy, Nova Olinda Member, X-ray techniques, petrography

Resumo. SIGNIFICADO PETROLÓGICO DAS UNIDADES ETNOESTRATIGRÁFICAS: CALCÁRIO LAMINADO DA FORMAÇÃO CRATO, BACIA DO ARARIPE, NE BRASIL. A Formação Crato, NE do Brasil, consiste em calcários laminados depositados em um ambiente lacustre durante o Cretáceo Inferior. O Membro Nova Olinda, unidade mais basal da Formação Crato, é mundialmente famoso por seus fósseis extremamente bem preservados. Os calcários de Nova Olinda têm sido economicamente explorados há séculos. Atualmente, essa escavação comercial ainda representa a principal atividade econômica da região. Durante o processo de mineração, os mineiros empregam uma nomenclatura estratigráfica informal para individualizar as diferentes camadas das pedreiras. Os trabalhadores locais reconhecem a sucessão como "lajão dos sete cortes", "matracão", "lajão branco", "pão de milho", "veio da paiba", "veio doidão", "lajão amarelo" e "veio do besouro". Neste trabalho, nós utilizamos princípios da etnoestratigrafia para verificar a origem e a validação das nomenclaturas estratigráficas informais, as classificando como etnoestratos. Para isso, aplicamos análises petrográficas em seções delgadas e técnicas de raios x de alta resolução para caracterizar cada etnoestrato. Os resultados sugerem possíveis links entre as nomenclaturas estratigráficas informais e formais no Membro Nova Olinda. Finalmente, esse estudo demonstra que a etnoestratigrafia pode ser utilizada como uma ferramenta auxiliar em estudos estratigráficos, atuando tanto como uma abordagem exploratória inicial como realçando a relação entre geólogos e a comunidade local.

Palavras-chave. Bacia do Araripe, Etnoestratigrafia, Membro Nova Olinda, técnicas de raios x, petrografia

1 Introduction

The Crato Formation contains an extraordinary wealth of well-preserved non-marine fossils and offers important insights into Early Cretaceous biota from the Gondwana. The laminated limestones of the Nova Olinda Member, which represent the lowermost and thickest limestone horizon of the Crato Formation, hosts many species of insects, fish, pterosaurs, birds, turtles, crocodiles, crustaceans, lizards, dinosaurs, and plants (Kellner, 1996; Martill *et al.*, 2007; Pinheiro *et al.*, 2012; Warren *et al.*, 2017; Pinheiro *et al.*, 2019). The laminites of the Nova Olinda Member are attributed to a lacustrine system deposited under microbial influence (Catto *et al.*, 2016; Warren *et al.* 2017). The excellent preservation of Crato fossils have been made it known worldwide as a Fossil *Konservat-Lagerstätte* (Wilby & Martill, 1992; Kellner, 1996; Pinheiro *et al.*, 2012; Barros *et al.*, 2019; Bezerra *et al.*, 2020).

Despite being a source of exceptionally preserved fossils, the finely laminated limestones of the Nova Olinda Member are quarried extensively probably since historic times (Moraes *et al.*, 2020). The easy way in which the laminated limestones split allows its commercial exploitation as building stone, paving slabs and table tops, popularly called *Pedra Cariri* (Vidal & Padilha, 2003; Moraes *et al.*, 2020). This commercial activity is the main source of income for the local people (Vidal *et al.*, 2011). The Nova Olinda, Santana do Cariri and Tatajuba municipalities have numerous quarries excavating the Crato laminites. The Nova Olinda municipality stands out for the quarries working upon Nova Olinda Member. After some field observations and interviews with local workers, we found out the existence of a traditional identification system of laminated limestone beds in “Talhado do Idemar” quarry, Nova Olinda, Ceará (Fig. 1).

The high-fidelity preservation of the Nova Olinda fossils has attracted a high number of paleontological studies dealing mainly with the systematic and taxonomy (Saraiva *et al.*, 2009; Prado *et al.*, 2016). However, little is known about the detailed stratigraphy of laminated limestone beds and the distribution of its macrofossil content. The existence of a robust relationship

between certain fossil groups and specific beds would yield a series of opportunities for new taphonomical and paleoenvironmental discoveries in the Crato Formation.

This study aims to investigate the feasibility of using an informal lithostratigraphic procedure (ethnostratigraphy) to describe the petrological and paleontological characteristics of beds within the Nova Olinda succession. Here, we proposed to test the bases of the informal stratigraphic subdivisions developed by the quarry workers, and then verify if this system could guide upcoming paleoenvironmental studies in the Crato fossil-*Lagerstätte*.

2 Materials and methods

2.1 Area

The Araripe Basin occupies part of the Brazilian states of Ceará, Pernambuco, Paraíba and Piauí, with an area of about 9.000 km² (Ponte & Ponte Filho, 1996), of which more than 50% are over the Ceará territory. This basin is nestled in the Precambrian terrains of the Transversal Fold Zone of Borborema Province, bordered by Patos shear zone, on the northern edge, and Pernambuco shear zone, southern edge (Matos 1999). These shear zones correspond to ancient dextral lineaments which have conditioned both installation and fragmentation of the basin (Matos, 1999). Structurally, the Araripe Basin is divided by grabens and half-grabens grouped into two main sets of the *Feira Nova* and *Cariri* sub-basins separated by Dom Leme High (Matos, 1992; Ponte & Ponte Filho, 1996).

The most remarkable geomorphological feature of the Araripe Basin is the *Chapada do Araripe*, a tableland with heights up to 900 m bordered by abrupt erosional scarps, where the Mesozoic deposits are exposed (Assine, 2007). Araripe plateau stands out in the landscape with its E-W oriented and smoothly inclined westwards relief. The Cariri Valley consists of sedimentary deposits distributed mainly on the east and northeast flanks of the Araripe plateau (Assine, 2007).

The sedimentary evolution of the Araripe Basin was strongly controlled by extensional tectonics following the opening of the South

Atlantic Ocean during the Early Cretaceous (Ponte & Appi, 1990; Assine, 1992; Ponte & Ponte Filho, 1996; Assine, 2007; Assine *et al.*, 2014; Custodio *et al.*, 2017). Araripe Basin stratigraphic framework consists of megasequences generated during the rift and post-rift stages. The Aptian post-rift I sequence (Assine, 2007) corresponds to the Santana Group, which includes, in upward succession, the Barbalha, Crato, Ipubi and Romualdo Formations. This group represents the apex of the thermal subsidence of the basin during the Cretaceous. The post-rift I megasequence is composed by three depositional sequences (DSs) that compose the Santana Group (from the base to the top): DS 1 related to the lower portion of Barbalha Formation; DS 2 related to the upper portion of Barbalha Formation and the entire Crato and Ipubi formations; and DS 3 related to the Romualdo Formation (Assine *et al.*, 2014).

The Crato Formation comprises a series of laminated limestone beds (Neumann, 1999) interbedded with sandstone, marls and claystones divided into four members (from the base-to-top): Nova Olinda, Caldas, Jamaracú and Casa de Pedra (Martill & Heimhofer, 2007). The Nova Olinda Member (Fig. 1) is composed exclusively by laminated limestones and represents the *Fossil Lagerstätte* that is the focus of the present work.

The authors opted to use a mix of three different lithostratigraphic proposals employed in the Araripe Basin stratigraphic framework (Martill & Heimhofer, 2007; Assine *et al.*, 2014; Custódio *et al.*, 2017). This compilation is presented on figure 2.

2.2 Ethnostratigraphy – general concepts

The ethnostratigraphy lies within the broader context of ethnoscience. According to Sturtevant (1964), ethnostratigraphy is the study of knowledge and cognition systems of traditional cultures, in order to allow their meaning by a robust methodological procedure. Therefore, we used concepts from ethnostratigraphy to organize geological strata based on traditional information (popular culture).

