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Assessing Holocene Evolution of the Parnaiba River Delta using Petrophysical, Radiocarbon Dating, and Sedimentological Analysis
Estudo da evolução Holocênica do Delta do Rio Parnaíba através de análises petrofísicas, de datação por radiocarbono e sedimentológicas

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Abstract

The Parnaíba River Delta, located in northeastern Brazil, is one of the few examples of a deltaic depositional system with its pristine characteristics well preserved. This has placed it the spotlight of scientific research for the most diverse areas. The present work aimed to identify changes in the depositional environment based on stratigraphic and sedimentological analysis. Vibracores were collected in several places such as an old mangrove forest, in active tidal channels and supratidal swamp zones. The study included sediment analysis associated with petrophysics (Gamma Ray Spectrometry) and age dating by the radiocarbon method. In the first phase, the gamma-ray spectral analysis and the photographic record of the cores were carried out, followed by the stratigraphic description (color, texture, presence of organic matter, fossil content, sedimentary structures), as well as the identification and selection of material for dating. Subsequently, the cores were sampled at regular intervals, every 4 cm, for grain size, compositional (organic matter and calcium carbonate quantification), and mineralogical analyses. The results obtained showed mineralogical variations, which indicate changes in sedimentary origin. The gamma-spectrometric data tend to show higher values with the decrease of the grain and are associated with the sedimentological, stratigraphic, and mineralogical data, improving the interpretation of the depositional history. The contents of organic matter and calcium carbonate, in general, presented variations related to the grain size, with fine sediments (fine sand, silt and clay) presenting higher contents of organic matter, while carbonate is related to the presence of shells. Datings showed ages ranging from 4057± 22 BP to recent (1950 AD). The integration and joint analysis of the data allowed a better interpretation of the Late Holocene evolution of the old channels of the Parnaiba river that are currently working as a system of tidal channels.

Keywords: Gamma Ray spectrometry; Vibracores; Sedimentology.

Resumo

O Delta do Rio Parnaíba, localizado no nordeste do Brasil, é um dos poucos exemplos de sistema deposicional deltaico com suas características primitivas bem preservadas. Isso o tem tornado alvo de pesquisas científicas nas mais diversas áreas. O presente trabalho visa identificar mudanças no ambiente deposicional baseado nas análises estratigráficas e sedimentológicas. Foram coletados testemunhos por vibração em locais como florestas antigas de mangues, canais de marés ativos e zonas de pântanos de supramarés. O estudo inclui análises sedimentológicas associadas com petrofísica (espectrometria de raios gama) e datação por radiocarbono. Inicialmente, a análise de espectrometria de raios gama e o registro fotográfico dos testemunhos são feitos, seguidos pela descrição estratigráfica (cor, textura, presença de matéria orgânica, conteúdo fossilífero e estruturas sedimentares), bem como a identificação e seleção de material para datação. Em seguida os testemunhos foram amostrados em intervalos regulares, a cada 4 cm, para as análises granulométricas, composicional (matéria orgânica e carbonato de cálcio) e mineralógica. Os resultados obtidos mostraram variações mineralógicas, o que indica mudanças na proveniência sedimentar. Os dados de espectrometria de raios gama mostraram elevados valores com a diminuição da granulometria e estão associados com os dados sedimentológicos, estratigráficos e mineralógicos, auxiliando na interpretação da história deposicional. Os teores de matéria orgânica e carbonato de cálcio, no geral, apresentam variações relacionadas a granulometria, com sedimentos finos (areia fina, silte e argila) apresentando altos teores de matéria orgânica, enquanto carbonato está relacionado com a presença de conchas. A datação mostrou idades variando de 4057± 22 BP até o recente (!950 AD). A integração e análise conjunta dos dados permitiram uma melhor interpretação da evolução durante o Holoceno tardio nos canais antigos do rio Parnaíba que estão atualmente atuando como um sistema de canais de marés.

Palavras-chave: Espectrometria de raios gama; Testemunhos por vibração; Sedimentologia.

1. Introduction

The Parnaíba River Delta (PRD) is located between Piauí and Maranhão states on the northeast Brazilian coast; its coastline is 100 km long within an asymmetrical shape, built in a wave-tide dominated environment (Gois Smith et al. 2021; Szczygielski et al. 2014). The PRD is a well-preserved environmental area, and because of this, it is possible to investigate its “pristine” geological and biological aspects.

Deltas, by definition, are transitional systems formed by sediments carried by a river into the ocean or another water body (Galloway 1975; Bhattacharya et. al. 2006), and of high economic significance because they can generate rocks of great potential for fluids storage (hydrocarbon and water) (Pedreira da Silva, Aragão & Magalhães, 2008). The PRD region is characterized by low population density and a low industrial capacity, with ecotourism and agriculture being its main economic activities (Ibáñez et al., 2018). Therefore, it has been the subject of studies in the most diverse areas of science.

For a delta to be formed the sediment supply of the river must be greater than the reworking capacity of the ocean or water body the river goes into. Thus, the sediments are accumulated in the river’s mouth and its vicinities. The energy of the river flow must be strong enough to keep one or more river channels open (Martin, Suguio & Flexor, 1993).

The Parnaíba River delta has been subject to many studies due to its state of preservation, which allows a better understanding of a natural delta’s morphological and hydrodynamical characteristics and its evolutionary process. We highlight the works by Szczygielski et al. (2014), Aquino da Silva (2015), Aquino da Silva et al. (2016), Gois Smith (2020), Gois Smith et al. (2021), and Barbalho (2022), carried out along the delta, using sedimentological analysis, remote sensing and high-resolution shallow seismic.

Discussions about recent processes of delta lobe switching in the PRD as an example of significant natural changes in the evolution of a delta have been one of the focuses of these studies. According to Szczygielski et al. (2014) and Gois Smith et al. (2021), the PRD underwent a process known as delta lobe switching, based on geochemical (organic Carbon/ total Nitrogen ratios) and provenance studies, respectively. Barbalho (2022) identified U and V shaped paleochannels (plan view) in the western and eastern portion of the delta, respectively, and their morphology (width and depth) was similar to the incised valleys determined by Aquino da Silva et al. (2016). The U-shaped was associated with the main channel of the Parnaíba River, and V-shaped was associated with distributary rivers, which means evidence for the delta lobe switching.

