International Journal of Geosciences, 2025, 16(7), 405-422
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Geological Evolution of the Southern Coast of the Gulf of Mexico: Geomorphological and Sedimentological Evidence from the *Coatzacoalcos paleolagoon*

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How to cite this paper: Infante-Pacheco, V.E. (2025) Geological Evolution of the Southern Coast of the Gulf of Mexico: Geomorphological and Sedimentological Evidence from the *Coatzacoalcos paleolagoon*. *International Journal of Geosciences*, **16**, 405-422.
https://doi.org/10.4236/ijg.2025.167020

Received: June 28, 2025
Accepted: July 21, 2025
Published: July 24, 2025

Abstract

Geomorphological and sedimentological evidence and depositional ages of different geological units in the northern part of the lower Coatzacoalcos River basin suggest the existence of a previously unreported paleolagoon on the southern Gulf of Mexico coast. In this paper, we refer to it as the *Coatzacoalcos paleolagoon*. We developed a digital elevation model to simulate the accumulation of sand sediments that, over time, filled the paleolagoon, an event that began approximately 12,000 - 10,000 years ago. It collected 22 sediment samples to analyze their grain size distribution, percentage, and color, revealing their affinity in defining the boundaries and shape of the *Coatzacoalcos paleolagoon*. The grain size distribution was obtained by sieving. The volume-grain size plots revealed differences between the two sediment types: cream-colored sand and red-orange silty sand and clay. Results showed that the sand sediments originated in the Chiapas Massif, which is formed by quartz-rich intrusive igneous rocks (granite and granodiorite) that filled the paleolagoon. Silty sand and clay sediments are present at the boundaries of the paleolagoon, having a distinct origin from the sand. They originate from extrusive igneous rocks of the Sierra de Santa Martha (andesites, andesitic tuffs, and basalts).

Keywords

Gulf of Mexico, Coastal Sedimentology, Coastal Geology, Paleogeography, Veracruz Geology

1. Introduction

Understanding the geological evolution surrounding cities' sedimentary environment is essential to better understanding the natural phenomena currently occurring in the physical environment and the hydrological risks that can occur after a meteorological event, such as storms and their resulting flooding.

Evidence such as the geomorphology, sedimentological distribution, and depositional ages of the different geological units in the northern part of the Lower Coatzacoalcos River Basin has shown the existence of a previously unreported paleolagoon in the geological literature or other branches of science. In this work, we refer to the *Coatzacoalcos paleolagoon*.

In this work, we collected 22 sediment samples to analyze their particle size distribution, grain size percentage, and color. We considered that the affinity between the sediment samples could determine the boundaries and shape of the *Coatzacoalcos paleolagoon*.

Recognizing this geological event during the development of coastal evolution in the southern Gulf of Mexico (GOM) helps us better understand many of today's phenomena, such as flooding risks associated with heavy rainfall.

It also helps to understand the dynamics of contaminant mobility in the Lower Coatzacoalcos River Basin, as mentioned in the work carried out by [1]. However, it is worth noting that the sediments that fill the *Coatzacoalcos paleolagoon* act as a buffer, regulating the water level so that it does not increase rapidly. Most of the water volume is drained as groundwater, not only through the Coatzacoalcos River channel.

2. Location

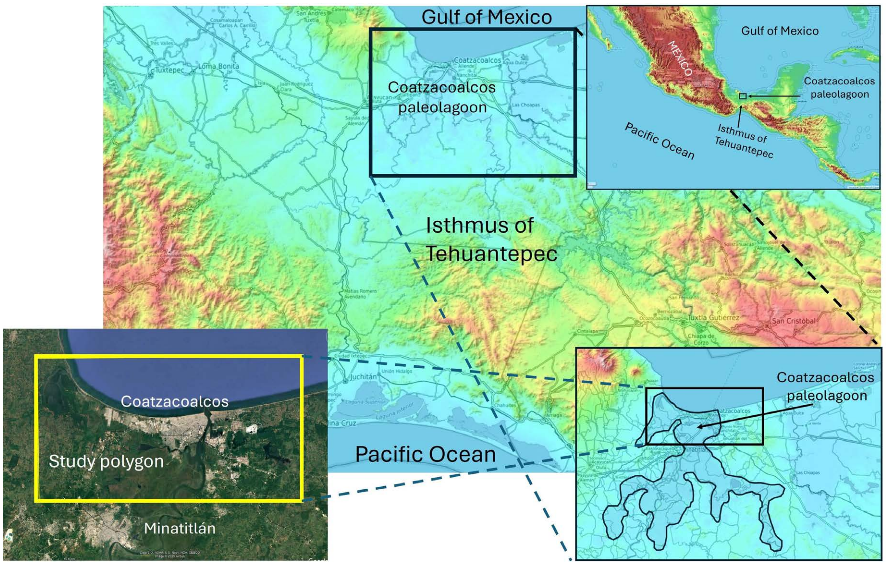

Figure 1. Location of the study area in the northern part of the *Coatzacoalcos paleolagoon* within the isthmus of Tehuantepec area in Mexico to the north lies the gulf of Mexico, and to the south, the pacific ocean.

The *Coatzacoalcos paleolagoon* is in the Isthmus of Tehuantepec at the southernmost point of the GOM, in the southeastern part of the State of Veracruz in

Mexico. The study area is located in the northern part of the *Coatzacoalcos paleolagoon*, within a polygon of 810 km^2, situated in the geographic zone Q 15, between UTM coordinates 324,690.0 and 365,190.0 mE; 1994,700.0 and 2016,600.0 mN. The largest cities in the area are Coatzacoalcos and Minatitlán, as well as other smaller towns, such as Nanchital and Ixhuatlan (**Figure 1**).

3. Geological Development of the Northern Part of the *Coatzacoalcos paleolagoon*

The geological development of the Isthmus of Tehuantepec area, where the *Coatzacoalcos paleolagoon* is situated, dates back to the opening of the GOM. The opening of the GOM remains an exciting topic of debate. It raises many questions and opens the possibility of new evidence that could shed greater light on the geological events there.

The opening of the GOM is a widely discussed topic in scientific literature and publications. According to several authors, this event began with the breakup of the supercontinent Pangea approximately 230 million years ago (Ma) in the Late Triassic and continued into the Jurassic. The GOM opening process is estimated to have occurred between 160 and 140 Ma and is associated with a mantle plume of 8 to 10 Ma duration. The estimated ages and timings for each event vary according to authors' interpretations, leaving the debate ongoing [2]-[12].

