Sedimentological and morphological characterization of the Cartagena Bay (2000 - 2020)

Caracterización sedimentológica y morfológica de la bahía de Cartagena (2000 – 2020)

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Abstract

This research focused on the identification of the morphological units and the textural and compositional characterization of the bottom sediments of the Cartagena Bay, with information from the year 2020. The bathymetric data available for the last 20 years were collected from the National Hydrographic Service, obtaining data from surveys with single beam technology from the years 2000, 2004, and 2012, and a survey with multibeam technology from the year 2020. With this information, digital elevation models were generated, using which seabed geoforms and bathymetric comparison were interpreted. As a result of this process, it was concluded that one of the main changes in the geoforms of the bottom of Cartagena Bay is the progradation of the delta and sedimentation of up to 18.5 m during the period studied, which was caused by the sediment contribution of the Canal del Dique. In addition, there are increases in depth in sectors near ports, which may be due to dredging carried out to ensure the navigability and functionality of the ports of Cartagena. With the textural and compositional information of 85 samples from the bay, collected every 1 km in February 2020, it was identified that the bay is greatly influenced by lithoclastic sediments, making up 73% of the samples, while only 4% of the samples are classified as being of bioclastic material. Similarly, a predominance of muddy sediments was observed, with 65.26% of samples classified in this size range (4φ to 10φ); followed by 31.10% sand (-1φ to 4φ) and only 3.64% gravel (φ < -1). This highlights the prevalence of fine sediments and gives support to the argument of several authors stating that the calcareous sediments present in the bay are being covered by terrigenous sediments transported mainly by the Canal del Dique, which plays a fundamental role in the sedimentation of the area.

Keywords: Morphology, Cartagena Bay, sediments, Canal del Dique.

Resumen

Esta investigación se centró en la identificación de las unidades morfológicas y la caracterización textural y composicional de los sedimentos de fondo de la bahía de Cartagena, con información del año 2020. Se recolectaron los datos batimétricos disponibles de los últimos 20 años en el Servicio Hidrográfico Nacional, obteniendo datos de levantamientos con tecnología monohaz de los años 2000, 2004, y 2012, y un levantamiento con tecnología multihaz del año 2020. Con esta información se generaron modelos

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digitales de elevación, con los que se realizó un proceso de interpretación de geoformas del fondo marino y comparación batimétrica. En este proceso se concluyó que uno de los principales cambios de las geoformas del fondo de la bahía de Cartagena es la progradación del delta y la sedimentación de hasta 18.5 m durante el periodo estudiado, lo cual fue ocasionado por el aporte sedimentario del Canal del Dique. Adicionalmente, se presentan aumentos de profundidad en sectores cercanos a puertos, los cuales pueden deberse a dragados realizados para garantizar la navegabilidad y funcionalidad de los puertos de Cartagena. Con la información textural y composicional de 85 muestras de la bahía, recolectadas cada 1 km en febrero de 2020, se identificó que en la bahía se presenta una gran influencia de sedimentos tipo litoclástico, ya que el 73 % de las muestras se encuentra en esta clasificación; mientras que, solo el 4 % de las muestras se clasifica como material bioclástico. De igual forma, se observó una predominancia de sedimentos lodosos, con un 65.26 % de muestras clasificadas en este rango de tamaño (4φ a 10φ); seguido de un 31.10 % de arena (-1φ a 4φ) y solo un 3,64 % de grava (φ < -1). Resaltando la prevalencia de sedimentos finos y dando soporte al argumento de varios autores, afirmando que los sedimentos calcáreos presentes en la bahía están siendo cubiertos por sedimentos terrígenos transportados principalmente por el Canal del Dique, el cual cumple un papel fundamental en la sedimentación del área.

Palabras Clave: *morfología, bahía de Cartagena, sedimentos, Canal del Dique*

Introduction

Cartagena is one of the most important centers of economic, urban, tourist and port development in the Colombian Caribbean. These activities have influenced the sedimentological and morphological evolution of Cartagena Bay. The distribution and characterization of its sediments was studied by Klingebiel and Vernette (1979) and by Vernette, Lesueur and Klingebiel (1984), who generated the first sedimentological chart of the country, and recently by Andrade *et al*. (2004); Franco, Restrepo, Sanabria and Gutiérrez (2013) and Restrepo *et al*. (2013).