The present study aims to investigate the PRD evolution through gamma-ray spectrometry and radiocarbon dating performed on sediments along the delta. For this purpose, vibracores collected in ancient mangrove forests, active zones of tidal channels, and supratidal swamps were used.

2. General Settings

The Parnaíba River Delta’s tidal conditions are classified as mesotidal and semidiurnal, with a 3.3m range during spring tide and 1.7m during neap tide (Aquino da Silva et. al. 2015). The wind has a northeast direction with average velocities ranging from 2m/s to 6m/s and the wave is dominant in a southwest direction with 1m height (Bittencourt et al. 2005).

The Parnaíba River (PR) originates from the east Brazilian highlands and flows north, forming the boundary between Piauí and Maranhão states (Szczygielski et al. 2014). On the east side of the PRD flows the Iguaraçu river, which is the last distributary river of the PR, and the west side is composed of complex tidal channels connected to the PR by an artificial channel opened in the 1960s (Aquino da Silva et al. 2015).

The Parnaíba River Watershed (PRW) is located in the Brazilian northeast, between Ceará, Piauí, and Maranhão states, and is approximately 331.441 km². In addition, the PRW drains to two great structural units: the crystalline basement and the Parnaíba Sedimentary basin. Thus, the PRW area is covered by Cenozoic sediments (sand and clay), Mesozoic and Paleozoic sedimentary rocks (sandstone and claystone), and Precambrian rocks (gneiss, granite, and migmatite) (MMA 2006).

The Parnaíba basin covers an area of approximately 400.000 km² and is mainly composed of Paleozoic sedimentary rocks (Góes and Feijó 1994). The Barreirinhas Basin is located in the Brazilian Equatorial Margin, between Maranhão and Piauí states, composed of Quaternary sedimentary rocks and is approximately 46.000 km² (Trosdtorf. et al. 2007).

The PR flows mostly over sedimentary rocks from Parnaíba Basin and enters the Barreirinhas Basin lowermost section (Aquino da Silva et al. 2016).

3. Materials and methods

During two field campaigns, in 2015 and 2016, the sediments of the PRD were acquired by the vibracore method (Lanesky et al. 1979).

Eight vibracores were taken in the PRD (from PR's mouth to the west side's tidal channels) (Figure 1). The vibracores named TUT are from the 2015 field campaign, while those with VC prefixes are from the 2016 field campaign.

Gois Smith et. al., (2021) used some of these cores (TUT-07, TUT-02, VC-03, VC-10, VC-05 and VC-07) focusing on a provenance study using the mineralogy observed on the sandy fraction of the sediments. In this paper, the Holocene evolution of the PRD is investigated with radiocarbon dating, gamma spectrometry and sedimentological analysis.

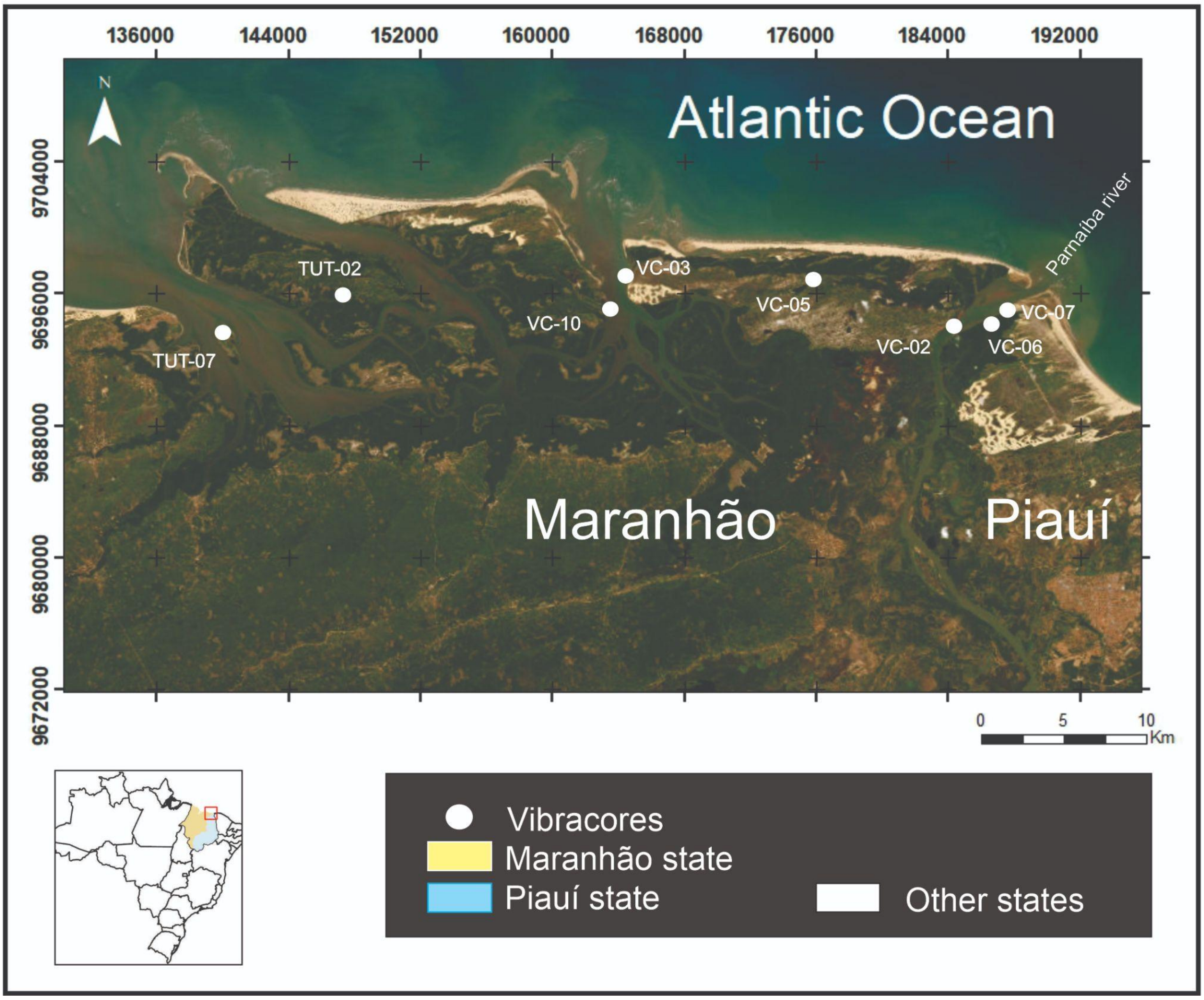

Figure 1. The location of the study area in the Parnaiba River delta shows all cores used in this study.

