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Anthropic Influence and Heritage Value of the Quaternary Deposits of Rio de Janeiro, Brazil

Influência Antrópica e o Valor como Patrimônio dos Depósitos Quaternários do Rio de Janeiro, Brasil

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Abstract

This study discusses the cause of local lithification in sediments from quaternary beach ridges of Paraíba do Sul Deltaic Complex (Rio de Janeiro, Brazil) and its application to the concept of geological heritage. These beach ridges were excavated to construct the Campos - Macaé Canal, opened in the 19th century predominantly by slave labor. A detailed sedimentological, mineralogical and petrological study was performed. The consolidated material consists to fine-grained sandstone with incipient parallel lamination. Kaolinite associated with iron oxides/hydroxides is organized in thin coatings, sometimes forming meniscus and bridges. The heavy mineral assembly of the sandstone is similar to those found in the beach ridges friable samples. The sandstone granulometry increases from east to west along the canal margins and the same pattern is observed in the adjacent beach ridges. We suggest that pedogenic processes acted intensively on Canal margins after its opening, causing mechanical infiltration and translocation of clay minerals, promoting differentiated consolidation of sediments only in that part that was deepened during the excavation. The anthropic action altered the local physiography by exposing the sediments of beach ridges. Therefore, this sandstone should be considered a geological heritage due to its unique occurrence, touristic, historical, scientific and educational value.

Keywords: Anthropocene; Beach ridges; Geological heritage

Resumo

Este estudo discute a causa de uma litificação local em sedimentos de cordões arenosos quaternários do Complexo Deltaico do Paraíba do Sul (Rio de Janeiro, Brasil) e sua aplicação no conceito de patrimônio geológico. Para isso, um estudo detalhado sedimentológico, mineralógico e petrológico foi realizado. Os cordões foram escavados para a construção do Canal Campos - Macaé, aberto no século XIX por mão de obra escrava. O material consolidado consiste em arenito fino com laminação paralela incipiente, cimentado por caulinita associada a óxidos / hidróxidos de ferro organizados em finas cutículas, por vezes formando meniscos e pontes. O conjunto de minerais pesados é semelhante àqueles encontrados nas amostras friáveis dos cordões arenosos. A granulometria do arenito aumenta de leste a oeste ao longo das margens do canal e o mesmo padrão é observado nas cristas de praia adjacentes. Sugerimos que processos pedogênicos atuaram intensamente nas margens do Canal após sua abertura, causando infiltração mecânica e translocação de argilominerais, promovendo consolidação diferenciada de sedimentos apenas na parte que foi aprofundada durante a escavação. A ação antrópica alterou a fisiografia local, expondo os sedimentos dos cordões litorâneos. Portanto, este arenito deve ser considerado um patrimônio geológico por se tratar de uma ocorrência única, com valor turístico, histórico, científico e educacional.

Palavras-chave: Antropoceno; Cordões litorâneos; Patrimônio geológico

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1 Introduction

Anthropogenic activity can interfere with geological processes, since humans have become geological - geomorphological agent and their actions have consequences on the physiography of landscapes. This anthropic influence occurs from the creation, induction, intensification or modification of external dynamics processes such as erosion, mass movements, infiltration and runoff of rainwater, sedimentation rates and underground flows (Peloggia 1997).

With the increase in human activity interfering in the natural environment, there is a demand to adapt some concepts to incorporate the anthropogenic influence. This is the case of geodiversity, in which some authors such as Kozłowski (2004) and Serrano and Ruiz-Flaño (2007) have included human activity in this concept. Brilha (2016) defines geological heritage "in situ", or geossite, as occurrences of geodiversity with high scientific value in terms of geological / geomorphological relevance. It may also have educational and touristic values but, for the author, the scientific is the unique value essential to determine a geological heritage. This is the most restrictive definition of geological heritage and, for this reason, it was chosen for this study.

The excavation of the Campos - Macaé Canal (Figure 1), located in the Rio de Janeiro state (Brazil), was executed by slave labor in the middle of the 19th century with the purpose of production outflow from Campos dos Goytacazes and Norte Fluminense to Rio de Janeiro, through the Imbetiba port in Macaé municipality (Penha 2009, 2012). The inauguration for navigation took place in 1861, although it was not fully concluded until 1872. The Canal operated regularly for about three years after its conclusion, and it became obsolete due to the inauguration of the Macaé - Campos railway in 1875 (Lamego 1958). This is considered the second longest artificial Canal in the world because of its length of 106 km, only surpassed by the Suez Canal (Egypt) (Penha 2009).

The Canal passes through Campos dos Goytacazes, Quissamã, Carapebus and Macaé municipalities, connecting the Paulista Lagoon in Quissamã, to the Lagomar district, in Macaé, both located inside the Restinga de Jurubatiba National Park (PARNA Jurubatiba). The section has approximately 25 km, as recorded in the map dated 1846 that presents the Canal plan (accessed in Digital Archive of the National Library - Archivo Militar 1846 and Penha 2012, Figure 1).

In 2017, a field trip was carried out to collect field data and samples aiming a collaboration between Geopark Costões e Lagunas of Rio de Janeiro Project and ICMBio (Chico Mendes Institute for Biodiversity Conservation, park manager), in which was identified an intense consolidation of the sediments that compound the canal margins, forming a friable sandstone. In view of this, this article aims to answer two questions: (a) Is the excavation of the Campos - Macaé Canal responsible for the local differential lithification in a part of the beach ridges? and (b) Could this anthropic sandstone be considered a geological heritage?

To achieve these goals, the following studies were carried out: (a) delimitation of the area of occurrence of this outcrop within the PARNA Jurubatiba and conduction of a sedimentological and petrological characterization in order to discriminate the processes responsible for its lithification; (b) comparative sedimentological and mineralogical study between the lithified beach ridges and the sands of the adjacent beach ridges and inter-ridges to understand if there are differences in these parameters that may have accelerated or assisted the evolution of the pedogenetic/ diagenetic processes; and (c) discussion about the inclusion of this sandstone in the group of so-called anthropic rocks and in the geodiversity and geological heritage concepts.