Studies on the geoforms of the bay and its bathymetric changes (Vernette, Buitrago, Campos and Llano, 1977; Andrade *et al*., 2004; Mora *et al*., 2018) and on the circulation of the turbid plume of the man-made Canal del Dique (Andrade, Arias and Thomas, 1988; Lonin, Parra, Andrade and Torres, 2004) have been conducted mainly due to the concern about the effects generated by the fluvial contribution of the Canal del Dique to Cartagena Bay. These authors have found changes in the bathymetry and sediment distribution of the bay. It has been reported that the Canal del Dique delta advanced more than 3 km into the bay between 1977 and 2004, beginning to interfere with the navigation channel (Andrade *et al*., 2004).

The main objective of this study is to identify the geoforms of the seafloor of Cartagena Bay, as well as its sedimentary characterization and bathymetric evolution in the last two decades, in order to understand the major effects on the sedimentation and/or erosion processes in the bay, mainly in the Canal del Dique sector. The document interprets the current geoforms of the seabed in the Cartagena Bay, and describes and compares available bathymetries, based on information collected by the National Hydrographic Service (SHN) in 2000, 2004, 2012 and 2020. In addition, an analysis of the textural and compositional properties of bottom sediments is presented based on information collected by the Caribbean Oceanographic and Hydrographic Research Center (CIOH) during the year 2020, associating their distribution to the morphological characteristics of the bay bottom.

Study Area

Cartagena Bay has an approximate area of 85.74 km^2 and is located on the continental shelf of the Colombian Caribbean, in the north of South America. It is located between coordinates 10º16’ and 10º26’ N, and 75º30’ and 75º35’ W, with average and maximum depths of 16 and 34 m, respectively. Geologically, it is located within the geomorphostructure of the southwestern Caribbean, in a complex zone of the San Jacinto belt province. The bay is separated from the Caribbean Sea by Tierra Bomba Island, with a connection to the north via the Bocagrande channel and to the south through the Bocachica channel (Figure 1).