Stratigraphy is a discipline that focuses on the description of rock successions and their interpretation in terms of a general time

scale (Holz, 1998; Rohn, 2010). The term ethnostratigraphy was originally proposed, according to the International Stratigraphic Guide (Salvador, 1994), as being a sedimentary unit of archeological content (Gasche & Tunca, 1983; Stein, 1990, 2008; Brown III & Harris, 1993; Stein & Holliday, 2017). Resolutions such as relative-age based on the law of superposition are often used in essentially all archaeological excavations. However, an archaeological excavation site may contain hundreds of superimposed sediment layers, or built structures such as ceramic pieces, foundation walls, streets etc, and it is difficult to attest to their contemporaneity with the sediments. Flemming (2010) suggested that the term ethnostratigraphy has a low archeological applicability, since it does not have a well-defined classification archeological standard, as in the biostratigraphy, which is based on fossil content. The prefix *ethno* is generally used to refer to the culture, *latu sensu*, being closely related to the ethnography concept. Since the methodology used in data acquisition was based on ethnographic surveys, the authors applied the ethnographic term to a new connotation: the study of traditional or lay identification system of geological beds, mentioning that as ethnostratigraphy.

Stratigraphic contexts that lead to the use of informal classification over the formal ones are generally characterized by lithological monotony and absence of discontinuities. In such way the North American Commission on Stratigraphical Nomenclature (NACSN, 1983) denominated informal stratigraphic procedures as “parastratigraphic approaches”. The revised version of this code (NACSN, 2005: pp. 1560) eliminated the former term in favor of “informal units”. The Brazilian Stratigraphic Code (Petri *et al.*, 1986) is also complacent with the use of informal terms. Overall, these terms are used for scientific or economic reasons, but maintaining the previous denomination. In this study, we proposed to investigate Crato quarry beds based on informal stratigraphy. Hence, informal geologic units are designated by ordinary nouns, adjectives, or geographic terms; and lithic or unit terms that are not capitalized (NACSN, 2005: pp. 1560).

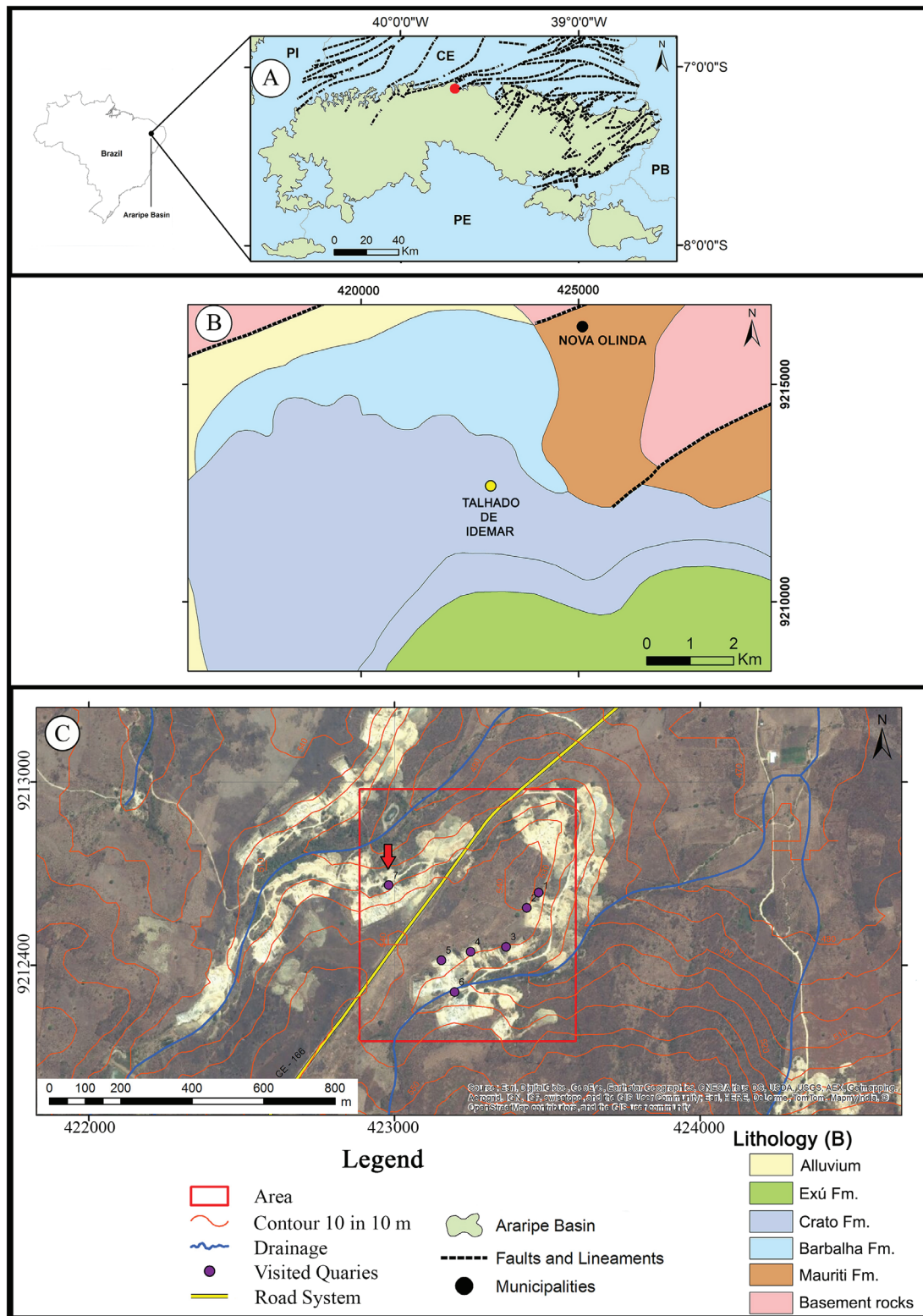


Figure 1. Geological setting of the study area. A) Geotectonic context (faults and lineaments) of the Araripe Basin (green) (PI = Piauí; CE = Ceará; PB = Paraíba and PE = Pernambuco); B) Local geological map; C) Location map of the "Pedra Cariri" quarries that were visited during the data collection. Highlight for the red arrow representing the "Talhado do Idemar" (UTM - WGS84 - 422980/9212662) (Fm. = Formation; Gp. = Group).

Figura 1. Geologia local da área de estudo. A) Contexto geotectônico (falhas e lineamentos) da Bacia do Araripe (em verde) (PI = Piauí; CE = Ceará; PB = Paraíba e PE = Pernambuco); B) Mapa geológico local; C) Mapa de localização das pedreiras de Pedra Cariri que foram visitadas durante a coleta de dados. Destaque para a seta vermelha que representa o Talhado do Idemar (UTM - WGS84 - 422980/9212662) (Fm. = Formação; Gp. = Grupo).

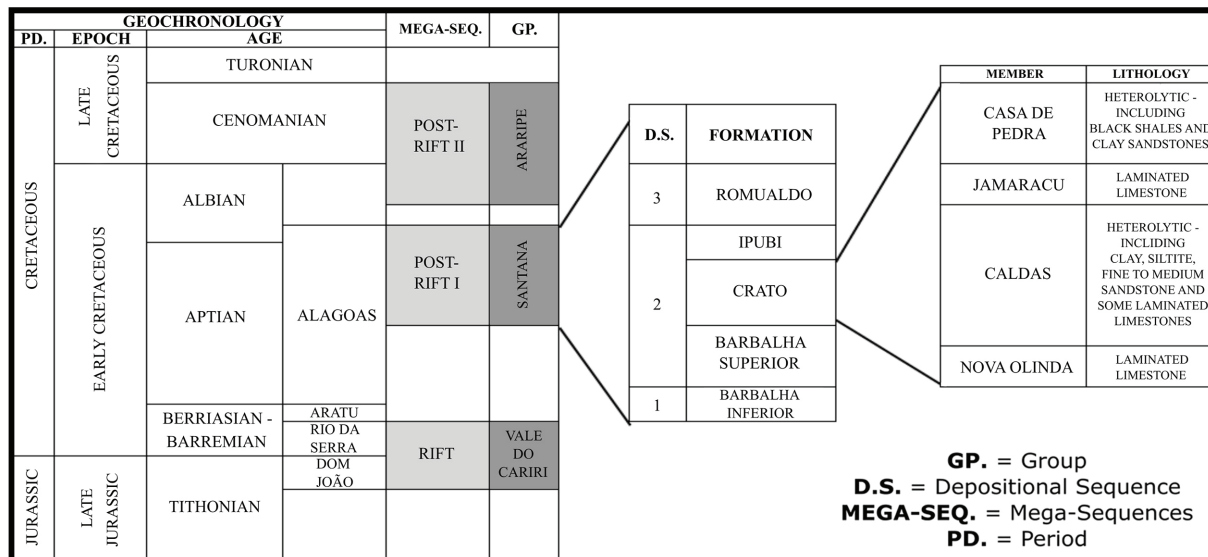


Figure 2. Lithostratigraphic framework of the study area (Adapted from Martill & Heimhofer, 2007; Assine et al., 2014 and Custódio et al., 2017).