During the GOM opening, which occurred between 160 and 140 Ma, the Isthmus of Tehuantepec area remained below sea level [13] [14] until, with time, the continental masses slowly began to emerge. Around 5.3 to 2.6 Ma, the *Coatzacoalcos paleolagoon* began to take shape, according to the ages [15] of sediments collected from locations surrounding it (**Figure 2**).

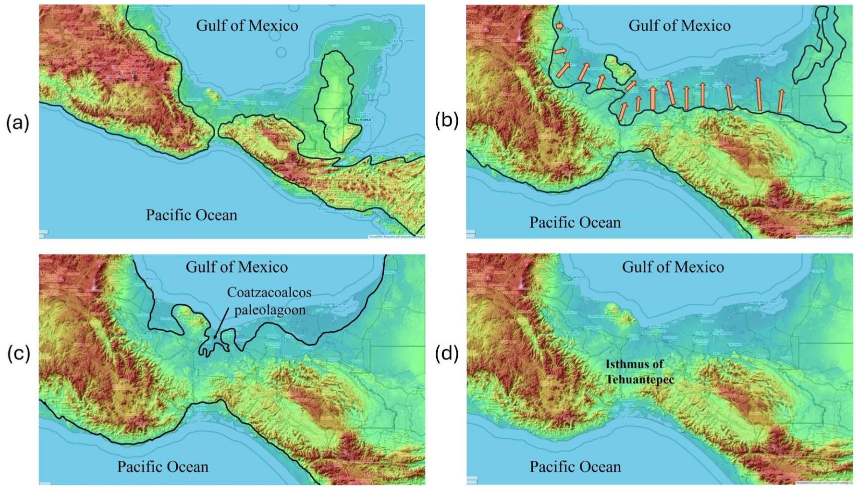

Figure 2. Paleogeography of the evolution of the Isthmus of Tehuantepec (a and b). During the opening of the Gulf of Mexico (160 Ma - 140 Ma), the area of the Isthmus of Tehuantepec was below sea level. Over time, the land surface emerged with the contribution of sediments from the higher elevations in the south and due to volcanism in the region. (c) Between 5.3 Ma and 2.6 Ma, the *Coatzacoalcos paleolagoon* began to take shape. (d) Today, the coastline of the Gulf of Mexico and the Pacific Ocean.

An important paleoclimatic event that played a determining role in the accumulation of sediments that shaped the shape of the paleolagoon was the Würm glaciation or Ice Age, which began about 110,000 years ago and ended around 10,000 years before our era. This ice age was the last glacial period in the Earth's geological history [16] [17].

The Ice Age or Würm glaciation occurred during the Paleolithic. It marked four periods in which low temperatures reached their maximum intensity, called Würm I, Würm II, Würm III, and Würm IV, as well as interglacial periods in which the temperature was less cold [17].

The last period of the Ice Age, Würm IV, is considered a late-glacial event characterized by three distinct colder temperature fluctuations: Dryas I, Dryas II, and Dryas III. The latter ended in the Paleolithic to give way to a less cold climate at the beginning of the Holocene [17]-[21].

To clarify the subdivisions established for the last phase of the Ice Age or Würm IV glaciation, we have that Dryas I is subdivided into Dryas Ia, between 19,000 and 17,500 years ago, a less frozen period called Lascaux, between 17,500 and 16,500 years ago, Dryas Ib, between 16,500 and 14,500 years ago, an interglacial period called Pre-Bölling, between 14,500 and 14,000 years ago, Dryas Ic, between 14,000 and 13,000 years ago, an interglacial period called Bölling between 13,000 and 12,100 years ago, Dryas II, between 12,100 and 11,800 years ago, an interglacial period called Alleröd, between 11,800 and 10,700 years ago, Dryas III, between 10,700 and 10,100 years ago [17] [18] [20].

The last glaciation (Würm IV) greatly influenced the accumulation process and the distribution of sediments (sand, silt, and clay) in the *Coatzacoalcos paleolagoon*.

With the temperature fluctuations in this last period, there were also fluctuations in the Gulf of Mexico sea level. According to [17], during the three Dryas, the sea level dropped due to the freezing of seawater, ice masses increased, and the coastline retreated from the continent, giving rise to marine regression. In the intermediate periods between the Dryas, the temperature increased, so the ice masses partially melted, and the sea level rose, causing a transgression of the coastline [18]-[25].

Two studies developed by Blum *et al.* suggest that changes in sea level occurred along the Texas coast in the northwest Gulf of Mexico, reaching a depth of −9 meters approximately 7.8 ka ago and rising rapidly thereafter [26] [27]. We believe that the sea level change observed on the Texas coast also occurred along the coast of southern Veracruz.

Sea level changes (transgressions and regressions) and marine currents led to the accumulation of sandy sediment banks in the northern part, where islands formed. Over time, these islands became sand barriers that restricted the free circulation of saltwater and effectively closed the communication between the sea and the paleolagoon. The influx of water from the emerging lands in the south began to cause changes in water salinity, which eventually shifted to freshwater.

Over time, sediments, primarily sand, silt, and, to a lesser extent, clay, accumulated in the *Coatzacoalcos paleolagoon* until it was practically filled with sediment. Samples obtained from different points in the paleolagoon and the ages recorded for the sediments date them to approximately 10,000 years old or slightly older, according to information from the [15].

4. Geology of the Study Area

According to information from the Coatzacoalcos E15-1-4 geological-mining map, Esc. 1:250,000, published by [15], the oldest rocks outcropping in the study area are in the southwestern part and correspond to the Filisola Formation (Tmar-Lu) of Upper Miocene age (11.6 Ma - 5.3 Ma), which consists of sandstone and shale.

Unconformably overlying the Filisola Formation is the Jaltepec Formation (TplCgp-Ar), considered Pliocene in age (5.1 Ma - 1.68 Ma). It is composed of polymictic conglomerate and sandstone. The Jaltepec Formation occurs in two locations within the study area: the central-western part and the southeastern part.

The Filisola Formation is transitionally overlain by the Pliocene Paraje Solo Formation (TplAr-Lu), which is composed of sandstone and shale and found in the study area's eastern and southeastern parts.