The gamma ray log can be used directly for interpreting environments of deposition, is one of the most useful logs for sequence stratigraphic analysis, and record characteristic coarsening-upward and fining upward sequences very efficiently (Bjørlykke 1989; Emery and Myers 2009; Posamentier & Allen 1999; Rider, 1986; Van Wagoner et al. 1990). The radioactivity measured by the gamma tool is generally a direct function of the clay-mineralogy content, and thus grain size and depositional energy. It is to distinguish between shale/clay and not shale/clay based on three radioisotopes K, Th and U. However, different types of shale have different total gamma ray depending on the Th, U and K concentrations associated with them. The total gamma ray is function of the radioactive material in the formation, and spectral gamma ray employed the same basic type of detection of the first one but using a broad energy region. The gamma rays are analyzed into a number of different energy bins, which allow point out some anomalies such as formations with unusual excess of K, U and Th (Ellis and Singer 2007).

It is possible to correlate Th and U to sedimentary provenance studies (Adams & Weaver 1958). Th and U ratios must indicate oxidation conditions in the depositional environment. Th/U lower than 2 characterizes a U rich environment (reducing conditions), which means deposition under marine conditions. Th/U ratios higher than 7 characterize the oxidizing environment, indicating deposition under continental conditions (Adams & Weaver 1958). Schlumberger (2005) proposes a diagram Th vs. K, which recognizes clay minerals from thorium and potassium such as micas, feldspar, chlorite, kaolinite, montmorillonite, illite, glauconite and heavy thorium-bearing minerals. In the diagram, Th/K higher than 25 indicates heavy minerals, and lower values indicates the presence of feldspar, micas and other clay minerals. The other mineral groups are in intermediated proportions.

Only on the cores with the VC prefix were performed gamma-ray measurements, which were done at the Sedimentological Laboratory of Petrobras facilities in Natal, Rio Grande do Norte, using a Spectral Core Gamma system.

The AMS radiocarbon dating was carried out in terrestrial organic material and bivalve shells collected from vibracores in different depths (one sample for each core). The AMS radiocarbon ages were determined at the Laboratory, University of Kiel, Germany and Poznań Radiocarbon Laboratory, Adam Mickiewicz University, Poland by a 3 MV HVEE Tandetron 4130 AMS system. That method is described in detail by Linick et al. (1989). Gois Smith et. al., 2021, presented five radiocarbon ages (TUT-07, TUT-02, VC-03, VC-10, VC-05 and VC-07), also used in this paper, with addition of one more (VC-02).

The vibracores were described and sampled (except VC-02, which was described macroscopically only) at regular intervals of 0.04m in 249 samples, used to morphoscopy, CaCO3 and organic matter contents.

The mineral assemblage and grains morphoscopy were described in a Zeiss binocular microscope, model Discovery - V8, in a 4 cm interval samples in the cores.

The CaCO3 content indicated the marine influence on the coastal environment and was determined using 10% hydrochloric acid (HCl) solution. The samples were pre-weighed using a laboratory precision balance before being subject to acid action until the reaction ceased, which was determined by visual inspection. After this, they were washed using distilled water in a pre-weighed paper filter, dried in the stove, and weighed to obtain the carbonate content.

The organic matter (OM) content was determined by the “Loss on ignition” method (Davies, 1974), in which the samples, previously weighed, were submitted at 600ºC for five hours in a laboratory oven.

4. Results

The two cores located further west of this study, TUT-07 and TUT-02, shows a finning up grain size with an increase in CaCO3 and O.M. contents. VC-03 and VC-10 were taken closely, on the same tidal channel, but have different logs (gamma ray, grain size, carbonate, and organic matter). VC-03 is coarsening to the top, while VC-10 is finning to the top. In both cores, the gamma ray, carbonate, and organic matter logs are increasing as the grains are decreasing as the grains are coarsening. VC-05 has no granulometric variation, and VC-07 and VC-06 are coarsening upward. VC-02 is similar to VC-07´s radiocarbon age but presents a different stratigraphic pattern.

Regarding the mineralogy of the sediment found, quartz and ilmenite are the only components observed in all cores, and the mineral assemblage changes across the delta. Some specific minerals, like garnet and cordierite, only occur on the west side (TUT-07 and TUT-02) and east (VC-05, VC-06, and VC-07). Pyrite is observed only in the Parnaíba River main channel (VC-07), and sillimanite is common only in the VC-10, the vibracore in which was found the oldest age. Table 1 shows heavy minerals observed in each core.

The radiocarbon ages were obtained from materials collected in the cores and are listed in Table 2.

The core TUT-07 was taken in a tidal channel near Tutoia city, in Maranhão state, and it is 194 cm long. The material used for radiocarbon dating was collected in 180-181 cm, and it was obtained 3280 ± 26 BP yr of radiocarbon age and 3.6-3.5 kyr of calibrate age. At the top of the core to 88 cm is a very fine to fine sand with medium to high sphericity and angular to sub-angular grains. The heavy mineral assemblage is composed of epidote, ilmenite, hornblende, muscovite, and tourmaline. In that interval is observed low content of CaCO3 (4.0% to 7.2 %) and high content of OM (3.4% to 18.1%). At 88 cm to 118 cm, the OM percentage decreases (1.2% to 2.7%), and garnets are observed in the heavy mineral assemblage. From 118 cm to 126 cm, the grain size increases to medium sand with subangular grains and low sphericity. The CaCO3 content is 12%, and the OM content is 5.1%. The heavy mineral assemblage is made up of ilmenite, tourmaline, monazite, muscovite and hornblende. Fine sand with low sphericity and angular grains is observed at the base (126 cm to 194 cm). The CaCO3 and OM percentage are low (4.6% and 3.0%), and the heavy minerals observed are epidote, tourmaline, monazite, ilmenite, garnet, muscovite, and hornblende.