Figura 2. Estrutura litoestratigráfica da área de estudo (Adaptada de Martill & Heimhofer, 2007; Assine et al., 2014 e Custódio et al., 2017).

2.3 Ethnostratigraphic terms

Ethnostratum: represents a stratum with an informal nomenclature conjectured by the quarry workers.

Ethnostrata: represents a set of ethnostratum.

2.4 Sample's acquisition

Although seven quarries have been prospectively visited, this investigation was carried out in the Talhado do Idemar quarry (UTM - WGS84 - 422980/9212662). The Talhado do Idemar quarry has better exposure where several limestone beds can be easily accessed.

This study set about questioning two quarry workers with about ten years of experience on the Nova Olinda quarries. With their support we identified the basal and top limits of each ethnostratum of the mining front from the "capa", first explored laminated limestone layer, to the "lajão dos sete cortes", the last one (in terms of commercial exploitation not stratigraphic). The quarry workers classify the laminated limestone layers according to their physical properties (e.g. color and tenacity) and fossil content (e.g. "piaba"

and "besouro"). That is why we applied the term ethnostratum here to define such layers. All the layers were measured, in meters. Eleven samples were collected, one from each ethnostratum (Fig. 3). The samples were analyzed utilizing a petrographic macroscopic (natural transmitted and polarized light), X-ray diffractometry (XRD) and X-ray fluorescence (XRF).

Some ethnostrata described have parallelism with those described by Moreira (2009), such as: "capa", "lajão dos peixes" (here "veio da piaba"), "matracão" and "pedra azul" (here "lajão dos sete cortes") (see Chart 1). These ethnostrata were basically the same of those described in the study performed by Félix (2017). Thus, this ethnostratigraphic model is considered valid as a starting point for future in-depth approaches. The possible uncertainty in traditional nomenclature does not invalidate the petrographic results, because its location on Nova Olinda Member is independent of the ethnostratum. Lastly, as suggested in the International Stratigraphic Guide (ISSC, 2010), descriptive meaning nouns (Chapter 3, Section A.5.b) and lowercase words (Chapter 3, Section B.4.i) have been maintained as ethnostrata designation, since they are informal units.

2.5 Petrographic analyses

Among the eleven analyzed ethnostrata, four ("lajão dos sete cortes", "embombado", "pão de milho" and "veio do besouro") were chosen to perform petrographic analyses. They were prepared at Laboratório de Laminação (LAMIN) of the Departamento de Geologia of the Universidade Federal do Ceará (UFC). The thin sections were made following the De Césaro *et al.* (1989) and Rocha Filho *et al.* (2018) guidelines. After that, we described them using the petrographic microscopes NIKON H 550S from the Fundação Núcleo de Tecnologia Industrial do Ceará (NUTEC) and from the Laboratório de Microscopia Eletrônica (LME) of the Departamento de Geologia of the UFC, both with natural transmitted and polarized light, including image capture.

2.6 X-ray fluorescence and x-ray diffractometry analyses

For the XRF and XRD analyses we take out around two grams of each ethnostratum sample. These samples were macerated with the aid of a pistil mortar until the clay size (≤ 0.064 mm, below 200 mesh), in order to optimize the analytical results (Hedges *et al.* 2006). This procedure was conducted in Laboratório de Geotécnica e Prospecção (LAGETEC) of the UFC.

The X-ray diffraction patterns were obtained using a Rigaku powder diffractometer in a Bragg-Brentano geometry. The Co-K α radiation was used and operated at 40 kV and at 25 mA. XRD measurements were taken into the 2θ range of 10–90°, using the step scan procedures (0.02°) with a counting time of 5 s.

The X-ray fluorescence spectroscopy was performed using a ZSX Mini II equipment from Rigaku, operating with a Pb tube, using a power of 40 kV $\times$ 1.2 mA. The XRD and FRX analyses were performed at the Laboratório de Raios-X of the Department de Física of the UFC.

The XRF and XRD data treatment was made by Highscore Plus and Origin (data analysis and graphing softwares). In order to reduce the background generated by the XRD data, we used the Inorganic Crystal Structure Database (ICSD). The Rietveld refinement was performed in all the analyzed samples to refine the theoretical

line profile until it matches the measured profile (McCusker *et al.*, 1999). According to McCusker *et al.* (1999), the structures should be refined to convergence. The maximum shift/estimated standard deviations (e.s.d) in the final cycle of refinement should be no more than 0.10. All parameters (profile and structural) were refined simultaneously to obtain correct estimated standard deviations. It was sought to use the convergences the weighted-profile R (R_{wp}) and statistically expected R (R_{exp}) between 10 to 20%, beyond μR as close as 1 as possible, because according to McCusker *et al.* (1999), if μR was larger than 1, the simple form of the absorption correction is no longer valid and a more sophisticated correction is needed. For more details about R values see McCusker *et al.* (1999), section 11.

The ethnostratigraphic survey results were then compared to petrographic, mineralogical and chemical analysis, allowing the identification of particular characteristics of each ethnostratum.

3 Results

"Lajão" or "veio/veia" are informal denominations used by quarry workers to nominate the different laminated limestone strata observed in Talhado do Idemar quarry' fronts. Nine main ethnostrata were individualized in the Talhado do Idemar quarry, Nova Olinda, Ceará. Their discrimination is based on distinctive characteristics such as color, tenacity and chemical composition. They are (from base-to-top): "lajão dos sete cortes", "matracão" (subdivided into "caroço" and "embombado"), "lajão branco", "pão de milho", "veio da piaba", "veio doidão", "lajão amarelo", "veio do besouro" and "capa". Nevertheless, the contacts between the different ethnostrata are inaccurate, being difficult to recognize them without the quarry worker's assistance. These terms are explained in Chart 1, and their stratigraphic distribution can be seen in figure 3.

At hand scale, all the collected samples range from grayish (Hue 2.5 Y - 8/4) to beige (Hue 2.5 Y - 7/6) (Munsell Color Charts - Pendleton & Nickerson, 1951; Thompson *et al.*, 2013) calcilutite (Folk, 1959) with indistinct to flat lamination.

Chart 1. Glossary with some ethnoterms used at this work. F3 Code = Codification presented in figure 3
 Quadro 1. Glossário com alguns dos etnotermos utilizados neste estudo. F3 Code = Código presente na figura 3.

Ethnoterm	Translation/Meaning	Explanation/Observation	F3 Code
“Capa”	Cap	Upper layers of quarry fronts; not quarried due their fragile nature.	10
“Caroco”	Lump	Level with silica nodules.	2
“Embombado”	Without translation	Something like “lumpy”.	2
“Lajão”	Big slab	A “lajão” usually has around 0.1 m thick that represents the cutting depth of mobile saws (“policorte”). Plural: “lajões”.	-
“Lajão amarelo”	Yellow big slab	Yellowish color.	8
“Lajão do bacalhau”	Codfish big slab	“Bacalhau” is the denomination of the adult form of “piaba”, the traditional term for little fossil fishes (<i>Dastilbe</i>).	6
“Lajão branco”	White big slab	Whitish coloration when compared to the rest of the exposed limestone.	5
“Lajão doidão”	Very crazy big slab	The designation is explained by the fashion of breaking: randomly (due to high angle micro fractures?); not well defined by lamination.	7
“Lajão dos peixes”	Fishes big slab	Same as “veio da piaba”.	6
“Lajão dos sete cortes”	Seven cuts big slab	Set of light grey strata also described as “Pedra Azul” by the quarrymen. At the Talhado do Idemar, it is exploited until 70 cm depth bellow its top, comprising seven “lajões” till the groundwater is reached.	1
“Matracão”	Without translation	In the context of the Araripe Plateau, it is traditionally used to designate hard carbonatic/silicic layers, relative sterile in fossils; can also be used for layers of similar nature among the Romualdo Formation’s mudstones (Fara et al., 2005).	3
“Pão de milho”	Corn bread	Beige coloration.	5
“Pedra azul”	Blue stone	Same as “lajão dos setes cortes”.	1
“Talhado”	Quarry front	The main study spot was “Talhado do Idemar”. “Idemar” is the first name of the owner of the quarry.	-
“Veio/veia”	Vein (male and female forms, respectively)	Refers to an individual lamination. Thus, “lajão” is a set of “veios/veias”. However, these denominations may be used as synonyms.	-
“Veio do besouro”	Beetle vein	Relative to the insect fossils’ abundance.	9
Veio da piaba	Little fish vein	“Piaba” is a traditional term for little fishes. Paleontologically, this term refers to young stages of <i>Dastilbe</i> , a very common fossil of Nova Olinda Member; sometimes it can also be named as “lajão do bacalhau”.	6