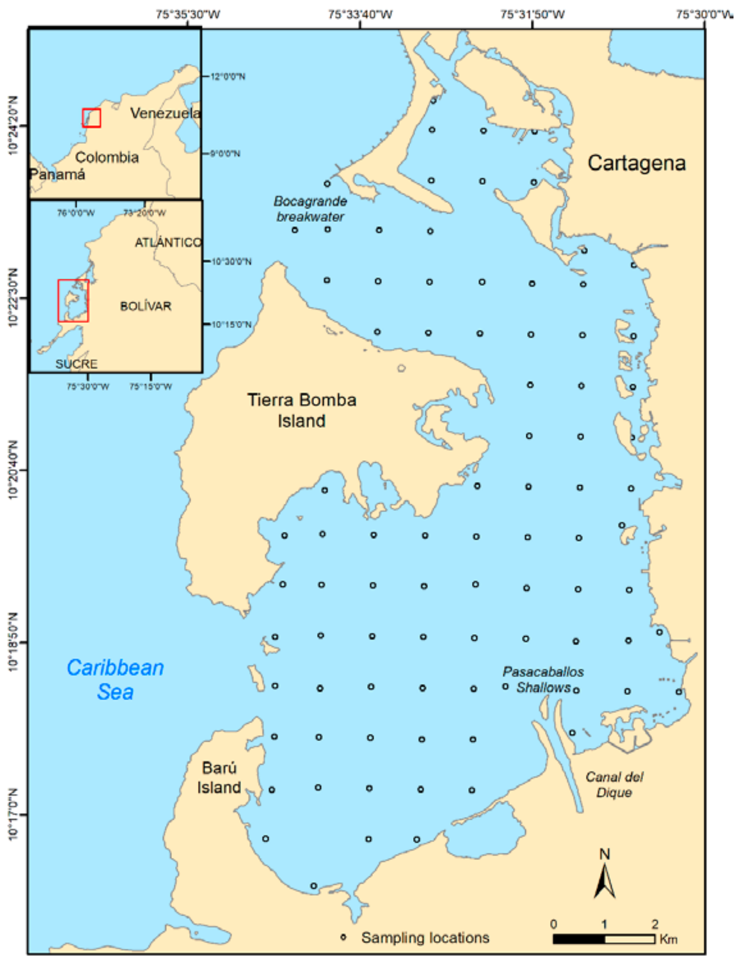


Figure 1. Location of the study area and sampling points (black dots).

The Bocagrande channel has depths that vary between 1 and 7 m and is crowned by a submarine breakwater built in colonial times, between 1768 and 1786, in order to prevent the entry of vessels through the Bocagrande opening, between the tip of Tierra Bomba Island and Icacos Point (Díaz and Serrat, 2019). Bocachica channel is the main navigable route for entering and leaving Cartagena Bay, so it is an area in which dredging is evident, and in which maximum depths of 30 m have been achieved (Andrade *et al*., 2004).

The bay has two main climatic seasons and a transition period. The dry season, characterized by a decrease in precipitation and an increase in wind speeds, runs from December to April. The wet season extends from August to November, when there is an increase in precipitation and a decrease in wind speeds. Finally, the transition period occurs between April and July, and is characterized by winds that begin from the north but shift to coming from the south (Molares, 2004). The tide in the bay is semi-diurnal, mixed and micro-tidal, with an average amplitude of 33.5 cm (Rueda, Otero and Pierini, 2013).

Methodology

In order to analyze the bathymetric evolution of Cartagena Bay, the information available from the SHN for the last 20 years was collated. Data were acquired from single beam technology surveys carried out in 2000, 2004, and 2012, with which Digital Elevation Models (DEM) were generated at a resolution of 10 m. In addition, information was obtained from a multibeam survey for shallow waters carried out in 2020, with a resolution of 5 m.

DEMs were generated in CARIS HIPS and SIPS 11.3 software for each available period. These models represent the referenced bathymetry, which consists of the depth of the ocean floor in relation to sea level. In Colombia the official bathymetric surveys and nautical charts made by the SHN are referenced in the vertical to the Mean Low Water Springs (MLWS), guaranteeing the same reference level at the time of comparison between DEMs of different periods. This correction is made using measurements collected by tide gauge stations of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and the General Maritime Directorate (Dimar), based on the methodology explained in the study by Pulido, De Lisa, Viteri and Guzmán (2013).

The main input for the interpretation of the geoforms of the seafloor of the bay was the 2020 DEM, based on the information obtained from a shadow model and a slope model generated with the available tools of the ArcGIS 10.8 Software and the 3D observation module of CARIS Base Editor 4.2. A shadow model is a shaded relief raster file. It was generated using the "Hillshade" function, with an azimuth angle of the light source of 315° and altitude angle of 45° above the horizon. A slope model is an analysis of the slope gradient of the ocean floor. This model was obtained by means of the slope tool, establishing five slope ranges in degrees from flat, gently sloping to very steep, based on Smith and Taft (2000), as seen in Table 1.

Table 1. Slope steepness classification of submarine geoforms (Smith and Taft, 2000).

Slope range	Description
0° - 3 °	Flat, gently sloping
3.01° - 6°	Sloping
6.01° - 12°	Strongly sloping
12.01° - 19°	Steep
>19.01°	Very steep

The difference between each DEM and the following one was identified through a bathymetric comparison process, obtaining the difference in depth for the periods 2000-2004, 2004-2012 and 2012-2020 with DEMs at 10m resolution. This procedure was performed in CARIS HIPS and SIPS 11.3, using the "Difference" tool. Additionally, 3 depth cross-sections were made for the years 2000 and 2012 in the area near the mouth of the Canal del Dique, in order to compare the bathymetric differences in the selected years. The cross-sections were performed on the bathymetries from these two years due to the density of data in this area in particular.