Likewise, the Paraje Solo Formation is concordantly overlayed by the Cedral Formation (TplQptAr-Cgp) of Pliocene-Pleistocene age (5.1 Ma - 1.5 Ma), composed of sandstone and polymictic conglomerate, which outcrops in the eastern and northeastern part of the study area.

Towards the west and northwest of the study area, basaltic volcanic breccias and basalts (TplBvB-B) are considered Pliocene in age (2.7 Ma - 0.15 Ma). These basaltic volcanic breccias and basalts are related to the Sierra de Santa Martha event in the Los Tuxtlas volcanic field that almost covers the mentioned sedimentary formations.

North of the study area are Quaternary eolian deposits from the Holocene (10,000 - 8000 years ago), formed by sand, mostly quartz. These eolian deposits form the present-day coastline and, in the past, formed islands and coastal barriers that separated the waters of the Gulf of Mexico from the less salty waters of the *Coatzacoalcos paleolagoon*.

In the central part are Quaternary deposits from the Holocene (10,000 - 8000 years ago). These dark-hued marsh deposits are chiefly composed of sand, silt, and clay and have a high organic matter content resulting from the decomposition of vegetation typical of marshy areas.

During the last sedimentation phase, Holocene Quaternary alluvial sediments (fine gravel, sand, and silt) were deposited in the northern and eastern parts of the *Coatzacoalcos paleolagoon* (4000 - 3000 years ago).

Figure 3 shows the distribution of the geological formations and the Quaternary deposits.

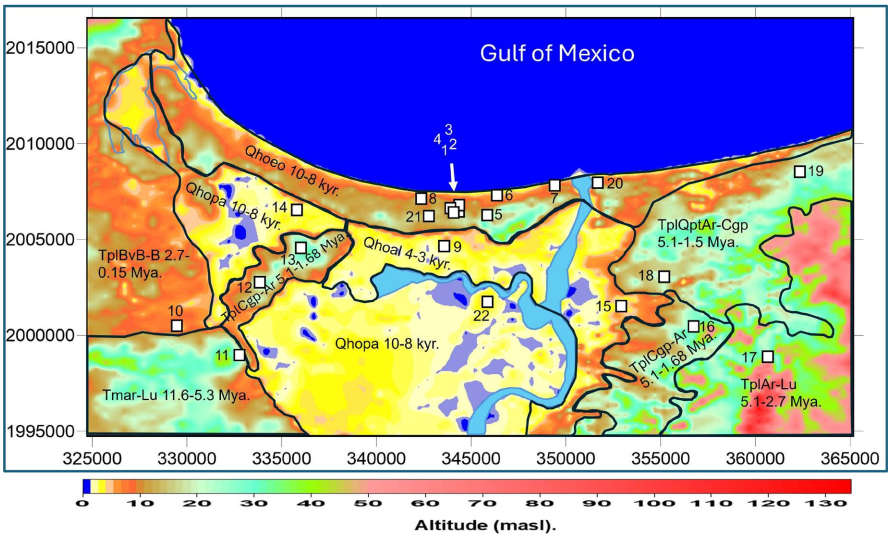

Figure 3. Geology of the study area and location of the 22 sites sampled for granulometric analysis (white squares).

5. Methodology

The development of this work considered five stages to achieve the goals of this study, described below.

Stage 1 involved the development of a detailed digital topographic model of the northern part of the *Coatzacoalcos paleolagoon*, which today is geographically the northern part of the Lower Coatzacoalcos River Basin. We configured the elevation model with elevation points obtained from satellite and aerial images from Google Earth. The elevation data has a resolution of one meter. The study polygon was formed with 82 N-S lines, each 20.0 km long and with a line spacing of 500 m, covering a total area of 20.0 km × 40.5 km.

To configure the digital elevation model, we used commercial software to obtain the ground relief. The interpolation calculation method was the Nearest Neighbor; the grid size was 300 rows by 600 columns, so we obtained 180,000 nodes. The grid geometry was an x-spacing of 67.61 m and a y-spacing of 73.24 m. In altitude, we achieved a median absolute deviation of 3.1337%.

Stage 2 consisted of incorporating the outcrop areas of the different rock types of the study area according to geological information from the Coatzacoalcos E15-1-4 geological-mining map, Esc. 1:250,000 [15] into the digital elevation model.

Considering the distribution and ages of the rocks in the outcrops, a simulation of sediment deposition was carried out, from the most recent to the oldest, thus obtaining the sequence of geological development of the northern part of the *Coatzacoalcos paleolagoon*.

Stage 3 consisted of collecting samples from the outcrop locations of each rock type within and outside the northern part of the paleolagoon to set up its geospatial boundaries, considering information from the Coatzacoalcos E15-1-4 geological-mining map of [15].

Stage 4 consisted of sample preparation and grain size measurements using sieves of different sizes and their percentage.

Stage 5 consisted of analyzing the study results to obtain evidence that would allow us to show the existence of a lagoon (*Coatzacoalcos paleolagoon*) in the northern Isthmus of Tehuantepec. Over the last 10,000 years, detrital sediments filled this lagoon, so only small swamps are present today.

6. Work Development

We made a digital elevation model for the northern part of the *Coatzacoalcos paleolagoon*. We configured the model with 5062 points with their respective elevations. It obtained each elevation point from satellite and aerial images on Google Earth. The study polygon covers an area of 810.0 km^2, 40.5 km in an E-W direction, and 20.0 km in an N-S direction. Eighty-two digital elevation lines were drawn within the polygon, each 20.0 km in N-S direction, with a line spacing of 0.5 km.

It built the model with a calculated interpolation of the ground surface every 50 m to obtain a high-resolution representation and simulate level changes on the ground surface due to the accumulation of sediments in the paleolagoon over the last 10,000 years.

We incorporated the geospatial boundaries of the geological formations that outcrop the study area into the digital elevation model. The age of the rocks allowed us to focus on the area where sand sediments exist. According to data from the Mexican Geological Service, sand sediments were deposited 12,000 - 10,000 years ago [15].

These sand sediments were deposited by freshwater currents originating primarily from the south. Thus, their distribution delimits the area occupied by the *Coatzacoalcos paleolagoon* between 12,000 and 10,000 years ago.

The digital elevation model simulated the process of sediment accumulation that filled the *Coatzacoalcos paleolagoon* over time, an event that began 12,000 to 10,000 years ago (**Figure 4**).