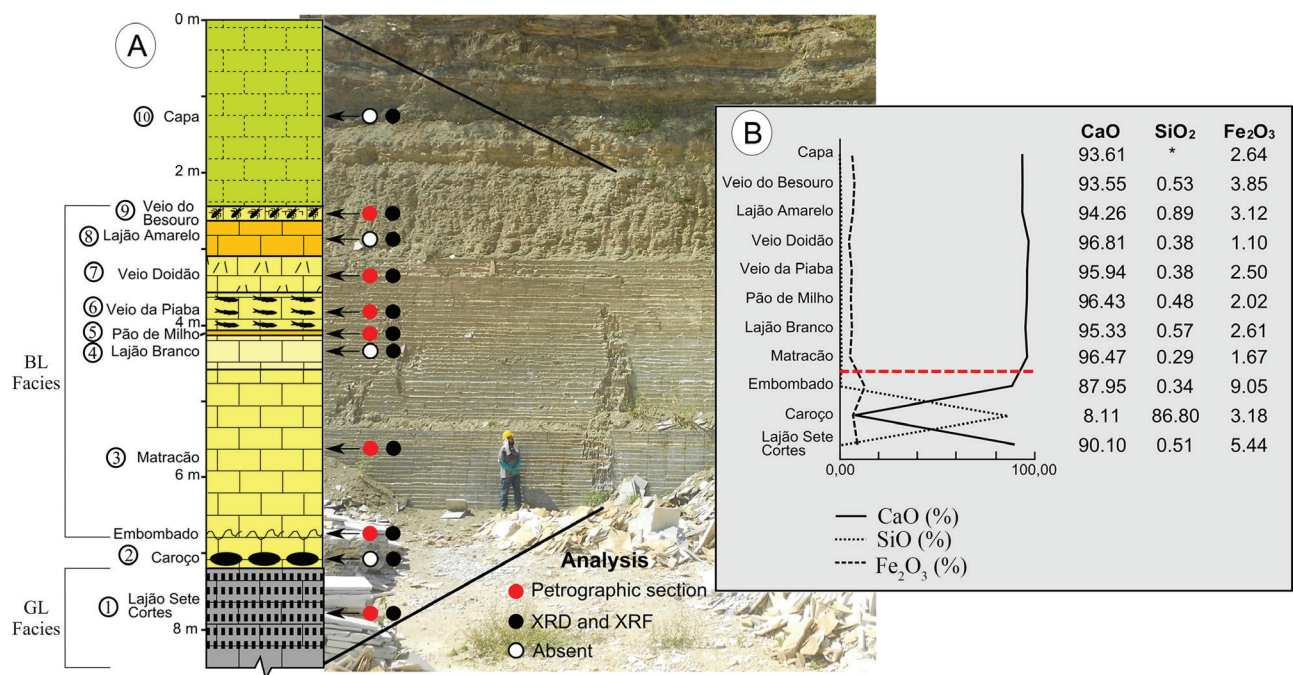


Figure 3. Quarry front in the Crato Formation showing ethnostrata. A) Columnar section of the laminated limestones of "Talhado do Idemar" locality with its ethnostrata and sampling sites identification; B) Main oxides (CaO, SiO₂ and Fe₂O₃) variation profiles. Possible discontinuity between "embombado" and "matracão" ethnostratum (dotted red line), based on sismoslumps identification in "embombado" layer, that could mark changes in the vertical movements rate of lake's substratum.

Figura 3. Frente de pedra na Formação Crato mostrando os etnoestratos. A) Seção colunar do calcário laminado da localidade Talhado do Idemar com seus etnoestratos e com a identificação dos pontos amostrados; B) Perfis de variação dos principais óxidos (CaO, SiO₂ e Fe₂O₃). Possível descontinuidade entre os etnoestratos "embombado" e "matracão" (linha hachurada em vermelho), com base na identificação de sismoslumps na camada "embombado". Estes podem demarcar mudanças nas taxas de movimentação vertical do substrato lacustre.

3.1 "Lajão dos sete cortes"

The "lajão dos sete cortes" (Fig. 3) is the lowermost bed of the Nova Olinda Member limestone. Its minimum thickness is around 0.70 m (the base of this "lajão" was not observed), but *in situ* measurements indicate that the basal part of the Nova Olinda Member, at least at Talhado do Idemar quarry, is around 1.0 m deeper (total thickness up to 1.7 m).

This bed represents a rhythmic calcilutite displaying millimetric and sub millimetric laminae varying in color from gray to pale beige. The sub millimetric lamination is parallel and displays millimetric to sub millimetric elliptical features (pellets or fenestral infillings - see thin section description). The alternating sets containing millimetric parallel and sub millimetric ripples, has about 0.01 m thick. The sub millimetric lamination's surface has a predominance of elongated, sometimes curved, structures bearing positive angle of almost 0.01 m long per a

couple of millimeters wide. It can resemble to algae filamentous replacements (these are the "fenestrae" in a crosscutting perspective). The surface of parallel lamination is devoid of algae filamentous remnants (at least at hand specimen scale).

In thin section, this sample exhibited around 1% of allochemical grains, with 15 simple peloids, one composite pellet and three charcoal fragments (Fig. 4C), the longest being around 0.9 mm long. These charcoal fragments are consistent with the macroscopic field observations and previous studies (e.g. Félix, 2017; De Lima *et al.*, 2019), which attests that is easy to find carbonized fossil wood in the "lajão dos sete cortes". The matrix is predominantly composed by microspathic calcite (~ 85%) with 0.02 mm average size; spathic grains, that represents ~ 5% of the matrix, occur filling fenestral voids. The lamination is notoriously crenulated and can be identified by Fe oxyde-hydroxydes (possibly with Mn, ~ 9%), as can be seen in figures 4A and B.