Core TUT-02 was taken near TUT-07 in a small tidal channel, 184 cm long. The radiocarbon dating age was obtained with plant fragments collected at 145 cm and, as a result, were observed at 3870 ± 40 yr BP radiocarbon age and 4.4 - 4.3 kyr of calibrate age. A silt layer with subangular and medium sphericity grains is observed at the top of the core to 72 cm. The heavy minerals observed are monazite, staurolite, ilmenite, magnetite, epidote, hornblende and cordierite. In that interval, medium contents of CaCO3 (4.4% to 1.2%) and OM (9.9% to 6.7%) are observed. From 72 cm to 140 cm, the grain size increases to sand with subangular and high spherical grains. The CaCO3 and OM percentage are lower than the previous sedimentary interval (3.0% and 7.5%, respectively) and the heavy minerals observed are cordierite, monazite, epidote, hornblende, tourmaline, ilmenite, sillimanite, magnetite, biotite, and garnet. Through that interval, the grain size increases, and the CaCO3 and OM contents decrease to below 0.4%. Fine sand with subangular to subrounded and low sphericity grains is observed at the base (140 cm to 184 cm). The CaCO3 and OM contents increased to 4.9% and 7.4%, followed by an abrupt decrease in CaCO3 values to 0.3%. The heavy minerals observed were magnetite, monazite, ilmenite, epidote, tourmaline, staurolite, titanite, garnet and hornblende.

Table 1. Heavy minerals observed in each core. Ep: Epidote; Ilm: Ilmenite; Moscov: Moscovite; Tourm: Tourmaline; Monaz: Monazite; Bt: Biotite; Staur: Staurolite; Magn: Magnetite; Tit: Titanite; Ap: Apatite; Sil: Silimanite; Pyr: Pyrite; Grnt: Garnet; Cord: Cordierite; Horn: Hornblende.

<table>
<tr><th></th><th>TUT-07</th><th>TUT-02</th><th>VC-03</th><th>VC-10</th><th>VC-05</th><th>VC-06</th><th>VC-07</th></tr>
<tr><td rowspan="10">0
10
20
30
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170
180
190
200</td><td rowspan="4">Ep, Ilm, hornb, moscov, tourm.</td><td rowspan="3">Monaz, staur, ilm, magn, ep, hornb, cord.</td><td rowspan="2">Ilm, ep, bt, magn, monaz, moscov.</td><td>Ilm, ap.</td><td rowspan="2">Monaz, Ilm, ep,magn, staur, hornb, grnt, cord.</td><td rowspan="2">Moscov, ilm, tourm, ep, monaz, bt.</td><td rowspan="2">Ilm, grnt, moscov, ep, hornb, monaz, cord, ap, tourm, magn.</td></tr>
<tr><td rowspan="7">Ilm, ap, grnt, magn, silim, moscov, tourm, hornb.</td></tr>
<tr><td rowspan="5">Ilm, ep, staur, Monaz, magn, moscov.</td><td rowspan="6">Monaz, Ilm, ep,magn, hornb, grnt, cord.</td><td rowspan="3">x</td><td rowspan="3">Ilm, ap, moscov, monaz, grnt, cord, hornb, tourm.</td></tr>
<tr><td rowspan="3">Bt, Grnt</td></tr>
<tr><td rowspan="2">Ep, Ilm, hornb, moscov, tourm, grnt, monaz.</td></tr>
<tr><td rowspan="2">Grnt, ilm, monaz, bt.</td><td rowspan="2">Ilm, grnt, ep, tourm, moscov, pyr, hornb.</td></tr>
<tr><td rowspan="4">Ep, tourm, ilm, monaz, Grnt, hornb, moscov</td><td rowspan="4">Monaz, staur, ilm, magn, ep, hornb, tourm, tit, grnt</td></tr>
<tr><td rowspan="2">Ilm, ep, staur, monaz, moscov.</td><td rowspan="2">Grnt, ilm, monaz, moscov ep, tourm.</td><td rowspan="2">Ilm, ep, monaz, pyr, hornb, moscov, grnt, tourm, cord.</td></tr>
<tr><td rowspan="2">Ilm, magn, ap, ep, moscov, sil, tourm.</td><td rowspan="2"></td></tr>
<tr><td>Bt, ilm, magn, moscov.</td><td></td><td></td></tr>
</table>

Table 2. Radiocarbon ages and calendar ages of each vibracore and the depth with which the material for datation was collected. *Published on Gois Smith et., al. (2021).

Vibracore	Depth (cm)	Material	Age Cal (kyr)	Radiocarbon age (yr)	Lab Code
TUT-07	180 – 181	Shell	3.6 – 3.4 BP	3280 ± 26 BP	KIA 52072*
TUT-02	145	Plant	4.4 – 4.3 BP	3870 ± 40 BP	KIA 51069*
VC-10	156 – 158	Plant	4.6 – 4.5 BP	4057 ± 22 BP	KIA 52069*
VC-03	194 – 196	Plant	> 1950	> 1950	KIA 52070*
VC-05	153 – 156	Shell	1.2 – 1.1 BP	1220 ± 18	KIA 52074*
VC-02	220 – 236	Plant	0.35 – 0.36 BP	336 ± 18 BP	KIA 52068
VC-07	170	Shell	0.44 BP	427 ± 14 BP	KIA 52075*