With information from the simulation of the *Coatzacoalcos paleolagoon*'s evolution and the Mexican Geological Service's geological-mining map, we identified the areas of interest on a Google Earth map to locate points with good accessibility for collecting sediment and rock samples.

At Stage 3, we collected sediment and rock samples at 22 points of interest. This stage began with several preliminary trips to verify site access, identify areas of undisturbed soil, and free areas for construction. Initially, the number of samples was undefined, depending on site access, soil undisturbedness, and visual observation of sediment characteristics. The distribution of sampling sites was irregular, based on the boundaries of geological formations on the geological-mining map of [15]. We took sediment sampling from cores at 20 to 30 cm of depth.

Upon arrival at each site, we inspected the area to select a location with no soil disturbance due to human activity. We recorded coordinates at each sampling site with a GPS (**Figure 3**).

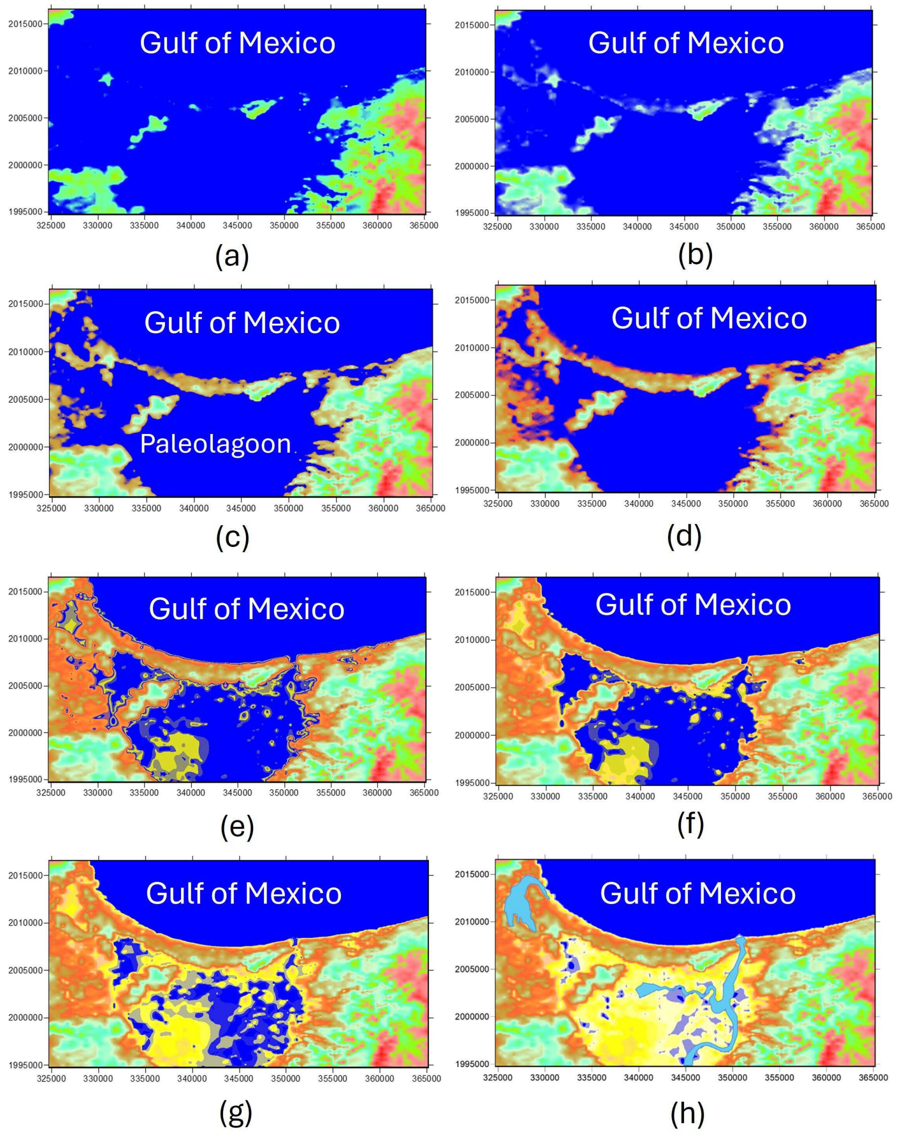

Figure 4. Simulation of the sequence of accumulation and deposition of sediments that filled the *Coatzacoalcos paleolagoon* from approximately 12,000 or 10,000 years ago (a) to the present day (h).

The coordinates of the sediment samples are shown below (**Table 1**).

Table 1. UTM coordinates (Zone 15Q) of the sampling sites.

Sample 1	343758.01 mE	2006689.80 mN	Sample 12	333529.20 mE	2001880.90 mN
Sample 2	343917.07 mE	2006797.67 mN	Sample 13	335838.70 mE	2004221.60 mN
Sample 3	343893.40 mE	2006904.38 mN	Sample 14	335819.20 mE	2006510.30 mN
Sample 4	343711.39 mE	2006834.60 mN	Sample 15	353011.00 mE	2001419.70 mN
Sample 5	345624.00 mE	2005968.00 mN	Sample 16	356899.20 mE	2000066.50 mN
Sample 6	346167.28 mE	2007458.33 mN	Sample 17	360609.70 mE	1998821.20 mN
Sample 7	349574.30 mE	2008040.90 mN	Sample 18	355231.99 mE	2002679.50 mN

Continued

Sample 8	342057.00 mE	2007524.00 mN	Sample 19	362584.70 mE	2008499.50 mN
Sample 9	343562.80 mE	2004649.20 mN	Sample 20	351390.60 mE	2007824.85 mN
Sample 10	328869.80 mE	2000097.00 mN	Sample 21	342280.00 mE	2006990.10 mN
Sample 11	333051.70 mE	1998699.70 mN	Sample 22	345600.45 mE	2001460.00 mN

Stage 4 consisted of sample preparation and particle size measurements using sieves of different sizes. Sample preparation involved homogenizing the sample and removing moisture from the sediment in an oven at 150˚C.

We used a high-precision digital scale with a resolution of 0.001 gr to measure the amount of material retained by each sample sieve.

To find the scale's standard deviation, we took 10 measurements from the same sample and recorded each value. The scale's standard deviation was 0.0087178 gr. We also calculated the Mean Absolute Percentage Error (MAPE), 0.0033463%.