2 Geological Setting and Study Area

The PARNA Jurubatiba is located in Campos Basin onshore, being part of the Paraíba do Sul Deltaic Complex. This deltaic complex occurs as a large quaternary coastal plain and consists of a set of sedimentary environments related to Paraíba do Sul River depositional phases, in which two coastal plains are delimited (Martin, Bittencourt & Vilas Boas 1982). The first is located north of Cape São Tomé and Feia Lagoon and is related to the current delta (Holocene). The second is located south of Cape São Tomé and is considered a paleodeltaic record, whose beach ridges were formed during the Upper Pleistocene last glaciation (Dias & Kjerfve 2009; Martin, Bittencourt & Vilas Boas 1982; Silva 1987).

From a geomorphological perspective, the study area is delimited at the southwest by the Precambrian basement as a smooth hill domain; at the north by the terraces of the Barreiras Formation; and at the northeast by Feia Lagoon and by fluvio-lagoon plains (Rocha et al. 2013). The Jurubatiba Sandbank is composed of quaternary beach ridges (Figure 2) as a product of relative sea level variations combined with coastal drift currents, in which each crest represents a paleo shoreline (Rocha et al. 2013). Those are intersected by lagoons arms with perpendicular or parallel orientation to the shoreline.

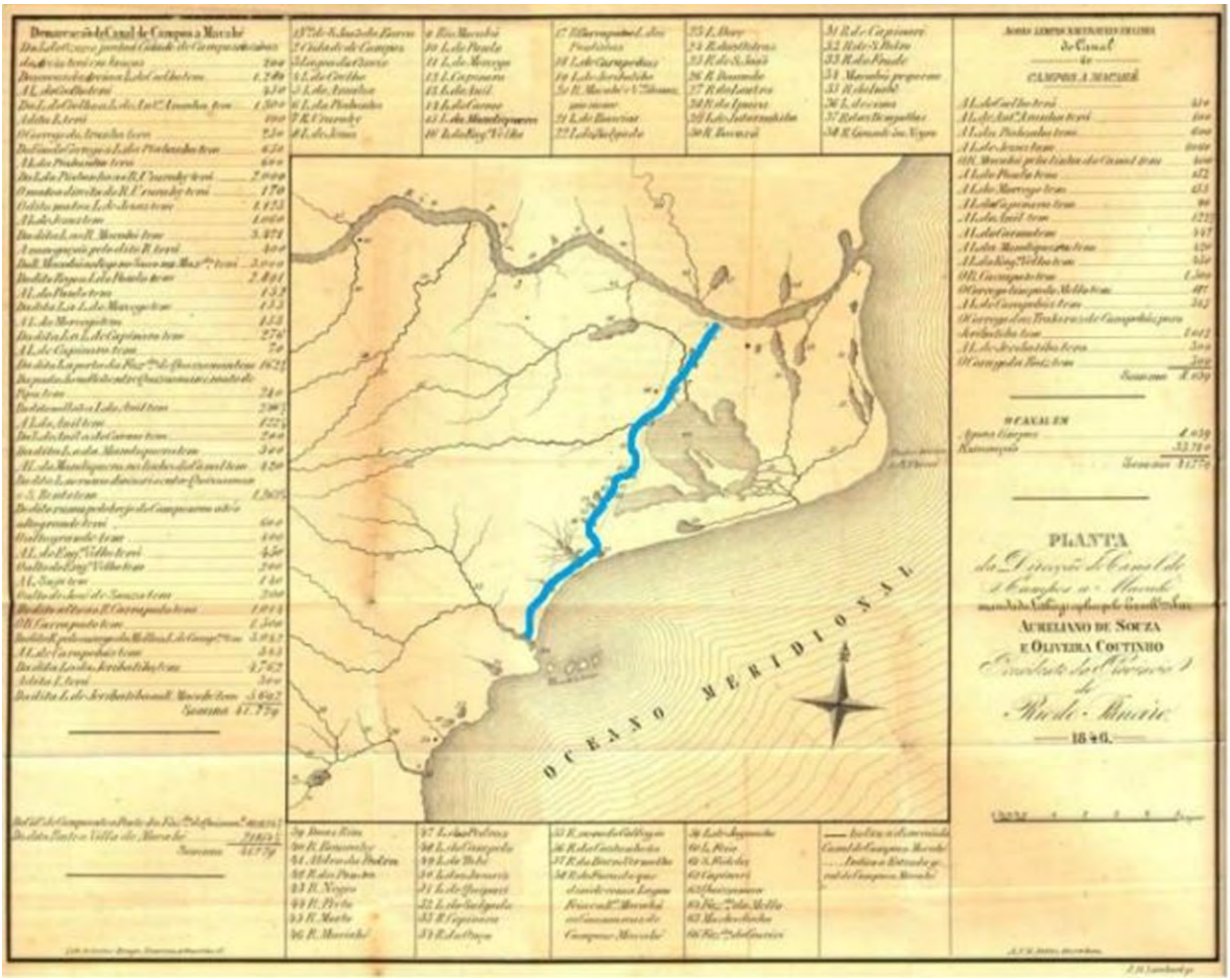

Figure 1 Map of the Campos - Macaé Canal dated 1846 (highlighted in blue). Modified from Penha (2012), original map from Archivo Militar (1846).

Rocha, Peixoto and Fernandez (2012) obtained the absolute age of ≈ 85,000 years for these beach ridges using the optically stimulated luminescence dating technique. They also investigated the internal structure of the beach ridges that form a progradational regressive barrier sequence with a thickness of ≈ 8 m. This progradation event was associated with an expressive sedimentary contribution possibly related to the fluvial input of the paleo course of the Paraíba do Sul River during the Pleistocene age (Rocha, Fernandez & Rodrigues 2017). Vilela et al. (2016) studied a drill core (2-JU-1-RJ) with 128 m of depth located at the PARNA Jurubatiba area. The last interval (21.0 - 0.0 m) proposed consists of fine to coarse-grained sands, dominated by quartz and bioclastic fragments, that were interpreted as coastal sediments of the Pleistocene age. Besides the beach ridges, outcrops of organic matter rich sandstone with preserved trunks and branches fragments occur in some areas of the PARNA Jurubatiba. These organic fragments are, for the base and top of the section, 43,500 to 34,530 years in age dated by radiocarbon method (Barros et al. 2015).