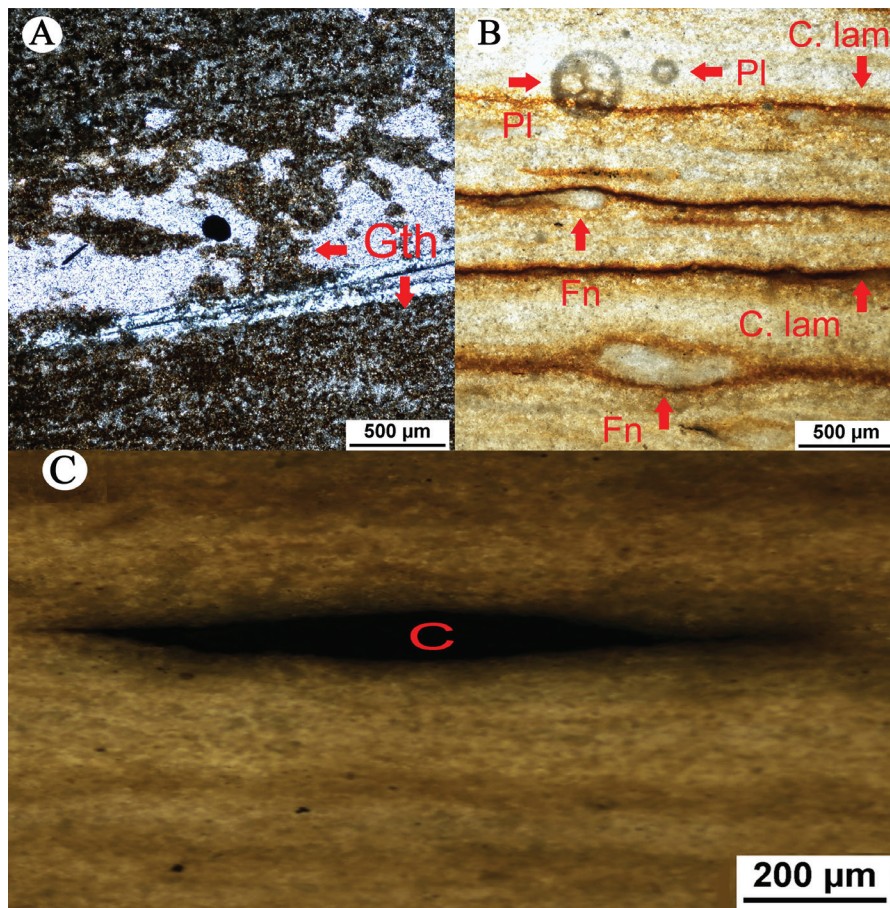


Figure 4 Thin section of the "lajão dos sete cortes" ethnostratum. A) Goethite (Gth) in polarized light (PL); B) Crenulated lamination (C. lam) marked by Fe oxide (darker), with fenestra (Fn) and some peloids (PI) in natural transmitted light (NL); C) Charcoal (C) fragment in natural transmitted light (NL).

Figura 4. Seção delgada do etnoestrato "lajão dos sete cortes". A) Goetita (Gth) em luz polarizada (LP); B) Laminações crenuladas (C. lam) marcadas por óxido de Fe (coloração mais escura), com fenestras (Fn) e alguns pelóides (PI) em luz natural transmitida (LN); C) Fragmentos de charcoal em luz natural transmitida (LN).

The XRF results of the "lajão dos sete cortes" revealed the second highest percentage of Fe_2O_3 (5.44%) and MnO (1.54%) of the studied section (Supplementary Material). These results are similar to the "embombado" level (few decimeters above). The CaO content (90.10%), probably related to microspathic calcite, is not as high as the overlying the "matracão" ethnostratum and the Al_2O_3 and SiO_2 (aluminosilicates) content are very low (0.20% and 0.51%, respectively), as SO_3 (0.32%) (Supplementary Material). XRD values, for this ethnostratum, are lying near the maximum margin of error of this method. Therefore, XRD identification phases were not treated for this ethnostratum.

The quarry workers recognize the "lajão dos sete cortes" by its high mechanical resistance. Because of that, these layers are the most commercially exploited in the Nova Olinda quarries.

3.2 "Matracão"

The "matracão" is a 3.25 m thick bed (Fig. 3) that is extremely lithified. This lithification is probably due to the high CaCO_3 content and discontinuous nodular concretions at the basal level (Chart 1). Some of these "nodules" are domic and silicified ("caroço"). The silicified levels (including "caroço") are beige to yellow, with some red to brown parts due to iron oxide ("embombado"), measuring about 0.60 m thick.

The "matracão" displays wave ripple lamination calcilutites similar to those of the "lajão dos sete cortes". These microripples are associated to algae filamentous remains, especially at the dome structures. According to the quarry workers, "matracão" usually occurs as four limestone lenses. When these lenses are stuck together, they become very resistant to the exploitation ("cutting"). However, when

they are not completely fused, it is possible to explore them commercially. This unit has high CaO (96.47%) content, besides minor quantities of MnO (0.88%) and Fe_2O_3 (1.67%). It was confirmed by the CaCO_3 (ICSD – 28827), probably associated to the microspathic calcite and $[(\text{Ca}, \text{Fe}, \text{Mg}), \text{CO}_3]$, ICSD – 31336, which could be related to dolomitic phases, XRD phases which respectively represents 88.50% and 11.49%.

Macroscopically, the “caroço” has peculiar characteristics of low potential of hydrochloric acid reaction and extremely lithified (its surface cannot be scratched by a pocket knife). However, this lens still preserves the limestone laminations. These field observations were corroborated by the XRF analysis, with high SiO_2 values (86.80%) and low CaO (8.11%). The XRD results show quartz (SiO_2 /ICSD – 31288) as the dominant phase (99.12%).

The “embombado” (or also “caroço”) consists of a 0.6 m thick brownish (Hue 2.5 Y – 4/3) limestone lens, interdigitated at the base of “matracão”. According to Félix (2017), this

name comes from its irregular surface that resembles a “bubble-filled” area. It is a laminated micritic limestone that has plane-parallel laminae, sometimes deformed, in asymmetric to recumbent and somewhat irregular folds with local constancy of vergence, possibly associated to sismoslumps (Montenat *et al.*, 2007). The “embombado” has levels where the coloration is darker (Hue 2.5 Y – 6/4), probably due to organic matter, as previously suggested by Neumann *et al.* (2003).

At hand scale, the laminated limestone is predominantly microspathic, with 70% of neoformed crystals (average: 0.03 mm), 10% of micrite and 5% of spathic calcite filling the fractures. The allochemicals comprise less than 1% of the rock and are dominated by simple peloids. The “embombado” lens exhibits a considerable amount of oxydes and hydroxydes, such as goethite, hematite and limonite in its cementation matrix (~15%). Incipient occurrences of anatase and pyrite pseudomorphs can also be recorded (Fig. 5).

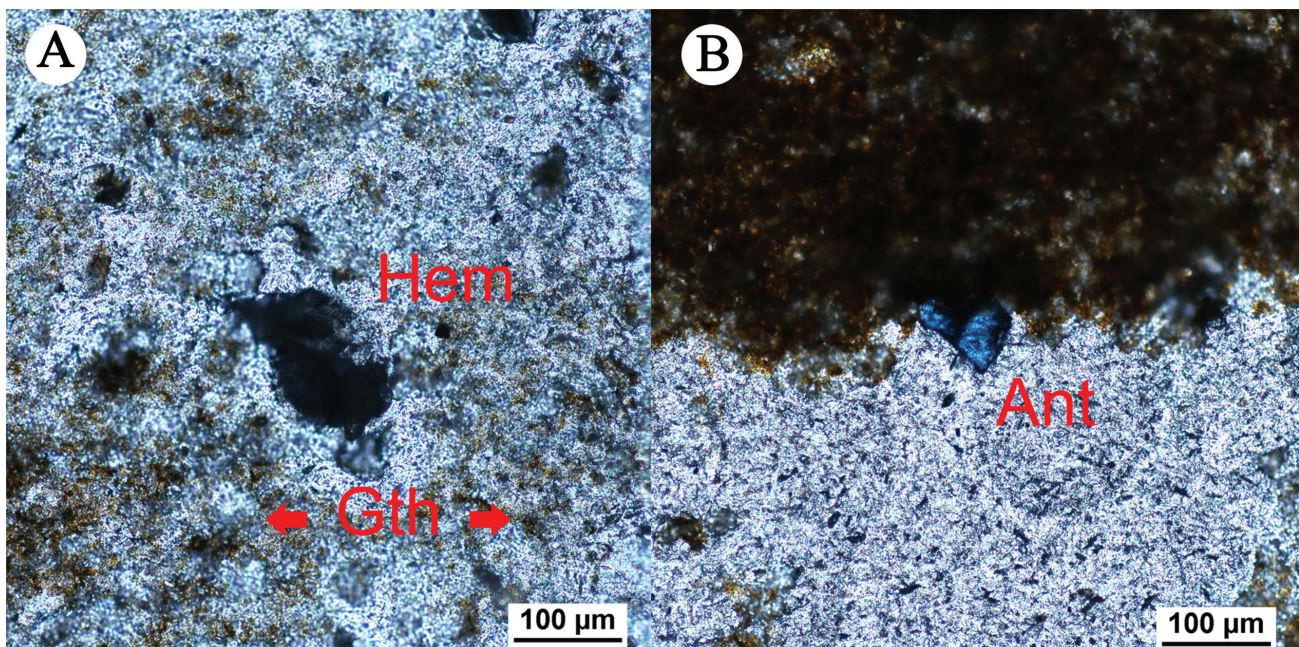


Figure 5. Thin section of the “embombado” ethnostratum. A) Hematite (Hem) and goethite (Gth) crystals in natural transmitted light (NL) (on the left); B) Anatase (Ant) crystal with bevelled contour in parallel nicols in natural transmitted light (NL).