The information on dredging and expansion of the Bocachica channel provided by the Port Captaincy of Cartagena (CP05), for the year 2005 records an approximate extraction of 2 000 m^3 along a length of 20 m, while for the year 2010 they performed dredging and expansion of the channel with an approximate volume of 254 488 m^3 reaching an average depth of 15 m (DIMAR, 2010).

The available sedimentological data correspond to information collected by the CIOH for the project "Distribution of the Bottom Sediment of the Cartagena Bay" (Padilla and Villanueva, 2020). The project collected 85 bottom sediment samples distributed in a 1 km grid spacing. The campaign used a Garmin GPS 72H system, with an accuracy of ± 2 m, and a Van Veen-type dredge, which was manually launched from a boat for each collection. Each sample underwent textural characterization and the CaCO3 content was determined in the CIOH laboratories.

The $CaCO_3$ content was determined using 0.25 g of sediment normalized with 4 mL of HCl (10%) in a Bernad calcimeter. The composition was classified following the scheme proposed by Vernette (1978) (Table 2).

The grain size distribution was obtained by implementing two methods: sieving and LA-300 laser diffraction analysis. The results obtained by both methods were entered into the GRADISTAT software (Blott and Pye, 2001) to determine their textural classification according to the size distribution scale of Udden (1914) and Wentworth (1922), modified and adapted in GRADISTAT software (Table 3).

Table 2. Compositional classification according to $CaCO_3$ content, established by Vernette (1978)

Name	$CaCO_3$ content	Name	$CaCO_3$ content
Bioclastic	Greater than 85%	Lithobioclastic	Between 50% and 15%
Biolithoclastic	Between 85% and 50%	Lithoclastic	Less than 15 %

Table 3. Udden (1914) and Wentworth (1922) scale of sediment size, modified and adapted in the GRADISTAT software.

Texture class		Size		Texture class		Size	
		µm	Phi (ϕ)			µm	Phi (ϕ)
Gravel	Medium gravel	8000	-3	Muds	Very coarse silt	31	5
	Fine gravel	4000	-2		Coarse silt		
	Very fine gravel	2000	-1			16	6
Sands	Very coarse sand	1000	0		Medium silt	8	7
	Coarse sand	500	1		Fine silt	4	8
	Medium sand	250	2		Very fine silt	2	9
	Fine sand	125	3		Mud	0	10
	Very fine sand	63	4				

Finally, the geostatistical treatment of the sedimentological information was performed by the Natural Neighbor interpolation method, one of the tools of ArcGis 10.8, which makes it possible to generate an estimated surface from a set of scattered points. This interpolation consists of finding the subset of samples closest to the query point and making an averaged that is weighted by the areas provided (Sibson, 1981). This made it possible to create surfaces showing the textural and compositional classification of bottom sediments, in order to determine the surface distribution patterns of sediments and complement the analysis of Cartagena Bay.

Results

Seabed geoforms

The qualitative analysis carried out with the bathymetry of the seafloor in 2020, with a resolution of 5m, allowed the identification of different geoform units in Cartagena Bay (Figure 2). The continental margin of Cartagena Bay and the islands of Manzanillo, Tierra Bomba, Barú and other small islands make up the *Continental Shelf Flat (PPC)*, a relatively flat geoform with depths of less than 7 m (Figures 2A and 2B). This geomorphological unit is connected to the bottom of the bay by a rough *Slope (LD)*, which consists of a wide strip to the west of the bay that reaches up to 600 m wide, and which has very steep slopes ranging between 20° and 25°. Meanwhile, in the eastern part of the bay there is a narrower slope, 200 m wide with steep slopes ranging between 10° and 20° (Figures 2A and 2B).

The largest geomorphological unit identified in Cartagena Bay is the *Bay bottom (FN)*, which has an area of 46 km^2 and presents a flat to gently sloping surface, with depths ranging from 7 m to 34 m (Figures 2A-D). To the south of the bay, within this seafloor unit, there are elevations that reach approximately 20 m and make up the *Reef (AF)* unit, which is mainly evident in the center and south of the Bay with a coverage area of 2.3 km^2 (Figure 2D).