3 Methodology and Data

The four sampling points were selected according to the site accessibility and the observed textural diversity on the Campos - Macaé Canal margins (Figure 3). At each point were collected samples for thin sections preparation, heavy minerals characterization and X-ray Diffraction analysis (XRD).

Eleven thin sections prepared from Canal margins samples were analyzed qualitatively, including the texture description, detrital composition, diagenetic composition and pore types. All samples were classified according to the textural and compositional diagrams of Folk (1968).

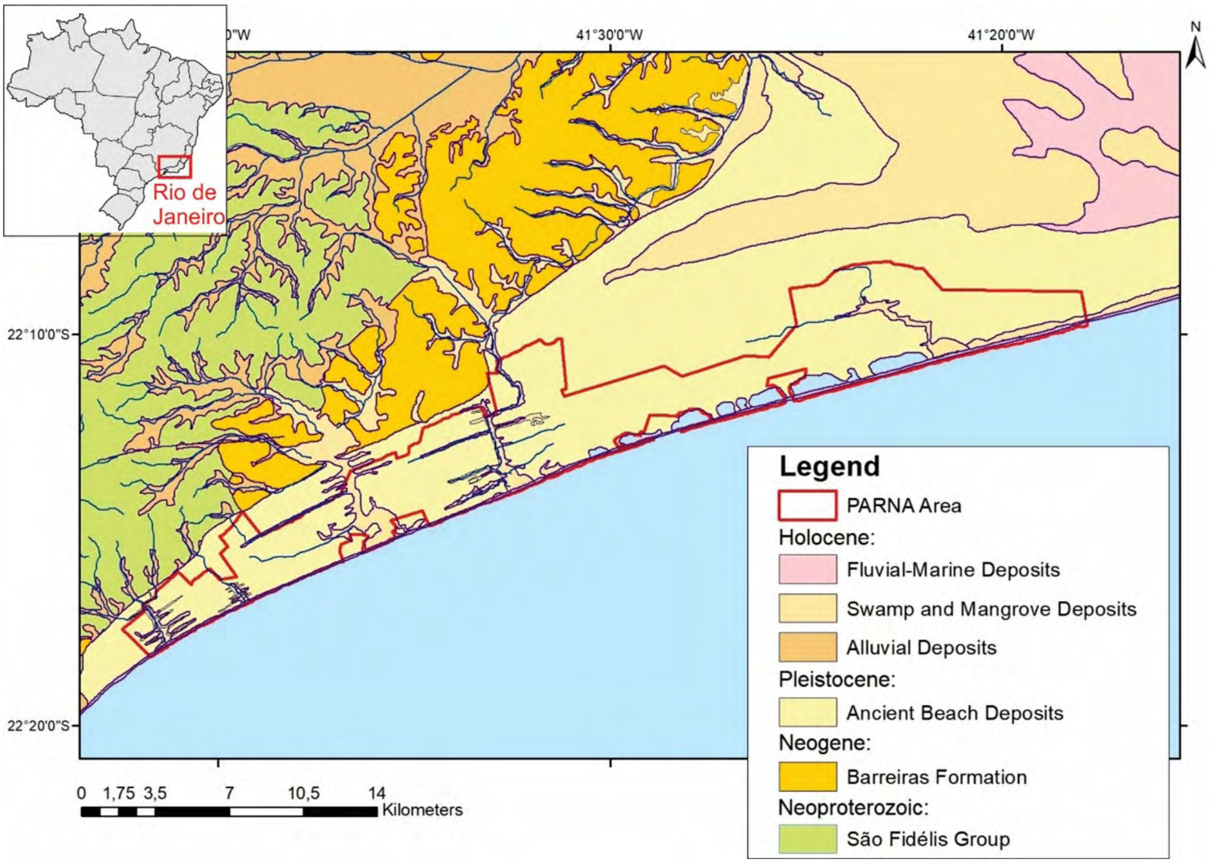

Figure 2 Geological map of the study area. Pleistocene beach ridges are represented in yellow color and the PARNA Jurubatiba area is delimited by the red polygon. Modified from CPRM (2018).

The sampling preparation for XRD analysis applied the gravity settling method from Embrapa (1997). Each sample was centrifuged and divided into three aliquots for natural conditions, saturated with $MgCl_2$ - Ethylene Glycol, and saturated with KCl and heated to 550 ºC (Jackson 1965). The slides were made using the smear mount method (Moore and Reynolds 1997) and analyzed in D8 ENDEAVOR XRD system - Bruker Corporation (Co Kα1, λ = 0.17889 nm, 40 kV, 40 mA). Qualitative interpretations of the spectrum were performed by comparison with standards contained in the ASTM standards database.

Furthermore, 23 samples were collected in four transversal profiles to the coastal beach ridges in order to compare with the sandstones collected on the Canal margins (Figure 3). In each profile, samples were taken from the beach ridges and inter-ridges. For this purpose, a one meter pit hole was made and about 4 cubic decimeters of sample were collected. These samples were dried and subsequently quartered in fractions of approximately 250 g to latter be subjected to granulometric and heavy minerals analysis. For granulometric analysis the samples were sieved using Mesh Sieves No. 10, 18, 35, 60, 120 and 230, in which the weight of each fraction was also measured. After running the statistical and macro functions the output was mean phi, standard deviation (selection), asymmetry and kurtosis parameters for each sample (Blott & Pye 2001).

For mineralogical analysis the heavy minerals were concentrated, washed with oxalic acid to remove the iron oxide from grains surface, and separated in dense liquid (bromoform - $CHBr_3$; 2.8 g/cm³). The magnetite grains were removed with the aid of a hand magnet. Subsequently, the separation of the paramagnetic and diamagnetic fractions was carried out in the Frantz Isodynamic Separator, using magnetic fraction in the range of 0.1, 0.3, 0.5, 0.7 and 1 A. The fractions were weighed on a precision scale, analyzed using a binocular stereomicroscope and compared to the literature database for mineralogical identification (Parfenoff, Pomerol & Tourenq 1970; Pereira, Ávila & Lima 2005).