Figura 5. Seção delgada do etnoestrato “embombado”. A) Cristais de hematita (Hem) e de goetita (Gth) em luz natural transmitida (LN); B) Cristal de anatásio (Ant) com contorno chanfrado à nicóis paralelos em luz natural transmitida (LN).

The XRF analysis of the “embombado” revealed relatively lower CaO content (87.95%) when compared to other ethnostrata. In addition, this lens (‘embombado’) presents the highest levels of Fe_2O_3 (9.05%) and MnO (2.15%) (Supplementary Material), probably related to oxi-hydroxides and clay minerals formed during the telodiagenesis.

The XRD analysis identified dolomite [$[\text{Ca}, \text{Mg}], (\text{CO}_3)_2$], ICSD – 86161 and ankerite [$[\text{Ca} (\text{Fe}, \text{Mg}), (\text{CO}_3)_2$], ICSD – 100417 phases, differing from the XRF results by the Mg presence (Supplementary Material 1). The dolomite phase represents 87.39% of the treatment's result, while the ankerite phase represents 12.61%.

3.3 “Lajão branco”

The “lajão branco” represents sets of laminated calcilutites with about 0.20 m thick (Chart 1 and Fig. 3). It exhibits grayish and whitish levels at the base with occasional occurrences of manganese dendrites. The whitest levels are concentrated at the top of this bed. It has impressions of algae filaments (Warren *et al.*, 2017).

The “lajão branco” sample exhibits high levels of CaO (95.33%), Fe_2O_3 (2.61%) and MnO (0.67%), similar to “matracão” (Chart 1). The XRD data revealed two phases: CaCO_3 , ICSD – 28827 (microspathic calcite) and $[\text{Ca} (\text{Fe}, \text{Mg}), (\text{CO}_3)_2]$, ICSD – 100417 (dolomitic phases) with 95.80% and 4.42%, respectively (Supplementary Material).

3.4 “Pão de milho”

The “pão de milho” ethnostratum (Chart 1 and Fig. 3) has about 0.05 m thick and is the thinnest unit of this section. This stratum consists of finely laminated calcilutites, where parallel-laminated limestones are whitish and sets bearing wave ripples are yellowish. According to the quarry workers, this carbonate level offers the highest “cutting strength”. Its matrix is mostly microspathic (~80%) with spathic grains filling microfractures (0.6 to 0.7 mm of spacing). Goethite is present as cementation matrix in

this unit (~10%). An anatase crystal and some fenestra filling by organic matter or iron oxide were found. The allochemical content represent ~3% of sample, mostly peloids (34 simple and 2 compounds), with 3 possible phytoclasts occurrences.

High contents of CaO (96.43%, Mn (0.69%) and Fe (2.02%) were detected. The only phase identified by XRD analysis was CaCO_3 (ICSD – 28827) (microspathic calcite), of around 100%, which validates the XRF results (Supplementary Material).

3.5 “Veio da piaba” or “Lajão do bacalhau”

The “veio da piaba” or “lajão do bacalhau” (Chart 1 and Fig. 3) is possibly the most laterally extended ethnostratum of the Nova Olinda Member with 0.45m thick, being recognized up to 30 km away from the Talhado do Idemar (Silva Filho, personal communication). This displays rhythmic calcilutite with about 3 mm thick. Their colors range from brownish (lower part) to yellowish (upper part). Marks of algae filaments were not recorded. Millimetric black “spots” of MnO dendrites on some lamination surfaces are observed.

High levels of CaO (95.94%) (microspathic calcite) and Fe_2O_3 (2.50%) (oxi-hydroxides and clay minerals) were detected. The XRD indicated a unique phase (about 100%) of CaCO_3 (ICSD – 28827), validating the fluorescence results (Supplementary Material).

3.6 “Veio doidão”

The “veio doidão” has 0.50 m thick (Chart 1 and Fig. 3) and is similar to “veio da piaba”, but with sub orthogonal fractures to the bedding. The denomination “doidão” means “very crazy” and is adopted by the quarry workers due to the unpredictable splitting behavior of these slabs. Marks of algae filamentous were not observed.

The XRF results revealed the highest content of CaO (96.81%) (microspathic calcite) among all analyzed samples. The only XRD phase was dolomite [$[\text{Ca}, \text{Mg}], (\text{CO}_3)_2$] / ICSD – 86161) (Supplementary Material).

3.7 "Lajão amarelo"

The "lajão amarelo" ethnostratum (Chart 1 and Fig. 3) shares many characteristics with the "veio doído", including the thickness (around 0.50 m), but it exhibits a more intense yellowish color. Here we also do not observe filamentous algae.

These ethnostrata have similar XRF CaO and Fe_2O_3 contents to the "veio do besouro", but the "lajão amarelo" has high CaO (94.26%) (microspathic calcite) and lower Fe_2O_3 (3.12%) values than the former (Supplementary Material).

3.8 "Veio do besouro"

The "veio do besouro" (Chart 1 and Fig. 3) represents the uppermost unit of the studied section. The quarry workers indicate that it has 0.10 m thick or less.

This ethnostratum consists of a parallel laminated calcilutite, more irregular than the "veio da piaba", with individual lamellar sets from 1.0 to 4.0 mm thick. Other distinctive feature is the presence of sub millimetric clayey laminae, especially at top. Near to the base, it has 2.0 centimeters thick of gypsum layer, with individual crystals showing "sword" terminations sub orthogonal to bedding (see thin section description). Finally, this stratum also differs from the underlying strata by the presence of a recrystallized calcite level on its top (Fig. 6C).

In thin section, the sedimentary matrix is predominantly composed by microspathic crystals (~70%) and micrite (~10%). Few bioclasts, ooids and pellet were also observed, making up about 10% of the sample. The allochemical grains are mostly composed by peloids (130 simple and 1 compound). The cement consists of iron oxyhydroxydes (goethite or limonite), as well as MnO. Anatase crystals were observed (Fig. 6A). The lamination is not preserved in the center of the thin section due to the presence of gypsum ($\text{CaSO}_4 \cdot n\text{H}_2\text{O}$) crystals which grows orthogonally to the laminae (Fig. 6B). They exhibit a nucleated background patterns and "zig-zag" textures (Shearman, 1978).

The XRF analysis exhibited, respectively 93.55%, 0.80% and 3.85%, for CaO, SO_3 and

Fe_2O_3 . The XRD analysis have identified CaCO_3 (ICSD - 28827) (microspathic calcite) and gypsum [$(\text{CaSO}_4) (\text{OH})_2$ /ICSD - 2057] phases, corroborating the XRF and microscopy results. The treatment of these phases showed a 95.3% of CaCO_3 and 4.63% for gypsum proportion (Supplementary Material).

4 Discussion

4.1 Geochemical patterns

The figure 3 and table 1 show the geochemical variation of all ethnostrata in the Talhado do Idemar section. The quarry workers reported properties such as color, hardness and splitting mechanisms that may be related to the chemical and/or mineralogical composition of these rocks.

Table 1 shows the correlation among the main oxides distributed in the samples. Here, we considered a high direct correlation when the Pearson's coefficient is equal or superior to +0.7, as well as, a high inverse correlation occurs when its value is equal or less than - 0.7. The table highlights the negative correlation between CaO and Al_2O_3 ; CaO and SiO. It is worth to note the positive correlation between Fe_2O_3 and MnO; Al_2O_3 and SiO.

The Al_2O_3 has an inverse correlation with CaO (Tab. 1) and a direct correlation with Si. This can be explained by its association with clay minerals. The presence of SO_3 in the "veio do besouro" can be associated with gypsum. A zig-zag bottom-nucleated growth texture was observed in gypsum's layer (Fig. 5B). According to Warren (2006), this is a strong evidence of hypersalinity, shallow water body deposited under arid climatic conditions.