After preparing the sediment samples, we measured the grain size using a sieve to obtain information about the transport, deposition, and provenance of sediments and rocks from each sampled site. We also identified minerals using a 30x magnifying glass with natural light.

The sieve number, sieve internal diameter, mesh number, and sediment type are shown below (**Table 2**).

Table 2. Sieve specifications.

Sieve model	Sieve hole inner diameter	Mesh	Sediment type
No. 1	2.00 mm and larger size	10	Fine gravel
No. 2	0.85 mm	24	Very coarse sand
No. 3	0.355 mm	50	Coarse sand
No. 4	0.25 mm	65	Medium sand
No. 5	0.18 mm	80	Fine sand
No. 6	0.15 mm	100	Fine sand
No. 7	0.125 mm	120	Fine sand
No. 8	0.09 mm	150	Very-fine sand
No. 9	0.075 mm	200	Very-fine sand
	Menor a 0.075 mm		Coarse and medium silt

The measurement process was as follows: 500 gr of sediment from each sample was weighed and recorded. After sieving, we recorded the quantities recovered by each sieve. The total weight of the sediment recovered was noted to control material loss due to sediment handling on the sieves, yielding a maximum sediment loss of 2.51 gr for sample 15 and a minimum loss of 0.36 gr for sample 20. The average loss fluctuated around 1.00 gr per 500 gr sample.

Stage 5 consisted of analyzing results obtained from the screening process and the correlations between the samples by the color of the sediments, their granulometric distribution, and their place of origin. We present the results and analyses of the measurements below.

7. Results and Analysis

The size and roundness of the grains that make up the sediments at a site provide information about the environmental conditions that affect the minerals during transport (distance, energy level, and whether water currents or wind transported the sediments).

The screening process results for the 22 samples showed each sample's particle size distribution and quantity (%) of the grains. The size-percentage graphs are shown below (**Figure 5**).

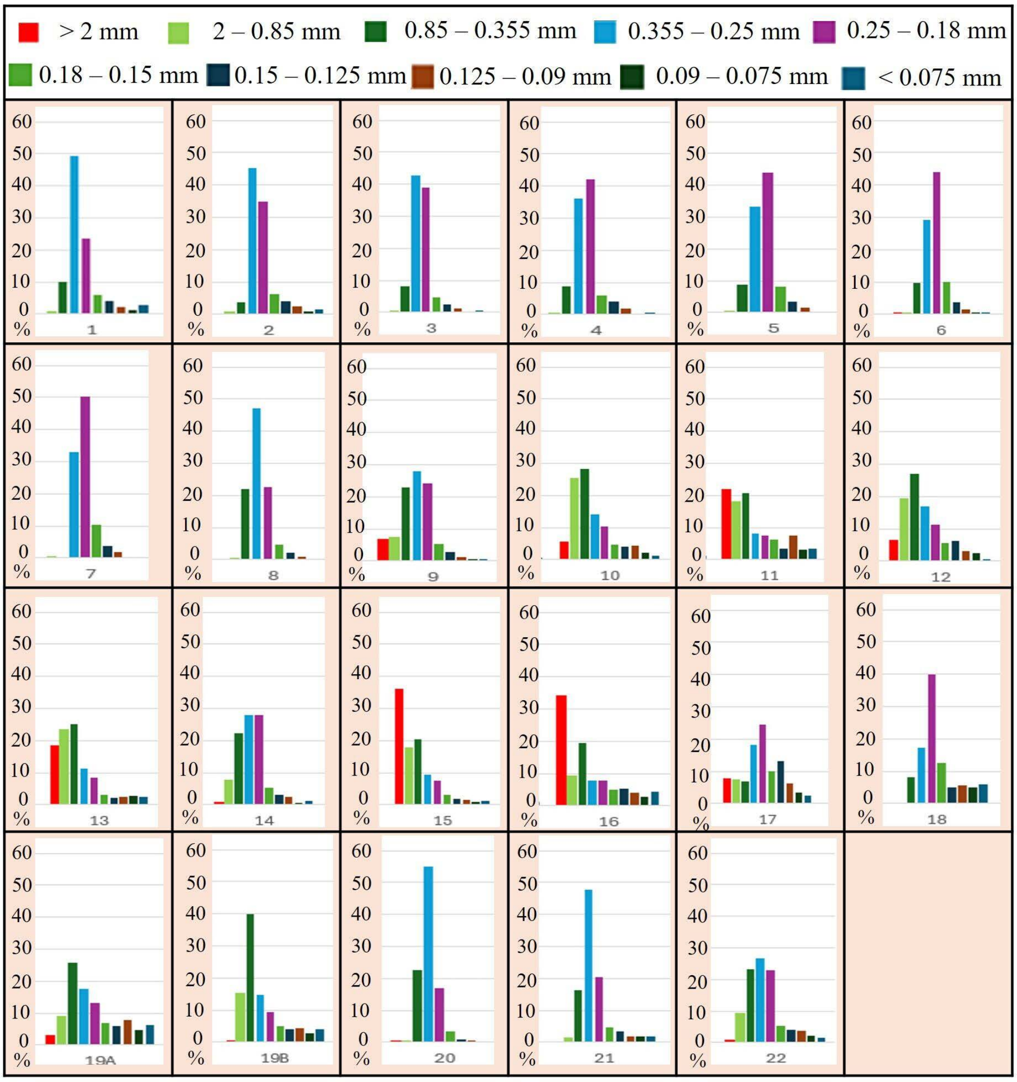

Figure 5. Percentage of material kept by each mesh in the 22 samples collected.

It distinguished two groups based on color affinity, grain size distribution, and percentage. The first group (A) is composed mainly of sands with affinity in grain size distribution, where the most abundant are sizes from 0.85 to 0.15 mm (very coarse sands to medium sands) and sediment color affinity (cream and light brown) (**Figure 6(a)**).

The Group A sands originate from the southern Isthmus of Tehuantepec in the Chiapas Massif, which consists of intrusive igneous rocks composed of granites and granodiorites. The Chiapas Massif developed from the Permian (ca. 290 Ma) to the Triassic (ca. 210 Ma) according to [28]. Other work in the Chiapas Massif has also dated the granites and granodiorites. For example, K-Ar and Rb-Sr radiometric dating methods show them as Permo-Triassic in age [29] [30].