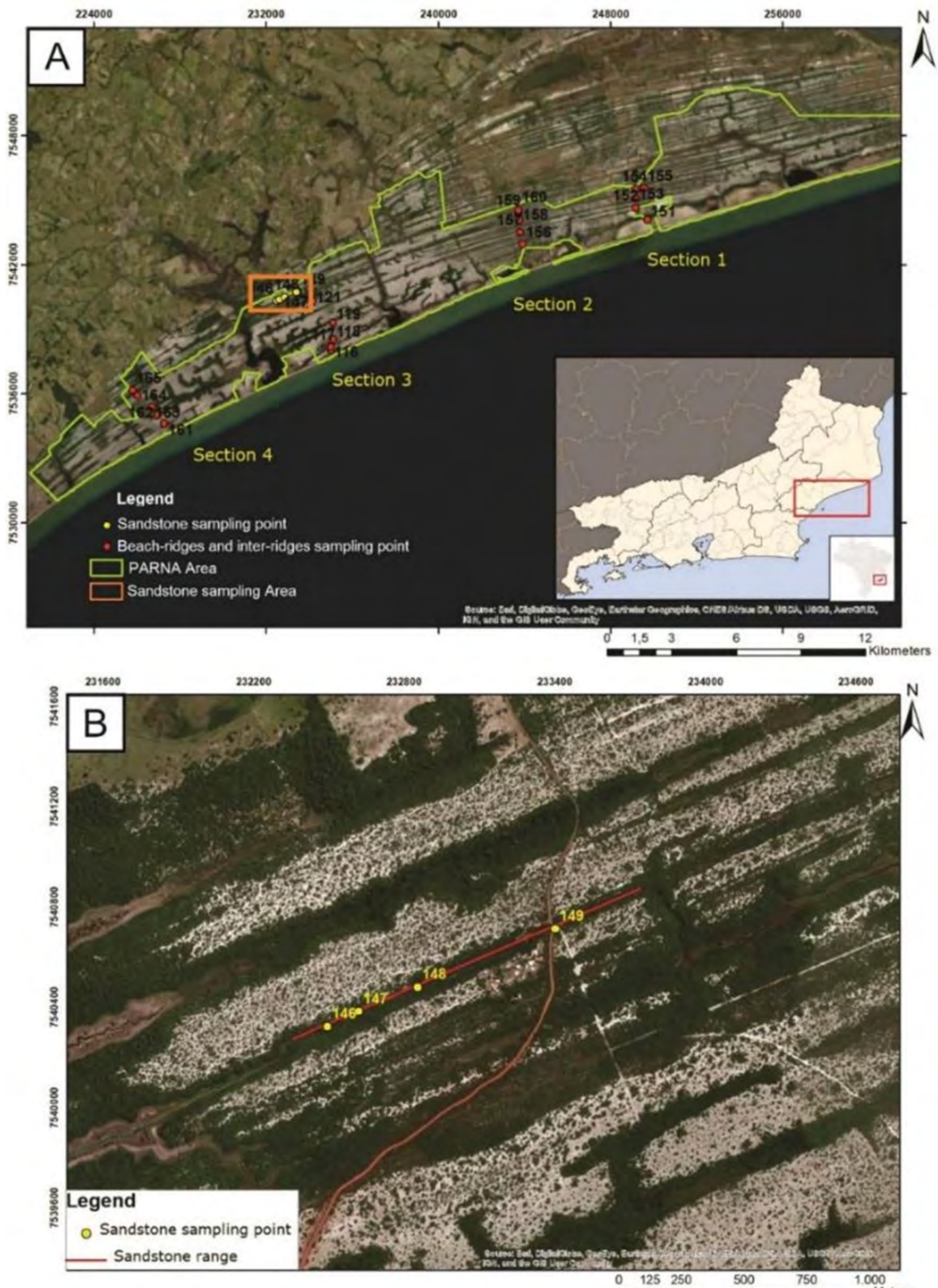

Figure 3 A. Sampling points of the beach ridges and inter-ridges sediments (red) and sedimentary rocks within the Campos - Macaé Canal (yellow). The green polygon delimits the PARNA Jurubatiba area; the orange polygon presents the distribution of the sampling points on the margins of the Campos - Macaé Canal, being zoomed in B.

4 Results

4.1 Macro and Microscopic Characteristics of Sandstone on the Margins of the Campos - Macaé Canal

The consolidated sandy material occurs only in a part of the Campos - Macaé Canal margins and has 1 km length, 50 m wide and 3-4 m high above the water level in dimensions. This differential consolidation in the beach ridges is not observed in other parts of the Canal or in other sites of the PARNA Jurubatiba. These deposits are organized in tabular beds, ranging from 5 to 60 cm, reddish-brown in color, are generally massive, but some beds present parallel lamination (Figure 4) marked by granulometric variations and clay minerals and carbonaceous matter concentration (Figure 4A). Rounded to oval perforations with centimeter dimensions (up to 2 cm) occur dispersed in the analyzed tabular beds, probably formed by the action of modern insects bioturbation (Figure 4D).

The sandstones are very fine- to very coarse grained, grain-supported, poorly to well-sorted with sub-angular to sub-rounded clasts and moderate sphericity. The coarse to very coarse sand grains are more rounded than the very fine to medium sands (Figure 5). The sandstones are classified as subarkose (*sensu* Folk 1968), composed mainly of quartz, plagioclase, microcline and orthoclase. Moreover, sillimanite, tourmaline, amphibole, epidote, spinel, monazite, ilmenite, magnetite, zircon, muscovite, biotite, rutile, titanite and volcanic rock fragments occur subordinately. Phytoclasts and clay peloids are concentrated in plane-parallel lamination.