The geoforms caused by the mud and gas emanation proposed by Mora *et al*. (2018) were identified in the southern area of Cartagena Bay. This diapiric activity is concentrated in the south of the bay and is made up of 42 mounds with rounded bases that rise in the shape of a cone up to approximately 12m, with rounded tops possibly caused by mud emanations, which constitute the presence of *Mud Volcanoes (VD)* (Figure 2C). Likewise, we identified about 151 *Pockmarks (Pk)*, consisting of circular depressions with diameters between 20 m and 40 m, and depths reaching 3 m (Figures 2C and 2D). These geoforms are generally caused by diapiric activity in an active gas emanation zone (Mora *et al*., 2018).

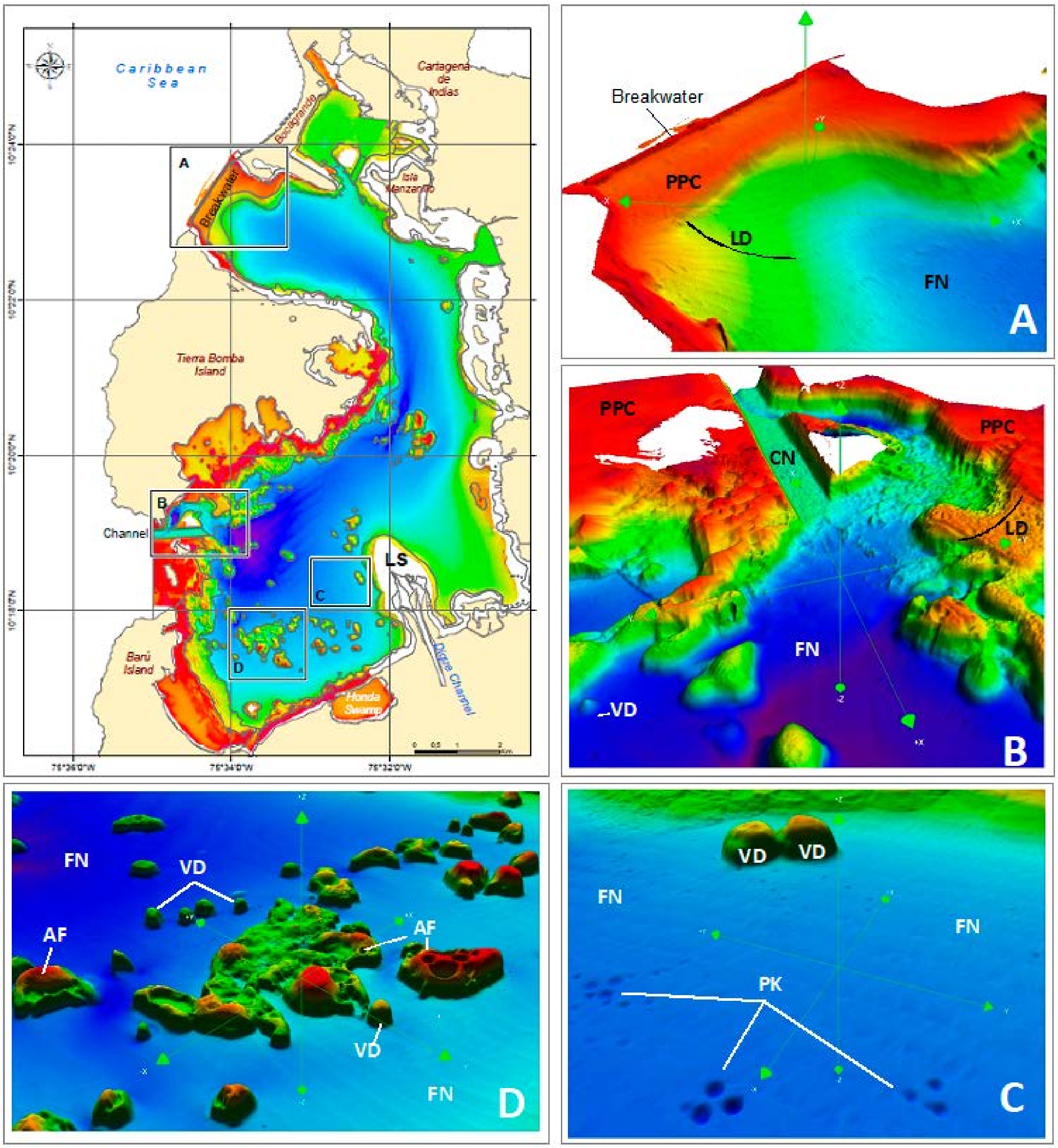


Figure 2. Geomorphological units: PPC: Continental shelf flat; LD: Slope; FN: Bay bottom; AF: Reef, VD: Mud volcano; PK: Pockmarks; CN: Channel; LS: Sediment fan; EC: Breakwater.

The mouth of the Canal del Dique is located to the southeast of Cartagena Bay. This mouth discharges sediments directly into the bay, generating a *Sediment Fan (LS)*, which consists of a sedimentary deposit of fluvial origin which, as it is muddy and shallow, makes it difficult to perform the bathymetric survey, so there is an absence of data in its shallowest area (Figure 2).

The Bocachica *Channel (CN)* is a relief form that constitutes the main access channel to the southwest of the Cartagena Bay, allowing the transit of vessels. Periodic dredging is carried out in this area so it maintains a suitable size. At the time the bathymetric information was collected, this landform had an approximate depth of 20.5 m and a sill width between 180 and 200 m (Figure 2B).

Finally, the *Breakwater (EC)*, is a landform of anthropogenic origin, built during the XVl and XVII centuries on the floor of the Cartagena Bay (Figure 2A). It is an underwater engineering work located in the north of the bay to restrict the passage of large vessels through the Bocagrande opening (Diaz and Serrat, 2019). This structure may influence the flow of currents and sediments, mainly in the north of the bay.

Bathymetric evolution

The main differences in the bathymetry during period A (2000-2004) are observed in a sediment fan formed to the north of the Canal del Dique, where there are decreases in depths of up to 13 m. This is evidence of strong sedimentation in an area where depths were between 10 and 20 m in 2000, while in 2004 depths were between 2 and 15 m (Figure 3A).