More recently, it performed a zircon dating using the U-Pb method using the SHRIMP (Sensitive High-Resolution Ion Microprobe), resulting in approximate ages of 272 Ma [31].

Environmental conditions on the Chiapas Massif have weathered and eroded the granites and granodiorites through the action of water currents. The Coatzacoalcos and Uxpanapa Rivers transport sediments from the Chiapas Massif to the Gulf of Mexico (GOM) since they originate in this massif and flow northward to the *Coatzacoalcos paleolagoon*. It is worth mentioning that the work of [14] provides a complete explanation of the geological evolution of southeastern Mexico, where the Chiapas Massif is.

The sandy-silty sediments constitute the second group (B), characterized by a grain size exceeding 2 mm (fine gravel) and a significant amount of sediment with a grain size smaller than 0.075 mm (clay), along with a color affinity of the sediments (red and orange) (**Figure 6(b)**).

The sandy-silty sediments of group B come from the western and northwestern parts of the *Coatzacoalcos paleolagoon*, where we found extrusive igneous rocks. These rocks gave rise to the Sierra de Santa Martha. Pliocene andesites and andesitic tuffs form them. Also, basaltic volcanic breccia and basalts are towards the northwest. Radiometric K-Ar dating gave ages of 2.7 Ma - 1.7 Ma [15] [32].

In a more recent work carried out in Los Tuxtlas, ages were found where the oldest is 7.0 Ma - 1.4 Ma for Montepío-El Vigía, intermediate ages of 1 Ma - 0.5 Ma for Santa Martha, and the youngest of 50,000 years to the present for the locality of San Martín Tuxtla [33].

Andesites have ferromagnesian minerals (pyroxene, biotite, and hornblende) rich in iron, and mafic basalts are rich in magnesium and iron silicates. Both andesites and basalts degrade and oxidize due to the presence of iron, which reacts with water. The decomposition of both rocks produces red and orange sediments (soils). Therefore, the red color of the sediments in the samples from group B correlates with the provenance of the andesites, basalts, and andesitic tuffs of the Sierra de Santa Martha area.

Regarding the minerals observed with a magnifying glass in the 22 samples, group A (sand) contains 40% to 70% quartz and 1% to 3% ferromagnesian minerals. We did not observe Fe oxides, because river currents may have washed them away. Group B, on the other hand, contains 10% to 20% quartz and 60% to 80% Fe oxide.

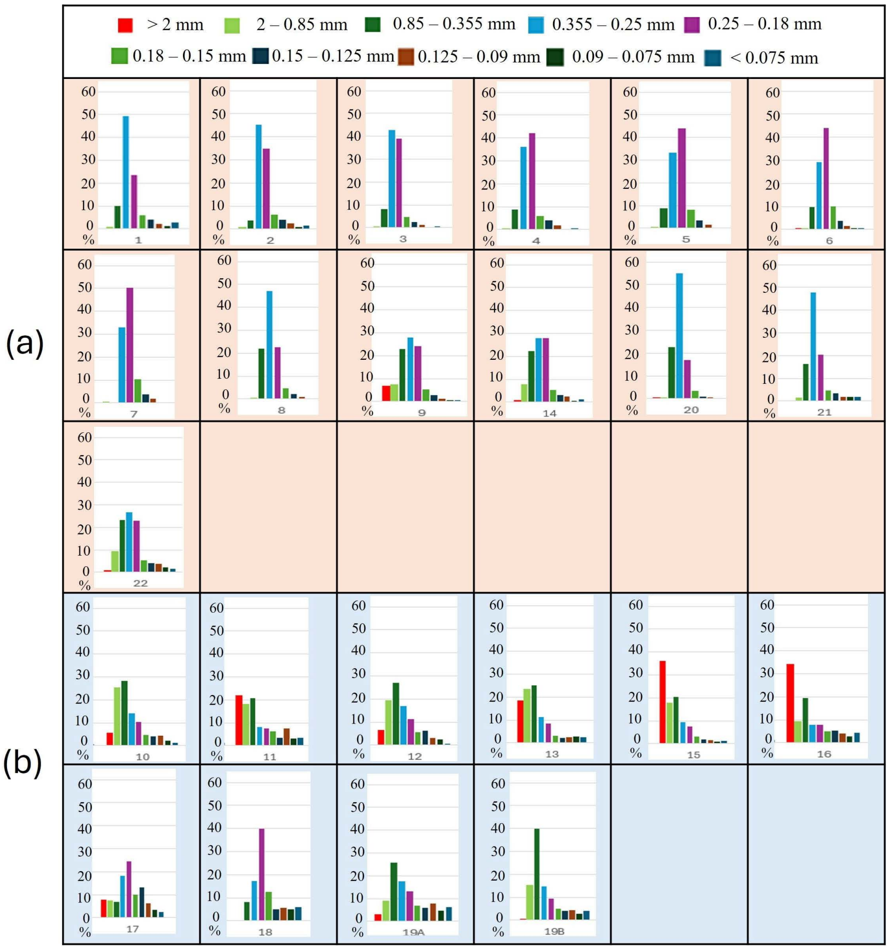

Figure 6. Groups A and B were classified according to their particle size affinity, texture, and color. Cream-color sands form group A (0.85 mm - 0.18 mm) and a small part of fine-sized sediments (6a). Group B is composed of sand-clayey sediments with fine gravel (>2.0 mm) and a significant content of very fine sediment (red and orange).

It saw some differences in group A (sands). Samples 1, 2, 3, 4, 5, 6, and 7 are composed of sand, where 80% - 90% of the sample has grains measuring 0.355 mm - 0.18 mm (coarse and medium sand). The uniformity in grain size in these samples shows that the wind deposited these sediments (eolian sediments). The wind energy and its ability to transport make the size of the sand grains more selective and homogeneous (**Figure 6(a)**).

On the other hand, samples 8, 20, and 21 contained 20% sand with a grain size of 0.355 mm - 0.85mm (very coarse to Compared with samples 1, 2, 3, 4, 5, 6, and 7, which had less than 10% of this grain size (**Figure 6(a)**). We took sample 20 on the east side of the Coatzacoalcos River channel; this shows that the channel's current transported and deposited this sand, rather than the wind.