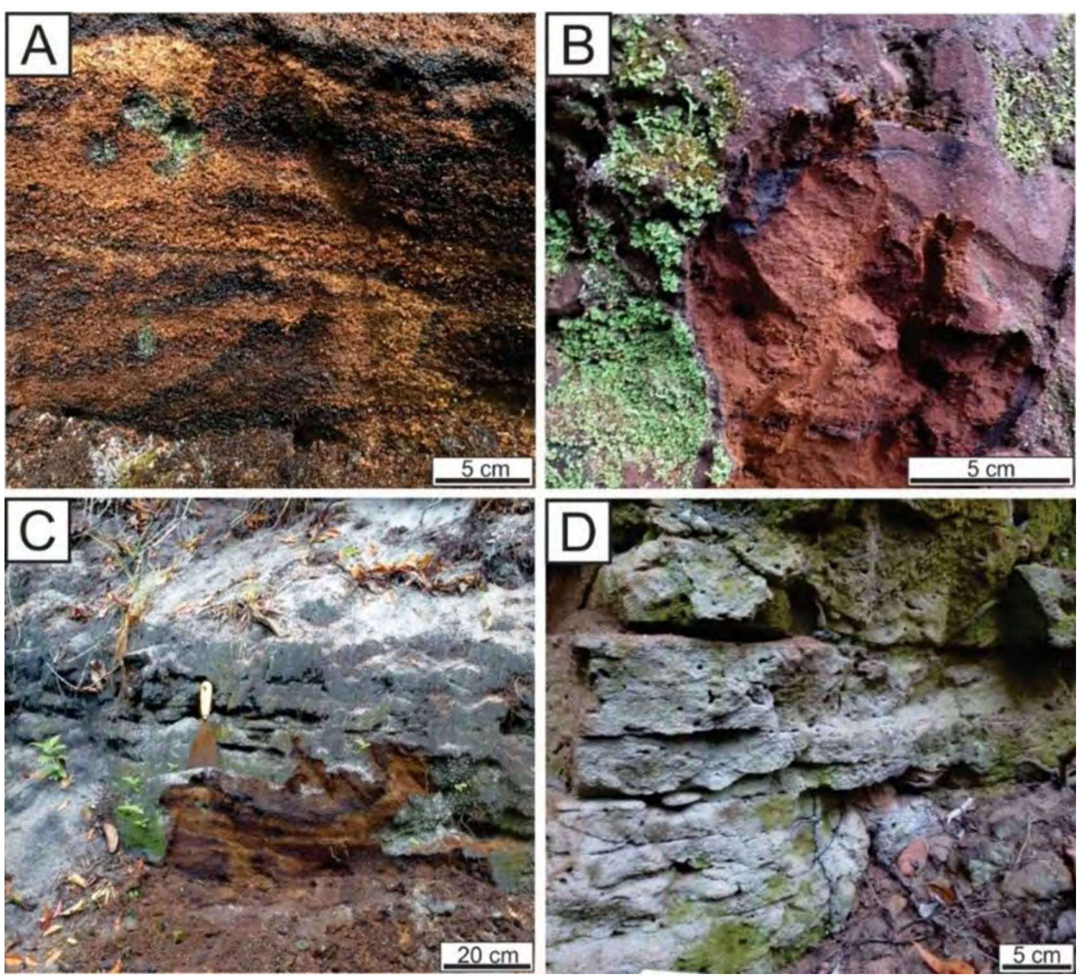

Figure 4 Macroscopic aspects of the sandstones of the Campos - Macaé Canal margins: A. Coarse-grained sandstone with parallel lamination, reddish color due to the concentration of iron oxides/hydroxides and organic matter (Point 146); B. Massive fine-grained sandstone with bioturbations (Point 149); C. and D. Tabular layers of sandstones with centimetric recent bioturbations.