During this period, minor differences with values between -2 and 2 m are observed in the rest of the bay; with the exception of the areas near the coast of Tierra Bomba Island, the shallows of Ciénaga Honda, and the Palito and Santa Cruz banks, where erosion processes increased water depths.

In period B (2004-2012), a similar sedimentation lobe is created in the Pasacaballos Shallows, with reductions in depths between 4 and 21 m. Additionally, in the sector near the Contecar dock, there is an area with values that indicate an increase in depth, which may be related to dredging carried out to ensure the navigability of the area near the dock. In the rest of the bay there are no differences as great as those mentioned above (Figure 3B).

In period C (2012 – 2020), the greatest differences occurred in the access channels, the ports, some shallows and especially in the Pasacaballos Shallows. Marked differences are observed with negative values indicating decreases in the depth of the areas. In the Bocachica channel, differences between 3 and 10 m are observed, and in areas near the Contecar and Mamonal docks, differences of up to 13 m are observed. In addition, an increase in depth of up to 8 m is observed in the access zone to the Port Zone, located between Castillogrande and Manzanillo Island. Finally, there was a delta progradation of approximately 500 m and sedimentation generated a decrease in depth of between 5.8 and 18.3 m in the Pasacaballos Shallows (Figure 3C).

When reviewing the differences in bathymetry over the last 20 years in Cartagena Bay, similar characteristics are found to those described above for each individual period. Depth increases of up to 16 m are observed in the areas near the Contecar and Mamonal docks, and the Port. Similarly, in the navigable sector of the Bocachica Channel, depth differences between 3.5 and 17.2 m were observed (Figure 3D). The opposite has occurred around Pasacaballos, where there is a delta progradation of approximately 1 km and a sedimentation rate that has generated depth decreases of up to 18.5 m in period D (2000-2020). Finally, some differences of up to 10 m are observed in the nearshore areas of Tierra Bomba Island, the shallows of Ciénaga Honda, and the Palito and Santa Cruz banks (Figure 3D).