The similarity of samples 8, 20, and 21 suggests that the sand from these samples was also transported and deposited by an old channel of the Coatzacoalcos River that no longer exists. At that time, some islands and sandbars in the northern part had already divided the paleolagoon from the sea in the GOM (**Figure**

4(a) and Figure 4(b)).

Samples 9, 14, and 22 showed similar particle size distributions. These are sediments deposited by water currents, *i.e.*, alluvial sediments. The predominant size of these sediments ranges from 0.85 to 0.18 mm (very coarse sand, coarse sand, and medium sand), accounting for 70% - 80% of the total sample. From these three samples, 14 and 22 are swamp sands with a darker color, due to their high organic matter content resulting from plant decomposition typical of swamps (Figure 3).

Sample 9 had 7 % fine gravel, unlike samples 14 and 22. Furthermore, sample 9 was a light cream color with no organic matter; this shows that the sediments in sample 9 were transported and deposited by river currents with greater hydraulic energy, which prevented the accumulation of organic matter in this place (Figure 3).

Another difference is the dating of the sediments; according to information from [15], the components of samples 14 and 22 are 10,000 to 8000 years old, while sample 9 is 4,000 to 3,000 years old, showing these sediments are more recent (Figure 3). The results are consistent with the information provided by [15].

On the other hand, silty sands with small clay and fine-gravel content form group B (samples 10, 11, 12, 13, 15, 16, 17, 18, 19A, and 19B). The color of the sediments is red and orange, easily distinguished from the sands of Group A. Group B has a greater quantity of fine grains of 0.15 – < 0.075 mm (silt and clay), which is 15% - 20% of the total sample. Another essential characteristic is the content of fine gravel (>2 mm), which had a variable volume in the samples (3% - 35%). The medium sand (0.85 mm - 0.25 mm) had 40% - 65% of the total volume of the sample.

Within Group B, samples 15 and 18 presented a particle size distribution different from the rest of the samples in this group. Sample 15 presented only 11% fine and very fine sand, silt, and clay (0.18 – < 0.075 mm). In contrast, sample 18 presented 55% fine and very fine sand, silt, and clay (0.18 – < 0.075 mm) (Figure 6(b)).

We took samples 15 and 18 at the eastern limits of the *Coatzacoalcos paleolagoon* (Figure 3). The distance between the two sites was 2.5 km. The granulometric differences between these samples are evidence of changes in water level and the area occupied by the paleolagoon during the Würm glaciation.

Volume-grain size graphs (Figure 7) showed the differences in the granulometric distribution and the grain size quantity of each group's samples.

In Group A, the graph showed three zones of concentration in the particle size distribution of the samples. The orange circle has the highest percentage of medium and fine sand volume. The purple circle is the finer material with a rate of less than 10%; the blue circle is the coarser material (0.855 – > 2 mm). According to the graph, two samples presented a small percentage of fine gravel (Figure 7(a)).

On the other hand, the samples from group B showed a different behavior; the graph showed four zones of grain size distribution within the samples. We observed two orange circles; one indicates a broader distribution of various sand grain sizes (55% - 70%), and the other shows a fine-gravel content in samples (20% - 35%). In both circles, the corresponding volume is high. The purple circle shows a greater amount of fine material, which is made up of fine-sized sand, silt, and clay, marking a significant difference from the samples of group A. The blue circle shows that some samples also have a small percentage of fine gravel (approx. 10%) (**Figure 7(b)**).

Sample 18, classified as part of group B, presented a grain size distribution distinct from the other samples in the same group. The sample consisted of fine material, with grain sizes ranging from very fine sand to silt and clay (**Figure 7(c)**).