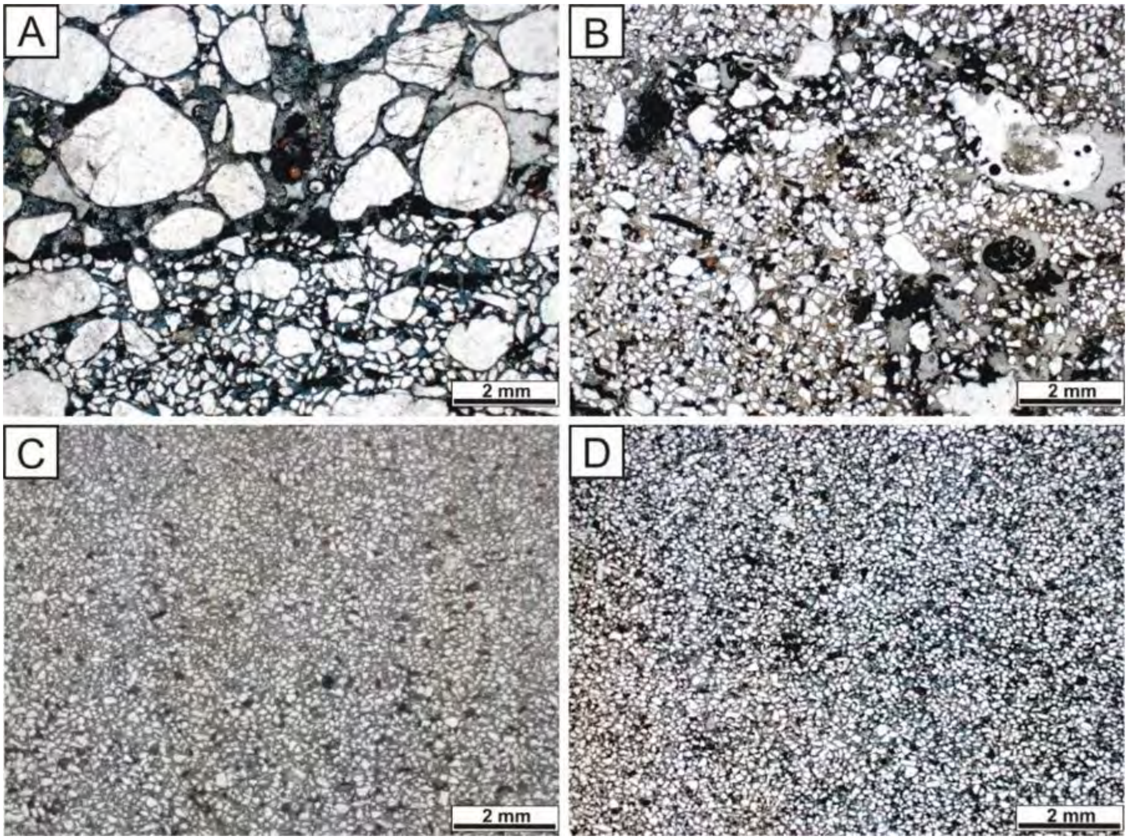

Figure 5 Microscopic aspects of the sandstones on the Campos - Macaé Canal margins: A. Medium- to very coarse-grained sandstone, bimodal, poorly-sorted, with planar parallel lamination marked by the grain size variation and concentration of carbonaceous matter; B. Medium-grained sandstone, poorly-sorted, with sub-rounded and sub-angular grains and moderate sphericity; C. and D. Fine-grained sandstone, well-sorted, massive, with phytoclasts and clay peloids dispersed.

The clay size fraction was identified by XRD as kaolinite and iron oxides / hydroxides. These minerals are organized as thin continuous and discontinuous coatings around the grains (Figure 6A). In some thin sections, the clay accumulates punctually, forming meniscus and bridges (Figure 6). In general, the clay content is heterogeneously distributed, concentrating in parallel laminas or in bioturbated areas. In respect of the total porosity, the sandstones have 7 to 18 % of intergranular and intragranular pores. The secondary pores are associated with the dissolution of feldspars (mainly orthoclase, Figure 6B) and quartz, as well as phytoclast fracturing and desiccation of argillaceous material (Figures 6C and D).

4.2 Grain Size Analysis and Heavy Minerals

The sandstone granulometry varies from east to west in the area of occurrence of the Campos - Macaé Canal. In the western sampling points (146 and 147), the sandstone is bimodal with predominance of medium- and very coarse-grained, poorly-sorted, instead of the eastern sampling points (148 and 149) that are fine-grained, well-sorted sandstones (Figure 5).

The frequency curves analysis of each sampling point present that the sands collected in the beach ridges usually have coarser grain size (Figure 7A). On the other hand, the inter-ridges are medium-grained, and sometimes present a bimodal distribution with a higher frequency of fine- and coarse sand grains size (Figure 7B). It was also observed that the granulometry of the profiles decreases and the sorting increases from SW to NE in the PARNA Jurubatiba area (Figure 8). These trends were also seen in the samples collected along the Campos - Macaé Canal.

Fourteen heavy minerals species were identified in all samples collected from the beach ridges, they are: cyanite, epidote, spinel, garnet, ilmenite, leucoxene, magnetite, monazite, iron oxide, rutile, sillimanite, tourmaline, xenotime and zircon. There were no significant variations in colors, shapes and rounding of these minerals between the samples studied. The minerals found in higher proportions were magnetite, rutile, sillimanite, tourmaline and zircon.

There was no increase or decrease trend in the mineral proportion along a profile, nor between profiles. Thus, the studied minerals are distributed evenly among the beach ridges located in the PARNA Jurubatiba area. The samples collected on the Canal margins have magnetite, zircon, tourmaline and sillimanite as the main heavy minerals assemblage. However, other minerals were also identified in the samples, but in minor content, such as anatase, kyanite, epidote, spinel, garnet, ilmenite, leucoxene, monazite, iron oxide and rutile.