Core VC-10 was taken in the eastern margin of Ilha do Caju, in a tidal channel between and close to Ilha das Canárias, in mangrove deposits. It is 195 cm long, and the material used for radiocarbon dating was collected between 156 cm and 158 cm, and the radiocarbon age is 4057 ± 22 y BP, and the calibrated age varies from 4.6 - 4.5 kyr BP. At the top, to 40 cm, it is a silt layer with subangular and subrounded grains and medium to high sphericity. Ilmenite and apatite were observed in the heavy mineral assemblage, and the CaCO3 and O.M contents showed high values (12.8% to 17.7% and 13.6% to 15.8%, respectively). The gamma-ray log also showed high values (8.84 API), corroborating the fine grains observed in the grain size. From 40 cm to 52 cm, it is a transitional silt to sand, and the heavy mineral assemblage observed was composed of ilmenite, apatite, hornblende, magnetite, and sillimanite. The CaCO3 and O.M contents showed medium to low values (5.90% to 11.03% and 0.97% to 4.97%, respectively), while the gamma-ray log showed a low value (0.30 API). A medium sand pack interval between 52 cm to 150 cm is observed with ilmenite, apatite, garnet, magnetite, muscovite, sillimanite, and tourmaline as heavy minerals assemblage. CaCO3 and O.M. contents are the lowest obtained in all cores (0.33% to 1.94% and 0.23% to 0.63%, respectively) as gamma ray log (0.43 API to 0.29 API). In 150 cm to 159 cm, it is a silt interval with some sand lens and the presence of ilmenite and magnetite is observed as heavy minerals. The CaCO3 and O.M. contents increase from 4.80% to 9.45% and 2.75% to 24.00%, and the gamma-ray log remains lower than 0.43 API. At the base (159 cm to 195 cm), it is a fine to medium sand interval with some silt lens and subrounded to angular grains and medium to low sphericity. The heavy mineral assemblage is composed of ilmenite, apatite, epidote, magnetite, muscovite, sillimanite and tourmaline. The CaCO3 and O.M. contents vary from 1.3% to 2.9% and 0.95% to 2.26%, respectively, and the gamma-ray log remains lower than 3.9 API.

Core VC-03 is 200 cm long and was taken in a western PR tidal channel near Ilha das Canárias' littoral deposits. Radiocarbon age was obtained in plants collected between 194 cm and 196 cm, and the result showed recent sediments with ages younger than 1950 AD. At the top to 55 cm, it is a fine to medium sand interval with plane parallel stratification with angular to sub-rounded grains and medium to low sphericity. The heavy mineral assemblage is composed of ilmenite, epidote, biotite, magnetite, monazite and muscovite. The CaCO3 and O.M. values vary, 1.55% to 6.40% and 1.85% to 2.50%, and gamma-ray log 0.32 API to 11.17 API. At 55 cm to 141.5 cm is a fine to medium sand interval with silt laminations and ilmenite, epidote, staurolite, magnetite, monazite and muscovite as heavy mineral assemblage. The CaCO3 and O.M. contents vary from 11.8% to 3.8% and 6.95% to 1.04%, respectively. The gamma-ray log significantly varied because of grain size variation (0.32 API to 8.38 API). Between 141.5 cm and 173 cm is a silt and sand interval with fine to medium sub-angular and sub-rounded sand with low to medium sphericity. The heavy mineral assemblage is composed of ilmenite, epidote, staurolite, monazite, and muscovite, and CaCO3 and O.M. contents are 8.9% to 11.8% and 5.1% to 6.95%, respectively. The gamma-ray log varies from 7.94 API to 8.38 API. At the base (173 cm to 200 cm) is a sand-silt pack with biotite, ilmenite, magnetite, and muscovite as heavy mineral assemblage. The CaCO3 and O.M. contents vary from 5.14% to 22.06% and 3.60% to 13.07%, respectively, and the gamma-ray log varies from 19.57 API to 7.69 API.

Core VC-05 is 160 cm long and was taken in a paleodunes system in Ilha das Canárias. Shell fragments were collected in 153 cm to 156 cm for radiocarbon dating, and the results indicated a 1.2 - 1.1 kyr BP cal age and radiocarbon age of 1220 ± 18 y BP. This core is composed of fine sand with some sedimentary structures (plane parallel stratification in 75 cm to 90 cm and cross-stratification in 110 cm to 115 cm). From the top to 60 cm, occurs medium sphericity and subrounded grains and the heavy mineral assemblage is composed of monazite, ilmenite, epidote, magnetite, staurolite, hornblende, garnet, and cordierite. The CaCO3 and O.M. contents vary from 5.2% to 10.5% and 11.6% to 20.2%, respectively. The gamma-ray log obtained the maximum 5.69 API. Sub-angular and low sphericity grains are observed at the base (60 cm to 160 cm). The heavy mineral assemblage is the same as the previous interval except for staurolite, which is no longer present. The CaCO3 and O.M. contents reached the maximum of 9.63% and 16.31%, respectively. The gamma-ray log varies from 3.67 API to 0.84 API.

VC-02 was taken in the west margin of PR, and along it, gamma-ray log, radiocarbon dating, and macroscopic description were obtained. It is 240 cm long, and plant fragments were collected at 220 cm to 236 cm for radiocarbon dating, resulting in a 336 ± 18 yr BP radiocarbon age and 0,35 – 0,36 BP kyr cal age. From the top to 100 cm is a silt layer with no sedimentary structures visible. The gamma-ray log is decreasing from 30 API to 18 API. Between 100 and 200 cm, the grain size increases with plane-parallel structures. According to this, the gamma-ray logs continue to decrease until 10 API. At the base, it is a fine sand interval with some medium sand.

VC-06 is 172 cm long and was taken in the east margin of PR. The sediment was not recovered from 64 cm to 100 cm, making it impossible to describe. From the top to 38 cm, it is a fine sand interval with medium to low sphericity and subangular and subrounded grains. The heavy minerals observed were muscovite, ilmenite, tourmaline, and epidote. Gamma-ray log increases from 4.82 API to 40.00 API, whereas CaCO3, and O.M. vary from 3.9% to 1.7% and 2.9% to 6.1%, respectively. From 38 to 64 cm there is a siltic interval with medium to low sphericity and sub-angular to sub-rounded grains, with some sand laminations and organic matter. The heavy mineral assemblage was composed of muscovite, tourmaline, monazite, ilmenite, epidote and biotite. The gamma-ray log remains at about 40 API. The CaCO3 and O.M. showed some increase until 4.18% and 8.42%. From 100 cm to 130 cm, the gamma ray values remain close to the found in the previous interval, about 29 API, confirmed with fine sand with medium to low sphericity and subangular to angular grains. Garnet, ilmenite, monazite and biotite were observed as heavy minerals. The CaCO3 and O.M. contents remain uniform, except at 120 cm (where it is the highest O.M. content in the core). At the base, there is a siltic interval with medium to low sphericity and angular and sub-angular grains. The heavy mineral assemblage is composed of muscovite, garnet, monazite, ilmenite, epidote and tourmaline. The gamma-ray log increases reaching its highest value at 172 cm (50 API), and the CaCO3 and O.M. remain uniform.