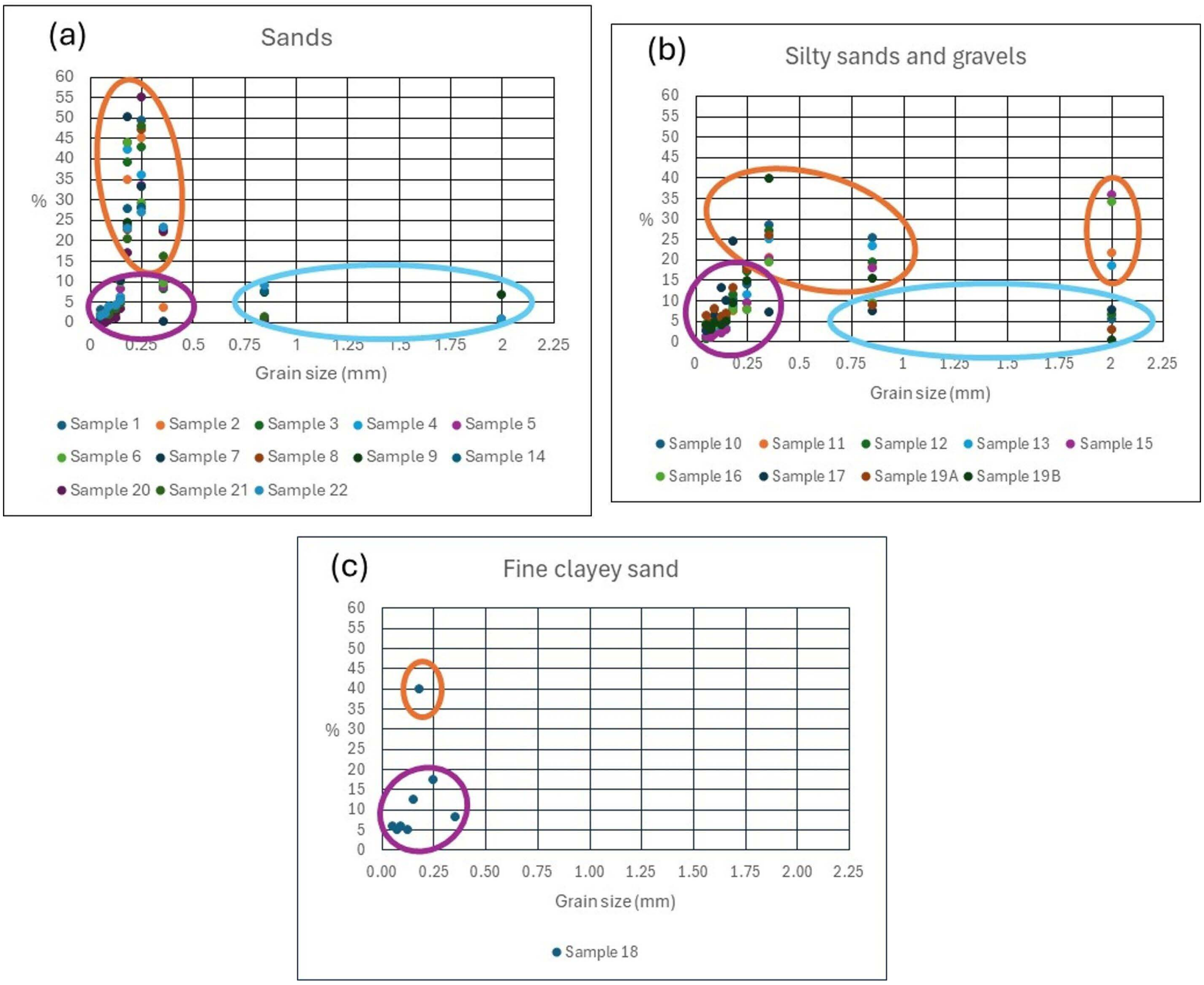

Figure 7. Volume-grain size graphs. The graphs show the grain size distribution of groups A and B of the samples collected in the study area of the *Coatzacoalcos paleolagoon*. (a) Samples from group A. (b) Samples from group B and (c) Sample 18 of group B.

According to the Volume-Grain Size graphs in **Figure 7**, it is easy to see the difference between groups A and B. Sands in group A are sediments that gradually filled the *Coatzacoalcos paleolagoon* from 12,000 or 10,000 years ago. In contrast, samples from group B showed transition areas at the boundaries of the paleolagoon where changes in water level occurred during the last glaciation; the granulometric distribution of the samples showed dynamic changes in the energy of the water currents. Likewise, the granulometric distribution of sample 18 showed a predominance of low-energy deposition and periods of tranquility.

Based on the collected evidence, a geospatial representation of the area that could have occupied the northern part of the *Coatzacoalcos paleolagoon* 12,000 or 10,000 years ago was made (**Figure 8**).

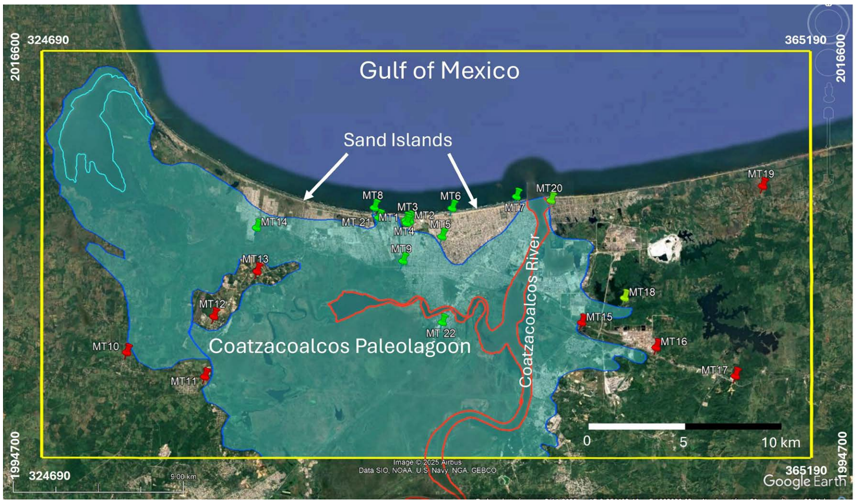

Figure 8. Area that occupied the northern part of the *Coatzacoalcos paleolagoon* between 12,000 and 10,000 years ago (edited in Google Earth).

8. Conclusions

The geomorphological evidence obtained from the digital elevation model of the study area, the simulation to reconstruct the sequence of sand sediment deposition that filled the *Coatzacoalcos paleolagoon*, and sedimentological analysis from 22 samples showed that a lagoon existed in the study area before 12,000 to 10,000 years ago. Over time, detrital sediments (sand) transported from the south part by water currents from the Coatzacoalcos and Uxpanapa rivers that come from the Chiapas Massif filled the *Coatzacoalcos paleolagoon*.

Of the 22 samples collected, 13 samples were classified as sands, which shows that these sediments filled the area occupied by the *Coatzacoalcos paleolagoon*.

Before the lagoon filling period, sediments of red or orange color, including fine gravel, sand, silt, and clay, were deposited. These sediments come from extrusive igneous rocks (andesites, andesitic tuffs, basalts, and basaltic breccia) from the Sierra de Santa Martha area, which is in the western and northwestern part of the study area.

We collected these sediments on the paleolagoon boundaries' eastern and western sides. The variety in grain size in the samples shows their origin and the periods of variation in the dynamics (energy) of the fluvial currents that transported these sediments to the area. Their location marks a transitional zone at the paleolagoon boundaries, both to the west and east.

Knowing about the existence of the *Coatzacoalcos paleolagoon* allows us to improve our knowledge and understanding of groundwater dynamics in the area, identify risk areas for flooding, risks in housing construction, and ways to communicate.

Specifically, it allows us to develop contaminant migration models in the paleolagoon area, considering that Minatitlán is found south of the study area and has a hydrocarbon refinery. Additionally, between Minatitlán and Coatzacoalcos, an old landfill is no longer in operation. To the east of the *Coatzacoalcos paleolagoon*, three large petrochemical complexes of great importance are potential sources of groundwater contamination.

Likewise, it allows us to develop contaminant migration models in this area, considering that the city of Minatitlán is found south of the study area and has a hydrocarbon refinery. Additionally, between Minatitlán and Coatzacoalcos, an old landfill is no longer in operation. Moreover, to the east of the *Coatzacoalcos paleolagoon*, there are three large petrochemical complexes of great importance, which are potential sources of pollution.

This work faced some limitations as follows. The number of samples was limited by the difficulty of accessing the sampling sites, the location of urban areas, or the fact that humans modified the soils. Another limitation was the lack of direct dating of the samples, so we considered the ages of the geological formations reported by the Mexican Geological Service. Likewise, concerning the digital elevation model of the study area, the elevation data were obtained from Google Earth, which has a resolution of every meter, so we did not have any values less than one meter.

Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The author thanks CONAHCYT for the support from the National System of Researchers (SNII).

The author thanks the anonymous reviewer for their valuable comments and recommendations for improving the manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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