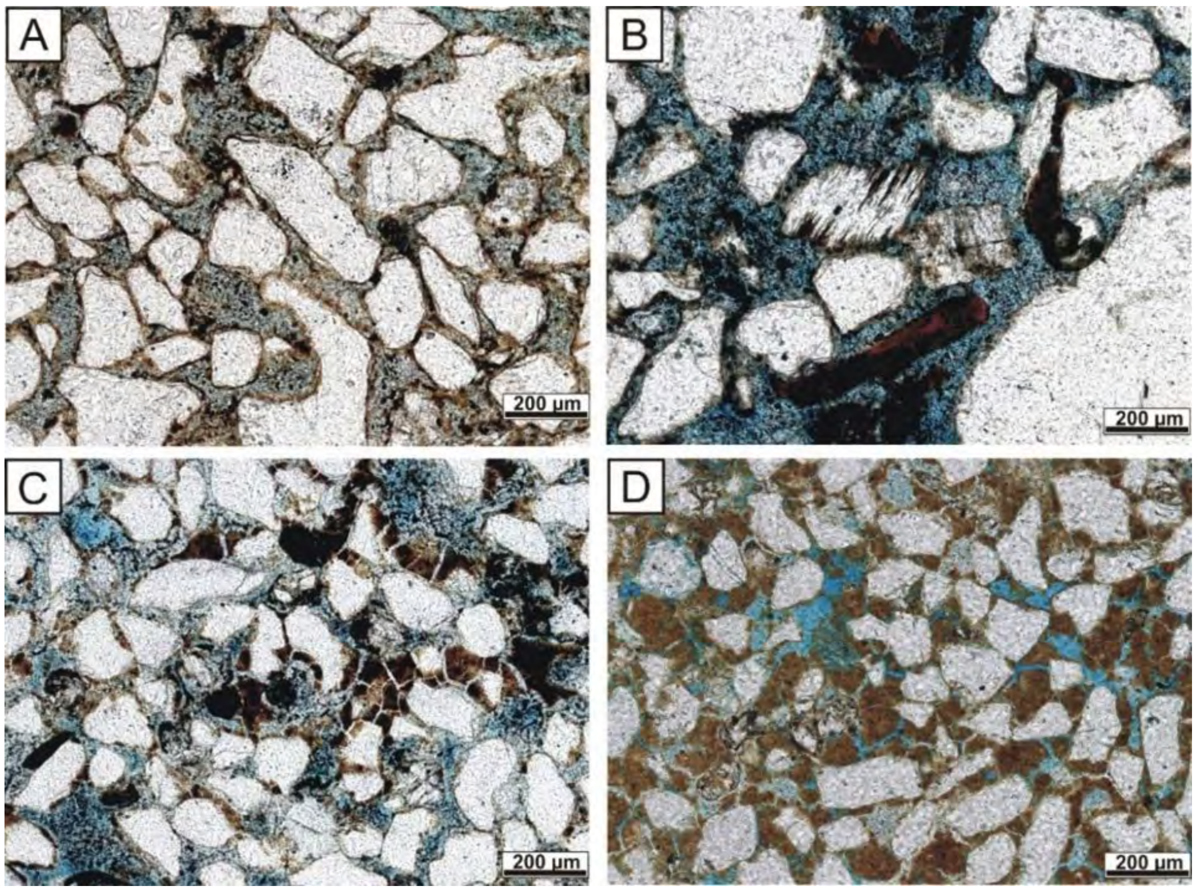

Figure 6 Microscopic characteristics of the sandstones on the Campos - Macaé Canal margins: A. Mechanical infiltrated clay mineral as continuous coatings; B. Dissolved orthoclase grain; C. Clay minerals and iron oxide / hydroxides concentration forming bridges between grains and shrinkage pores; D. Ridges and bridges composed of clay minerals and iron oxide / hydroxides, sometimes with shrinkage pores.

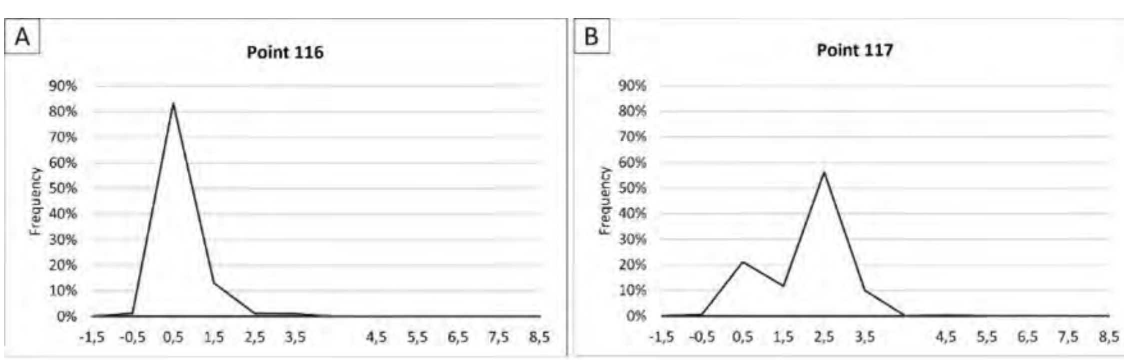

Figure 7 Grain-size histograms of samples from: A. A beach ridge; B. An inter-ridge.

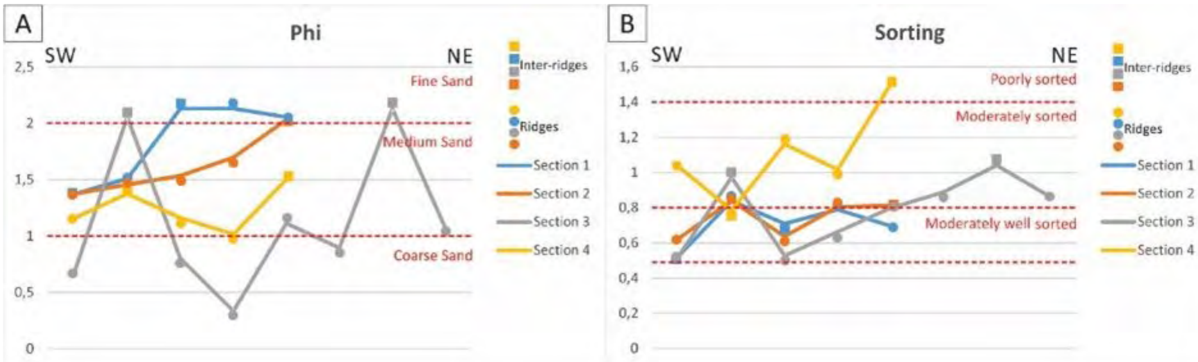

Figure 8 A. Krumbein phi (Φ) scale of each profile point; B. Grain sorting plot of the beach ridges and the inter-ridges samples.

5 Discussions

5.1 Conditions for the Differential Lithification in the Beach Ridges of the Campos - Macaé Canal

Despite its importance as a component of the PARNA Jurubatiba geodiversity, there are no records in the literature about the influence of the Campos - Macaé Canal excavation (anthropic action) over the geological processes and neither about its distribution. The exposure of part of the beach ridges induced the alteration and pedogenesis processes responsible for the local differential lithification. The discontinuous and continuous coatings of kaolinite with iron oxides / hydroxides, also sometimes forming meniscus and bridges, are the product of illuviation processes within the different horizons of the soil in formation (Andreis 1981; Lepsch 2011). The landscape conditions alteration due to the Canal excavation shifted the water table position, which subsequently influenced the clay infiltration and accumulation processes. Kaolinite can be originated by silicates alteration (mainly feldspars, Worden & Burley 2003) in response to the humid and warm climate of the study region. Additionally, a detrital origin is not discarded due to the proximity (1.3 km) between the studied outcrop and the beach ridges contact with the Barreiras Formation (Bezerra, Mello & Suguio 2006), a geologic unit with high kaolinite content (Suguio & Nogueira 1999), probably served as area source.

The granulometric analysis of the beach ridges sediments indicate that there is an increase in the sediments sorting and a decrease in the grain size from SW to NE in the study area. The same trends were observed for the current beach sands (Pereira et al. 2017), as well as in the outcropping sandstone on the Campos - Macaé Canal margins, and it is coincident with the current sediment direction transport along the coast area (from SW to NE) (Vilela 2015). The samples of the Canal and of beach ridges and inter-ridges present similar mineralogy, reflecting probably equivalent source areas. Although, there are granulometric and mineralogical variations in the Holocene coastal sediments in other areas of the Paraíba do Sul Deltaic Complex (Silveira 2017), our data do not present significatively variations that support the occurrence of local lithification in the canal margins.