Core VC-07 was taken in the east margin of PR and is 170 cm long. The radiocarbon dating was obtained from shell fragments at the base (170 cm), and the results indicated a 427± 14 BP radiocarbon age yr and 0.44 BP kyr cal age. At the top to 28 cm, there is a fine sand and silt interval, with sub-angular and high sphericity grains. The CaCO3 and O.M. contents vary from 1% to 4 % and 4.7 % to 1.6 %, respectively, and the gamma-ray log varies from 1.92 API to 12.92 API. The heavy mineral assemblage is composed of ilmenite, garnet, muscovite, epidote, hornblende, monazite, cordierite and apatite. From 28 cm to 68 cm, a fine sand interval occurs with sub-angular to sub-rounded and low sphericity grains. The CaCO3 and O.M. contents decrease compared to the previous interval (0.1 % to 1.1 % and 3.1 % to 0.2 %, respectively), and the gamma-ray log increases, reaching 33 API. The heavy mineral assemblage is composed of cordierite, tourmaline, apatite, hornblende, garnet, epidote, magnetite, muscovite, ilmenite and monazite. From 68 cm to 108 cm, silt subangular to angular and medium to high sphericity interval is found. The CaCO3 and O.M. contents remain low (0.9 % to 4.2 % and 0.3% to 8.0%, respectively), while the gamma-ray log remains high but lower than the previous interval (23.1 API). The heavy mineral assemblage is composed of ilmenite, apatite, muscovite, monazite, garnet, cordierite, hornblende e tourmaline. From 108 cm to 136 cm, the grain size increases to very fine sand with sub-angular and medium sphericity. The CaCO3 and O.M. contents remain low (4.2 % to 1.3 % and 5% to 7%, respectively), and the gamma-ray log remains high (20.7 API to 18 API). The heavy mineral assemblage is composed of ilmenite, garnet, epidote, tourmaline, muscovite, pyrite, and hornblende. At the base (136 cm to 170 cm), there is a silt sub-angular and medium to high sphericity interval. CaCO3 and O.M. contents vary from 5.8% to 2.6% and 12.2 % to 6.7 %, respectively, and the gamma-ray log reaches the highest values in all cores (45.4 API to 19.3 API). The heavy mineral assemblage is composed of ilmenite, epidote, monazite, pyrite, hornblende, muscovite, garnet, tourmaline and cordierite.

Figure 2 shows the core logs and the places where each core was taken, and Figure 3 shows the cores and where radiocarbon dating samples were collected.

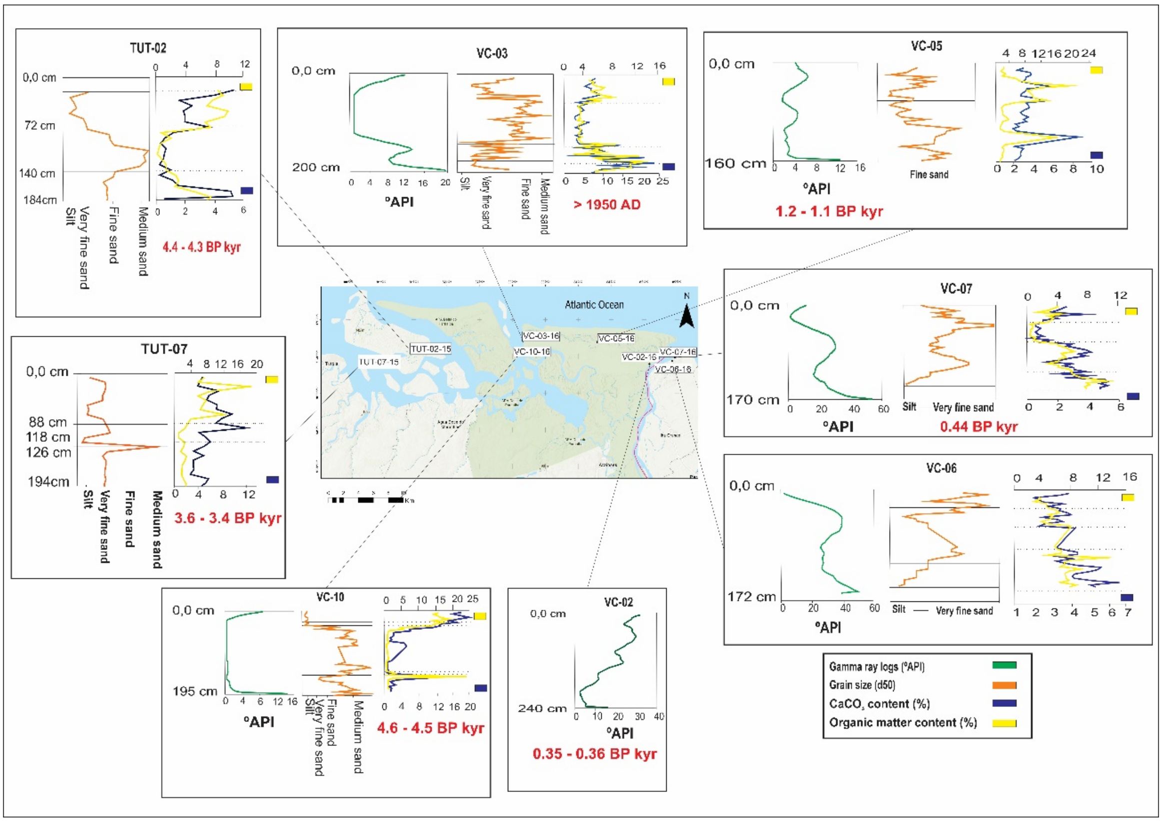

Figure 2: Core distributions along the delta, indicating the resulting logs from gamma ray, grain size, CaCO3 and organic matter contents analyzes.