The CaO origin is linked to the existence of carbonate minerals in the lacustrine sediments of the Araripe paleolake (Silva, 1988). The carbonate accumulation in the most distal portions is traditionally attributed to chemical precipitation unaffected by any microbial mediation (Heimhofer *et al.*, 2010). This interpretation seems to be verified in the upper portion of the ethnostrata. However, Catto *et al.* (2016) identified organic minerals precipitated by

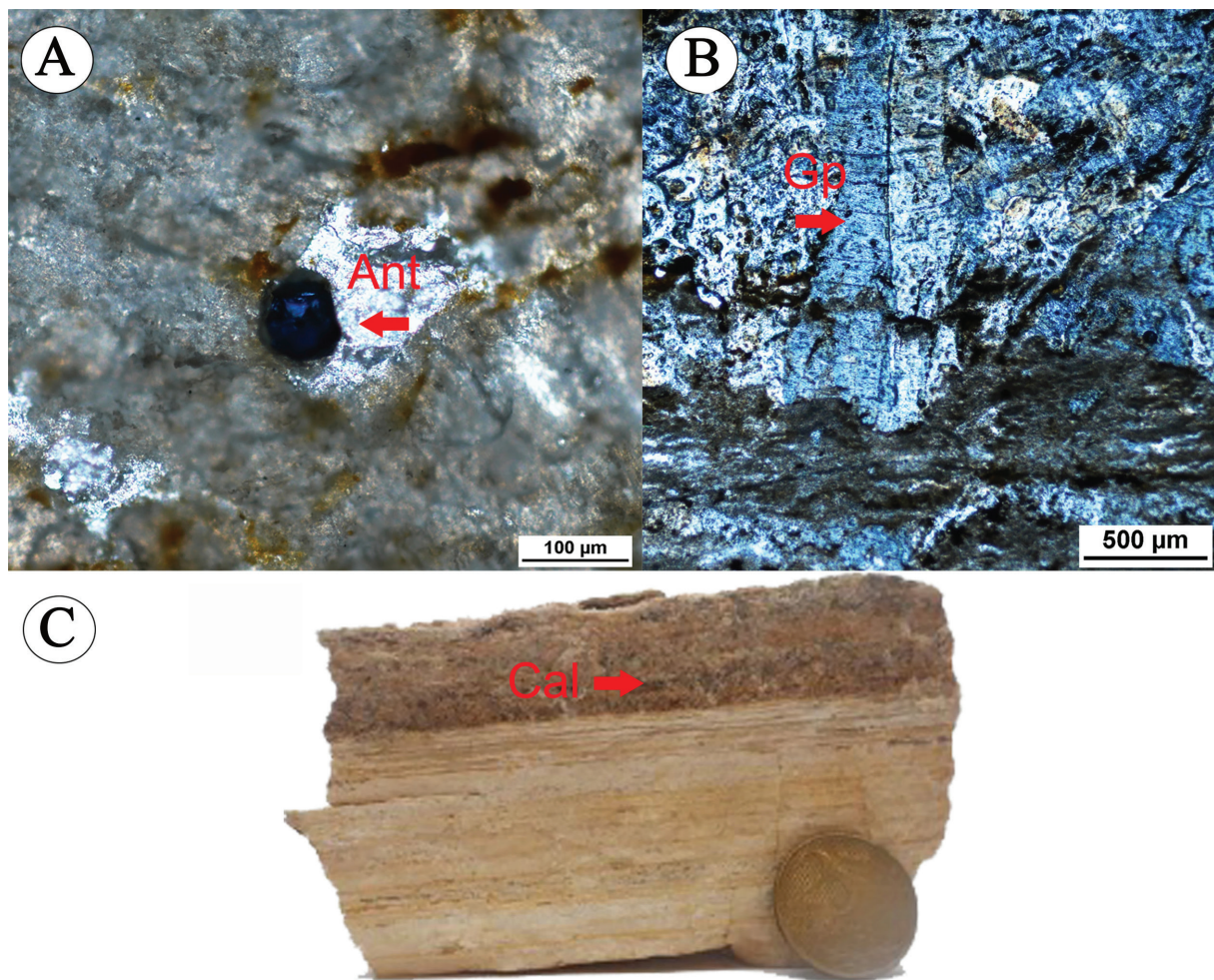


Figure 6. Thin section of the "veio do besouro" ethnostratum. A) An anatase crystal with very high relief, blue coloration (sometimes colorless or yellow), birefringence 0.073 ($>3^{\text{rd}}$ order – bright blue), beveled contours (squared), uniaxial interference figure (-), in natural transmitted light (NL); B) Gypsum crystals (Gp) ("sword like") with a nucleated background pattern and zig-zag textures, in polarized light (PL); C) Presence of a recrystallized calcite (Cal) level at the top of the sample (red arrow).

Figura 6. Seção delgada do etnoestrato "veio do besouro". A) Um cristal de anatásio (Ant) com relevo muito alto, coloração azul (por vezes incolor ou amarelo), birrefringência 0.073 ($>3^{\text{a}}$ ordem – azul brilhante), contorno chanfrado (quadrado), figura de interferência uniaxial (-) à luz natural transmitida LN); B) Cristais de gipsita (Gp) ("estilo espático") com padrão de fundo nucleado e texturas em zig-zag, em luz polarizada (LP); C) Presença de um nível de recristalização de calcita (Cal) no topo da amostra (seta vermelha).

Table 1. Pearson's elemental correlation applied to the oxides found in the analysis of the studied section.

Tabela 1. Correlação elemental de Pearson aplicada aos óxidos encontrados nas análises da seção estudada.

	CaO	FeO	AlO	MnO	SiO
CaO	1.000.000				
FeO	- 0.072782	1.000.000			
AlO	- 0.934798	0.002439	1.000.000		
MnO	0.089586	0.888446	- 0.101341	1.000.000	
SiO	- 0.994203	- 0.029876	0.932260	- 0.184334	1.000.000

*The red cells indicate high inverse correlation values and the blue ones, high direct correlation values.

*As células vermelhas indicam altos valores de correlação inversa e as azuis, altos de correlação direta.

microbial metabolic activity in Crato laminated limestones. The biologically-induced process was possibly more intense during the deposition of more basal "lajão dos sete cortes" (crenulated lamination with fenestrae) and "lajão branco" (algae filamentous). Overall, our results indicate that CaO values tend to increase from the base to the top, with a relatively high SO₃ content at the top of the section. The higher values of CaO and SO₃ at the top of the section probably result from intense aridity (Brookins, 1988). On the other hand, there is an upward decreasing trend in the Fe and Mn oxide values along the studied section, where the highest Fe concentration is observed in the lower ethnostrata (e.g. "lajão dos sete cortes" and "embombado"). This must have occurred due to higher amounts of organic matter and framboidal pyrite formed under reducing conditions (Neumann *et al.*, 2003; Heimhofer *et al.*, 2010; Osés *et al.*, 2017). Based on framboidal pyrite, it is possible to suggest that the Nova Olinda Member passed by dysoxic to oxic conditions during its sedimentation, like those observed in Chang 7 Member, in the Ordos Basin, China (Chen *et al.*, 2018). Most framboids from Chang 7 are crystallized during the early stage of diagenesis rather than remobilized from terrigenous detritus or formed in the water column (Chen *et al.*, 2018).