5.2 Anthropic Influence?

The studied sandstone occurs exclusively in the excavated section of the Campos - Macaé Canal, not being observed in the natural channels over inter-ridges that connect the lagoons located in the PARNA Jurubatiba. The differential lithification of the Canal margins was induced by an anthropic action, that promoted changes in the phreatic position and promoted the development of pedogenic processes.

No cases of siliciclastic rocks formed by anthropic action were found in the scientific literature. In general, sedimentary rocks induced by human activity are formed by chemical precipitation, mainly limestone. For example, in the rocky shore of the Arraial do Cabo municipality a thick layer of limestone covers Paleoproterozoic orthogneisses as a product of the industrial production of sodium carbonate by the Companhia Nacional de Álcalis, as explained by Carvalho et al. (2021).

Another example occurs in the eastern Mediterranean Basin (Israel), where Itkin, Goldfus and Monger (2016) indicated that some calcretes are human induced, formed where the soil was occupied for a long time, constructed agricultural terraces and accumulated archaeological materials like pottery. The criteria used to differentiate these anthropogenic from natural calcrete is its spatial distribution: whereas the natural calcrete has a regional environmental distribution, the profiles that are affected by anthropogenic actions have a very local distribution. The same interpretation can be used to discuss the anthropic origin of the studied sandstone, which occurs locally, only where the channel was excavated.

Also, in Saudi Arabia, the construction of an asphaltic road on a coastal zone transformed coastal lagoons environment with carbonate deposits into hypersaline ponds with evaporitic deposits. The road formed an artificial barrier separating the coastal lagoons from the Red Sea, leading to a severe contraction of the coastal lagoons. In this work, Khawfany, Aref and Taj (2017) demonstrated how an anthropogenic construction can affect the environment. Likewise, the construction of the Campos - Macaé Canal in the XIX century could affect the sediments of inter-ridges on its margins.

It was not possible to directly determine the type of this rock according to the Underwood (2001a, 2001b) or Peloggia (2018) classification. However, using the concepts of Peloggia et al. (2014), the studied sandstone could be classified as mechanically modified technogenic ground.

Nevertheless, considering the International Mineralogical Association (Hazen et al. 2017) proposal to classify produced compounds as minerals, (e.g., by the weathering of other minerals exposed by human excavations), it is possible to evaluate the studied rock from an anthropic perspective. Thus, this occurrence is an example of modified geodiversity by human action, since the local differential lithification formed only where the Canal was excavated.

5.3 Can this Anthropic Sandstone be Considered a Geological Heritage?

It is not uncommon to hear the phrase "natural is everything that was not made by human". This definition, which delimits the artificial scope of the natural, removes human being from their essence as part of nature. This vision, nurtured since ancient Greece, places people and nature in different fields. However, at the end of the twentieth century, emerged a movement where the human being begins to understand that it will need to unify the "world of man" with the "world of nature" to account for a healthier life and glimpse a future more optimistic (Mansur 2018).

Thus, progress was made toward the creation of environmental policies that also resulted in concepts and advances in the direction of geoconservation as a new branch of geosciences (Henriques et al. 2011). Terms such as geodiversity, geological heritage, geoconservation, geotourism, geoparks and geoethics were developed. Today, the creation of a new division of geological time is discussed, which is the Anthropocene.

Many authors, such as Brilha (2016, 2018), Carvajal and González (2003), Castro, Mansur and Carvalho (2018), García-Cortés and Carcavilla-Urqui (2009), conceptualize geological heritage within the scope of its natural origin. But, can we consider an anthropic rock as a geological heritage?

Researchers in this area of knowledge consider the values and characteristics of sites and samples to define a geological heritage, such as scientific value, rarity, cultural, tourist and educational value. We understand that this site meets all of these requirements. Its scientific value is based on the fact that the site provides direct information on the process of pedogenesis, especially in terms of time for lithification and the infiltration process of the clay, which in this case, was less than 200 years. As for rarity, we have not found in the international literature any other example of sandstone formed under these conditions. As for cultural value, its relevance is presented by the decision of the Emperor of Brazil, in the 19th century, which led to the construction of the second largest artificial channel in the world. Its geotouristic value can be used because it is perfectly visible for about 1 km when visiting the tourist boat of PARNA Jurubatiba. Regarding the educational value, we understand that it can be used at various levels of education.

6 Conclusions

The excavation of the Campos - Macaé Canal is responsible for the differential lithification in a part of the beach ridges that occur on its margins. The evidences found in this study indicate that: (a) it occurs locally, with narrow thickness along 1 km of Canal margins exactly where the Canal was excavated and deepened; (b) the mineralogical and sedimentological studies point out that there are similarities between the samples collected in the Campos - Macaé Canal and in the adjacent beach ridges, indicating that there are no natural variations that can explain the differentiated lithification of this Canal margins; and (c) the presence of kaolinite and iron oxides/hydroxides arranged in continuous coatings, meniscus and bridges is related to pedogenic processes induced by Campos - Macaé Canal excavation. The kaolinite-rich sediments from the Barreiras Formation probably served as a source for the clay minerals present in these beach ridges. Furthermore, this anthropic induced rock amplified the discussion about the geodiversity concept, since the genesis processes are natural, but induced by anthropic action.

And could this sandstone be considered a geological heritage site? This occurrence is unique, because no other similar ones have been identified in the literature and even the anthropic rocks classification studies do not present examples of similar occurrences. Its record the human being capability to produce unexpected and collateral geological processes that modified geodiversity. This singularity, insert this occurrence within the scope of the Geological Heritage concept. It has touristic relevance, historical importance, scientific and educational value. For these reasons, the anthropic sandstone restricted to the margins of the Campos – Macaé Canal has been proposed as a new geosite for the Geopark Costões e Lagunas of Rio de Janeiro Project.

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Tainá Paiva Pereira: formal analysis, methodology; writing – original draft; visualization. **Kátia Leite Masur:** methodology; conceptualization; validation; writing review and editing; supervision; visualization. **Amanda Goulart Rodrigues:** methodology; validation; writing review and editing; supervision; visualization.

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