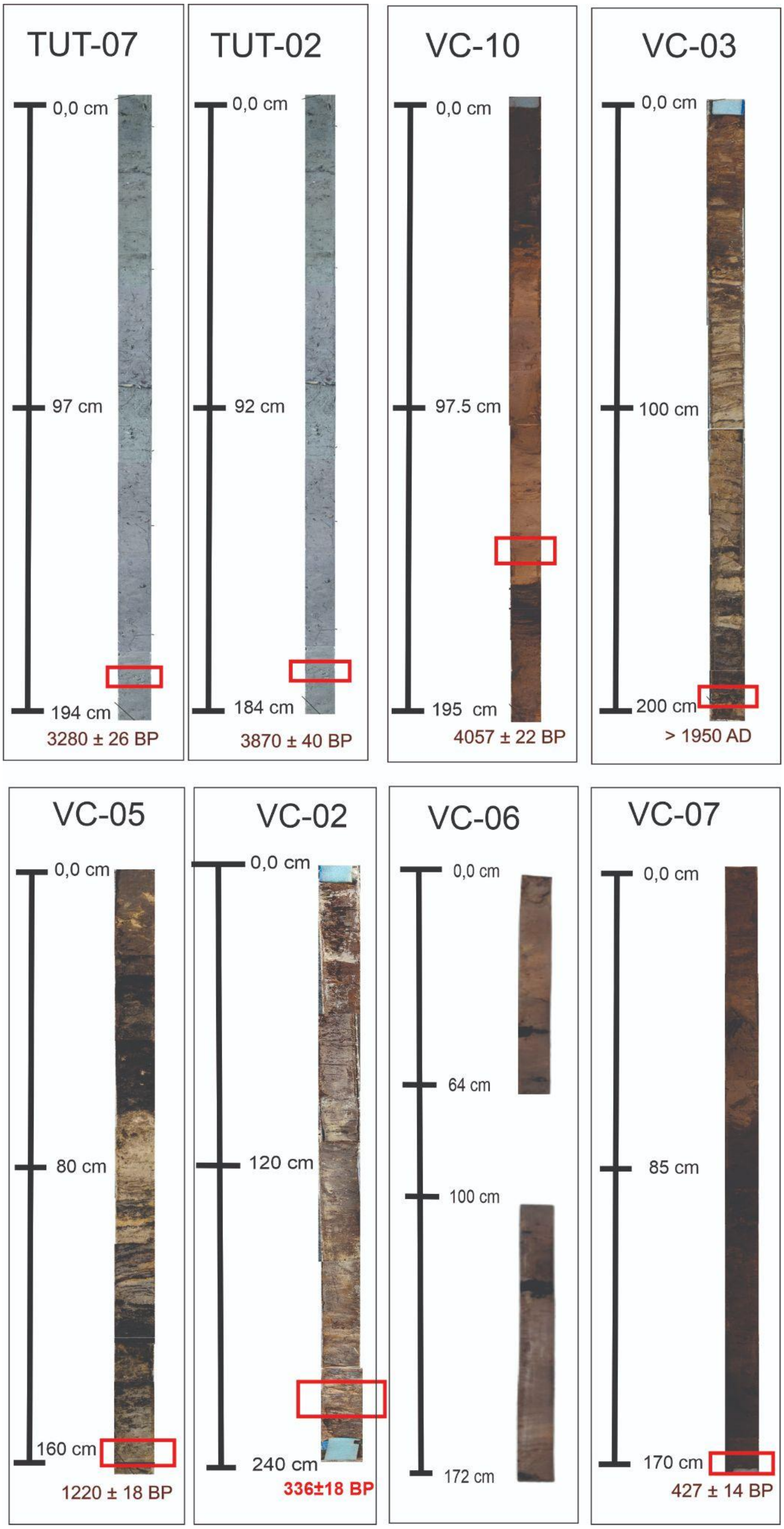

Figure 3. Photographs of all cores used in this paper with the red rectangle indicating where the dating material was collected and its respective radiocarbon age.

The Th/U ratio showed API values lower than 2 in almost all cores, suggesting a rich U environment, which can indicate reducing conditions in the paleoenvironment.

The Th/K ratio showed high values, which suggests the occurrence of heavy thorium bearing minerals (e.g. monazite, epidote, apatite) compared to clay minerals.

Generally, Th/K curves reach their highest values in fine sediments, except in the cores VC-06 and VC-07, which present higher values when the grains are coarsening. This log shows it is essential to verify hydrodynamics and sedimentary source changes, indicating changes in the depositional environment.

Figure 4 shows all the logs obtained from the Th/K (blue) and Th/U (red) ratios of each core and its gamma ray logs (green).