The darker color and greater cut-resistance of the "embombado" ethnostratum can be attributed to the higher levels of Fe and Mn (Fe₂O₃ – 9.05% and MnO – 2.15%), when compared to Silveira (2019) data (Fe₂O₃ – 1.17% and MnO – 0.60%), which studied carbonatic rock samples from the top of the Crato's Formation from the C6 level of Neumann (1999). The difficulty of cutting those slabs is frequently reported by quarry workers of the Talhado do Idemar. Similar situation was reported by Dill *et al.* (1997) in German rocks. A possible hydrothermal origin for the Si observed in the "embombado" ethnostratum can be speculated according to the attributes of Berg & Masters (1994). These authors proposed that the upward movement of groundwater heated by plutons in the basement can explain silicification of the carbonates. The co-precipitation of carbonate minerals and quartz as a result of acidic fluids is also a hypothesis. The exposition of the carbonates to the final processes during

telodiagenesis can also influence the formation of microcrystalline quartz formation (Ramos *et al.*, 2020). This last hypothesis can be associated with the telodiagenesis event that occurred in the entire Araripe Basin (Costa *et al.*, 2014). Nascimento Jr. *et al.* (2016) hypothesized a hydrothermal origin for the silica since there is another evidence of this in the overlapping Ipubi Formation. Oxidizing events associated with telodiagenesis may have produced the current amounts of Fe₂O₃ in the lower ethnostrata (below "embombado"). The presence of original ferric oxides in the middle to upper ethnostrata (above "embombado"), allow us to predict that this section was deposited under shallower and, probably, more oxidizing conditions, as proposed by Costa *et al.* (2014).

Although there is no petrographic evidence, for all the samples, only XRD and XRF results, the origin of the dolomite must be diagenetic and resultant of fluids migration through certain levels (e.g. "embombado" level, "veio doidão" and "lajão amarelo"). Similar situation was reported by Martill *et al.* (2008) that identified diagenetic dolomitization in pipes hosted in laminated limestones of Nova Olinda Member. According to Scholle & Ulmer-Scholle (2003), the presence of dolomite concretions in the rocks with ankerite (e.g. "matracão") are not uncommon in Cretaceous sediments, because they form a solid solution between them.

4.2 Pearson's correlation and depositional context

The Pearson's Correlation (Tab. 1) demonstrates a positive correlation between Fe₂O₃ and MnO (0.88), since they have similar geochemical behavior (Brookins, 1988). Al₂O₃ and SiO are also directly correlated (0.93) and, according to Brookins (1988), their minerals can precipitate in superficial environments from acidic to neutral or slightly basic pH (Si – pH ~ 1 to 12.51 and Al – pH ~ 4.34 to 11.15). Thus, it is possible to suggest that these cations co-precipitate in the same environmental conditions. On the other hand, CaO and Al₂O₃ (-0.93); CaO and SiO (-0.99) are inversely correlated. According to Brookins (1988), Ca minerals would be formed

preferentially over basic pH conditions (~ 8 to 14). Under certain environmental conditions, the Al and Si behaviors are opposite to the Ca, which could explain the high inverse correlation, in both, Ca-Al and Ca-Si. The other Pearson's coefficients are inferior to + or - 0.7 (reliable data correlation), then they will not be discussed here.

The inverse behavior between CaO and SiO in the studied section may be caused by the minor presence of clay minerals, except in "embombado" ethnostratum, where the silicification was probably formed by the dissolution of calcium from carbonate minerals (acidification of the surroundings) and quartz co-precipitation (Bennett & Siegel, 1987; Bennett *et al.*, 1988; Maliva & Siever, 1989). This deposition would have occurred by the carbonate substitution, which was not complete as evidenced by the low CaO concentration in its nodules.

Another particularity of Crato Formation is the disharmonic folds in "embombado" ethnostratum. These structures can be interpreted as earthquake responses of over pressured water between cohesive sediment pores, resulting in sismoslumps structures (Montenat, 2007). This interpretation is similar to that of Martill *et al.* (2008).

4.3 Facies correlation model

Our results exhibit section similarities with the stratigraphic model proposed by Neumann *et al.* (2003) and the taphonomical model proposed by Osés *et al.* (2017) for Crato Formation limestones. The hypothetical geochemical limit identified above the "embombado", at base of "matracão", is thought to be close to the limit between facies 5 (clay-carbonate rhythmite), at the base, and facies 6 (laminated limestone), at the top of the parasequence model developed by Neumann *et al.* (2003). The color pattern was used as criterion to differentiate Fe oxidation states of these two facies in the taphonomic model proposed by Osés *et al.* (2017). The gray limestone facies (GL) corresponding to facies 5 and beige limestone (BL) to facies 6. We emphasize that the Neumann *et al.* (2003) model is valid for the entire Crato Formation, while the study of Osés *et al.* (2017) is restricted to the

Nova Olinda Member.

The GL facies (Fig. 3) is composed by calcite anhydrous neomorphic crystals in spathic size, with dark lenses enriched in pyrite and peloids. Its bluish gray color indicates a greater accumulation of organic matter, reducing conditions and fossils preserved by kerogenization (Osés *et al.*, 2017). The BL facies (Fig. 3) is the laminated limestone *strictu sensu*, a microfacies with clay interlaminated (less than GL) lenses and scattered organic matter. Its beige color indicates more oxidizing depositional conditions when compared with GL facies. The fossils recovered from the BL facies are preserved by pyritization (Osés *et al.*, 2017).

According to our model, the "lajão dos sete cortes" ethnostratum is correlated to the GL facies. The overlying ethnostrata (upwards from "matracão" to "veio do besouro") correspond to the BL facies. The macroplant fossils are strongly associated with the darker carbonate (GL; "lajão dos sete cortes"), often being identified with naked eye (e.g. De Lima *et al.*, 2019). This fact is a relevant point in the comparison between these faciological models, especially, the one proposed by Neumann *et al.* (2003), which not considered the fossil content.

It is worthy to note that the "matracão" ethnostratum initiates with layer of unique characters: "embombado" (also named "caroço"). The origin of silica in "embombado" ethnostratum is still unclear. However, its preferential deposition trough layers can be due to local rises in vuggy/fenestral permoporosity within microbialitic bodies (Warren *et al.*, 2017). This reinforces that changes in depositional environment must have occurred due to modifications in the climate or in the subsidence rates. Since SiO₂ is an abundant diagenetic mineral in carbonate rocks (as cement or replacing the original material), as observed by Cabral (2017). In addition, the presence of possible sismoslumps in "embombado" could mark changes in the vertical movement rates of lakes' substratum, indicating seismic activity in post-rift deposits otherwise considered less, or non-affected, by tectonic activity. Recently, Alencar *et al.* (2021) suggested that these paleoseismic structures were probably associated with reactivation of the Patos shear zone.

According to Neumann *et al.* (2003) model, the evolution of Crato lacustrine system took place under a tropical-subtropical climate with alternating periods of higher and lower humidity context. This seasonality generated periods of increase and decrease in the water column. Periods of higher humidity increases sedimentation supply rates, as well as the organic matter input, giving origin to darker carbonates (enriched in organic matter – “lajão dos sete cortes” and “embombado”), as well as a deeper water column. According to Adams (1993) and Christidis *et al.* (2004), carbonates colors can be altered by the addition of organic matter. According to Hutchinson (1957), Wetzel (1981) and Neumann *et al.* (2003), this increase in the water body column implies in thermal water stratification (thermal meromixis). On the other hand, the decrease of the water column, during dry periods, implies a concentration of salinity that culminates in evaporite formation (“veio do besouro”), decreasing the siliciclastic supply. At Talhado do Idemar the ethnostrata related to the facies 5 (“lajão dos sete cortes”) and 6 (“matracão” to “veio doído”) were deposited in inner lacustrine zones far enough from terrigenous influence, allowing the deposition of rhythmic clay-carbonate couplets and pure micritic limestones (Neumann *et al.*, 2003).

5 Conclusions

The Nova Olinda Member ethnostrata organization is a cultural product of the Pedra Cariri workers from Nova Olinda municipality. It was validated, in general terms, by petrography, geochemistry and previous studies. These informal stratigraphic units can be used as a support to identify and individualize layers in more detailed petrological and taphonomic investigations. This study showed that ethnostratigraphy can be applied as an auxiliary tool in stratigraphic studies, in both, as an initial exploratory approach and as an enhancing the relationship between the geologists and the local community. In the particular case of Nova Olinda Member, the ethnostratigraphy has proved to be useful in situations where popular knowledge enters as a cultural element capable

of distinguishing layers in an outstanding *Fossil Konservat-Lagerstätte*, amid seemingly monotonous intervals by the conventional lithostratigraphic approach. Thus, we verify that these informal stratigraphic subdivisions are in fact consistent with individual strata and liable to be included in the formal stratigraphic nomenclature of the Nova Olinda Member.

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