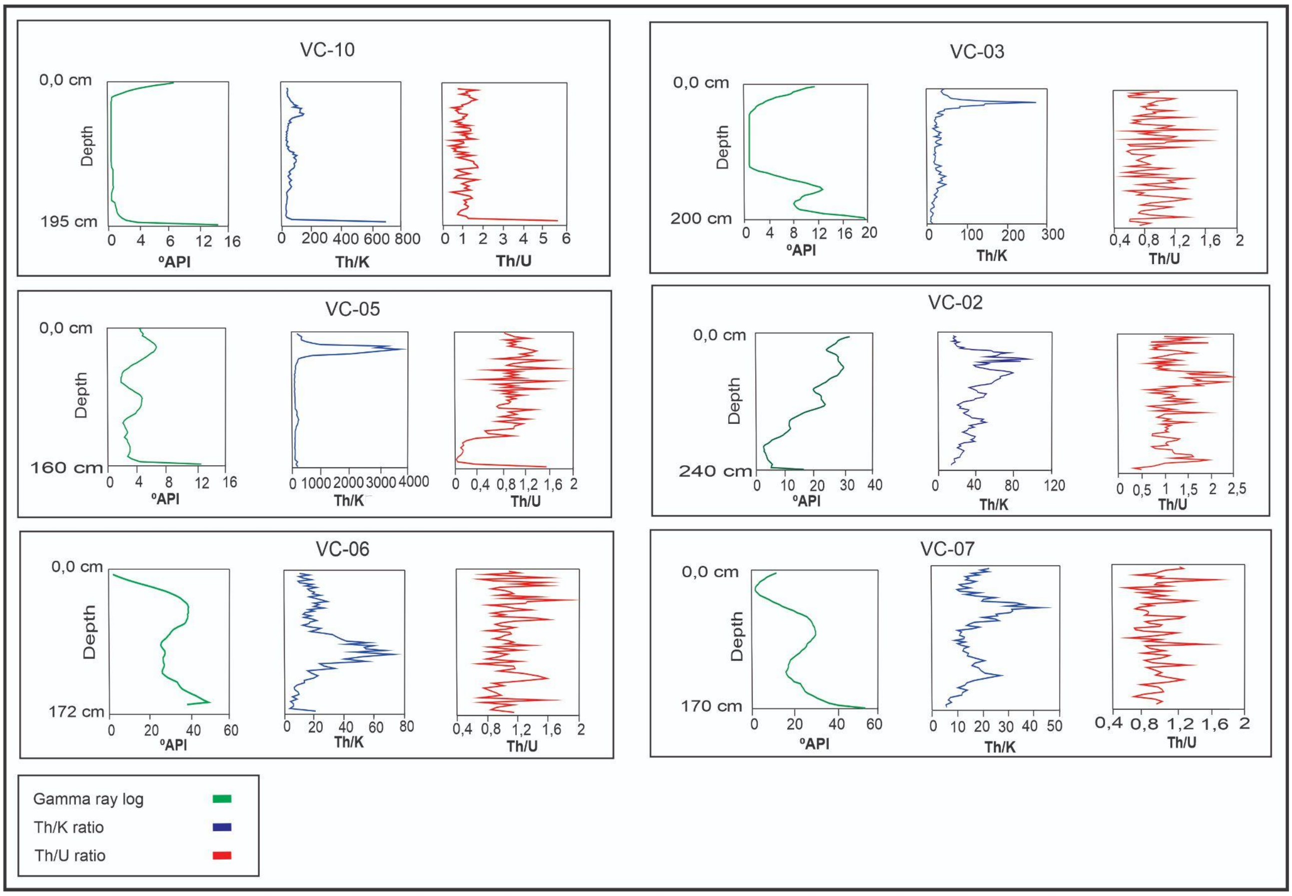

Figure 4. Gamma-ray, Th/K, and Th/U logs of each core.

5. Discussions

Mineralogy and morphoscopy analysis are commonly used in sedimentary provenance studies (Rosseto, 2013). In this study, key minerals like garnet and cordierite (found on the west and east sides), pyrite (present only in VC-07), and sillimanite (found only in VC-10) were determined. Hilbert et al. (2016) analyzed the dune field morphological pattern with grain size and heavy minerals in the eastern portion of Maranhão and, based on heavy minerals analysis, the westward alongshore drift brings sediments from the east coast of the Parnaiba River mouth and river itself.

TUT-07 and TUT-02, westernmost cores, show fining-up behavior, which could be interpreted as resulting from the reduction of hydrodynamic energy (Van Rijn 2007). The grains are angular on the base and rounded on top, indicating a possible upward increase in sediment transport distance.

VC-03, VC-06, and VC-07 are coarsening upward but did not show significant variation in morphoscopy (sphericity and rounding), which suggests a similar source or transport distance. On the other hand, VC-05 did not vary in terms of sediment properties compared to the other cores, suggesting deposition under constant hydrodynamic conditions. VC-10 was fining upward and observed significant grain size changes along the core (medium sand to silt), indicating that the depositional environment changed from high to low energy. Probably the Parnaiba River fed that tidal channel and, in 52cm the river changed its flow direction and the channel was abandoned, being under marine influence, common in asymmetric deltas tidal channels (Gois Smith 2020).

Gamma ray logs tend to show an increase in gamma count with the decrease of the grain size, related to the amount of clay minerals present (Myers & Bristow 1989).

On the west side, all cores have higher CaCO3 contents on the top than in the base, indicating an increase in marine influence over time (Barroso et al. 2019). On the other hand, in the east part, VC-07 has higher values on the base, indicating an increase in fluvial influence over time. VC-05 did not present significant variation, as already observed in terms of granulometry. VC-03 and VC-10 were taken close and both are the lowest and highest age obtained but have different logs, allowing relating radiocarbon age to CaCO3 values.

Radiocarbon ages vary along the delta, indicating some changes in the Parnaíba river flow direction in the late Holocene (Figure 2). Szczygielski et al. (2014) suggest a direct connection between the river and the western side of the delta; it only was confirmed later with mineral assemblage analysis done by Góis Smith et al. (2021). The results from this study, supported by gamma-ray logs, additional AMS radiocarbon dating, and associated with other geological analyses, showing different generations of sediments along the delta with different sedimentological patterns, corroborate the hypothesis of delta lobe switching.

6. Conclusions

Based on all analyses, different provenances were observed along the delta, confirmed with mineralogical analysis. The westernmost cores (TUT-07, TUT-02, and VC-10) present low CaCO3 and organic matter contents on the base, indicating that the west side was directly connected to the Parnaíba River at the beginning of the deposition.

The gamma ray logs were consistent with the stratigraphic description, granulometry, and CaCO3 and O.M. contents. Th and K ratios showed possible depositional or compositional changes. Th and U ratio results lower than 2 indicate the predominance of the marine environment.

VC-03 has the most recent radiocarbon age, and together with the results of other logs, it was interpreted as river sediments deposited on the delta plain, which were reworked and transported to the west side by coastal and beach related processes. At 140 cm, CaCO3 and O.M. decreases, indicating provenance changes, probably due to the influence of ephemeral rivers commonly found draining into the delta.

VC-05 logs showed no variation, this was attributed to its remote location with low hydrodynamic conditions the narrow tidal channel, without a direct connection to the Parnaíba River, in which it was taken. Moreover, VC-07 also did not present significant variation in granulometry, CaCO3, and O.M. logs, and morphoscopy showed angular and medium sphericity, indicating that its sediments belong to Parnaíba River main channel, where this core was taken.

VC-02 has a similar age to VC-07, but a different sedimentary pattern, in which their sediments may have been deposited from maritime currents from the east and VC-07 sediments, belong to the Parnaiba River source.

It was possible to conclude that the west side of the delta was directly connected to the Parnaíba River, and the present tidal channels are remnants of old fluvial channels. The transition from fluvial to tidal channels occurred after the event that caused the west part of the delta to be disconnected from the main PR channel. This is in accordance with the hypothesis proposed by other authors that a delta lobe switching event occurred in the Parnaiba River delta.

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