The depth cross sections conducted for the years 2000 and 2012 show a decrease of up to 20 m in depths around the mouth of the Canal del Dique, indicating a sedimentation trend over the 12 years studied (Figure 4). As mentioned above, the profiles were made with the bathymetries of these two years due to the density of data in the analyzed area, while no information was obtained in the shallowest areas in the 2020 survey. This can be seen in Figure 3, in which there are areas with no data near the mouth of the Canal del Dique and some other sectors near the coast.

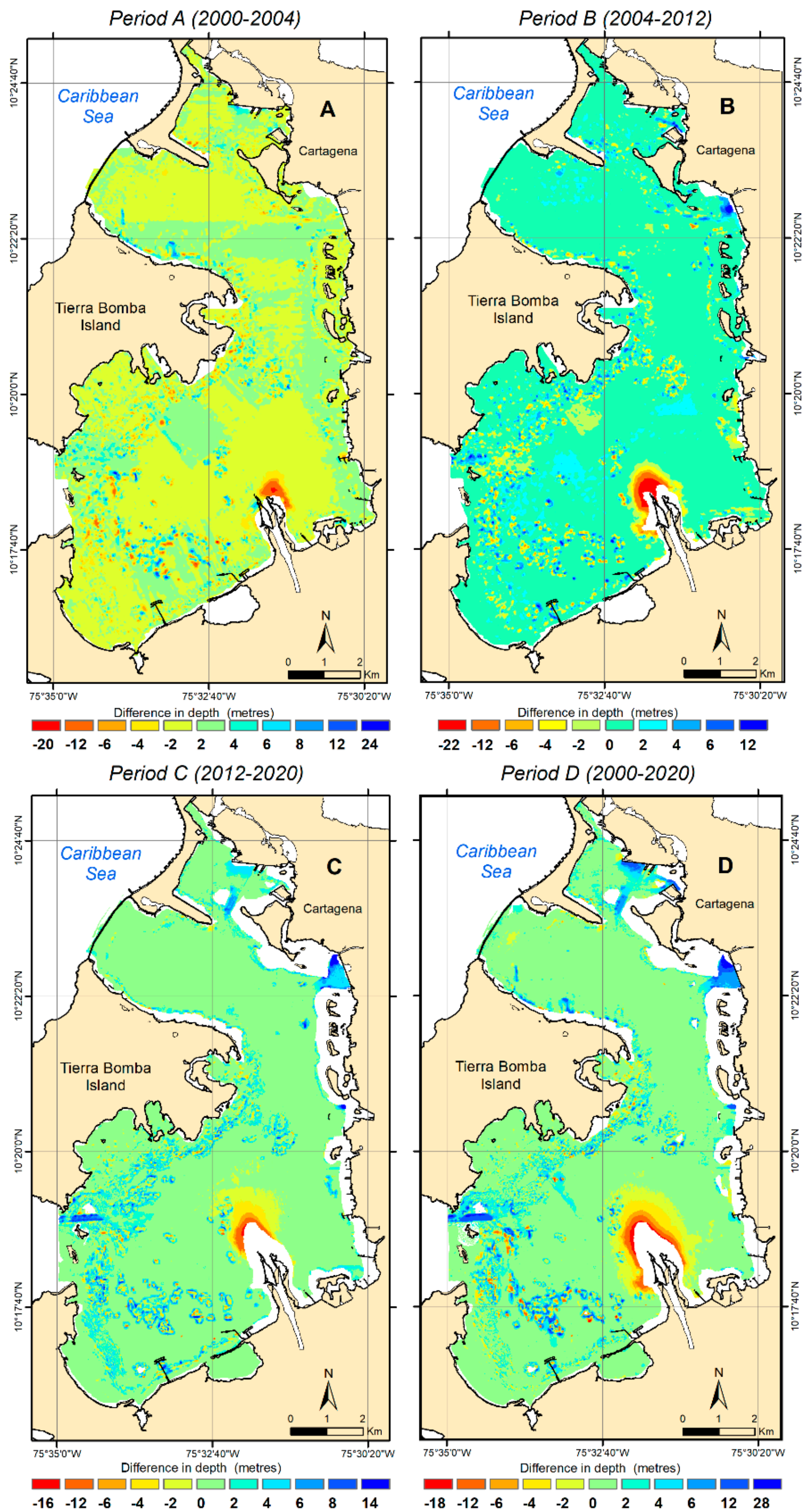


Figure 3. 2D view of the difference between the bathymetries of Cartagena Bay in four periods during the last 20 years

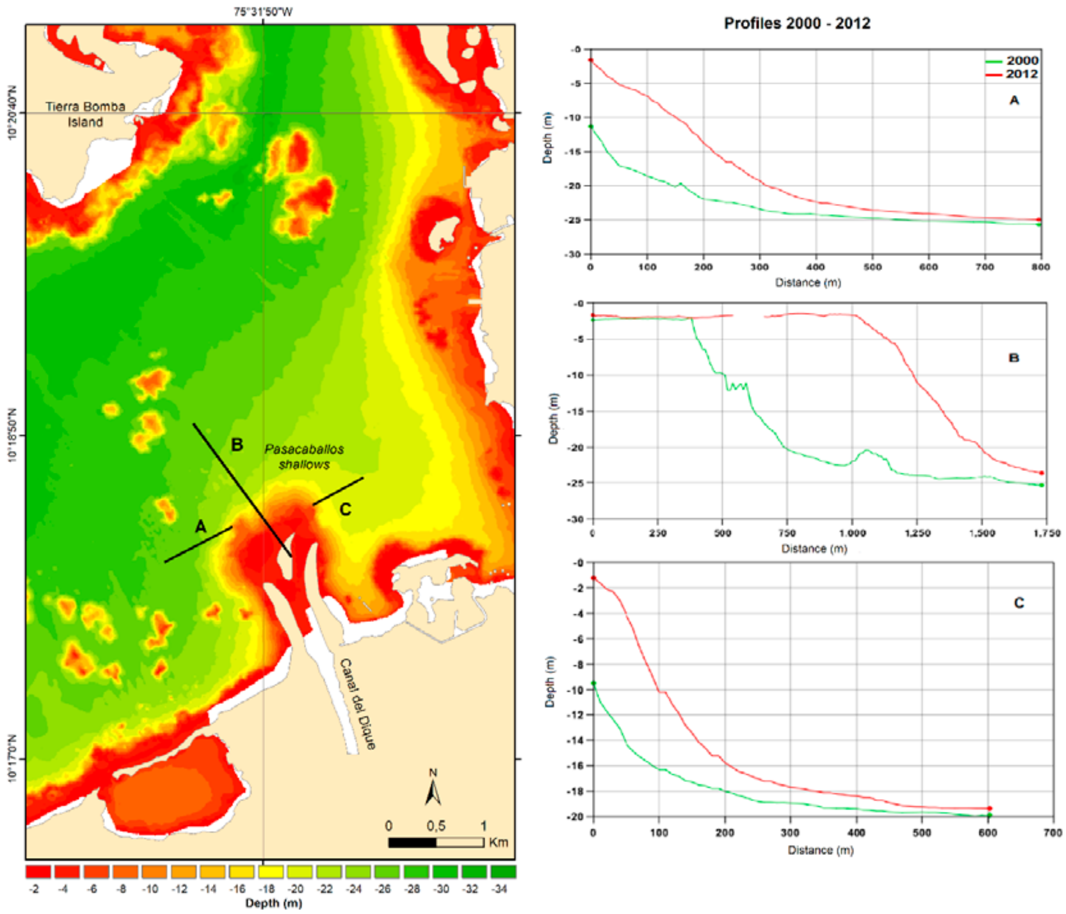


Figure 4. Depth profiles from the bathymetries for the years 2000 and 2012.

The cross sections were made in different directions, as shown in Figure 4, where they are located on the bathymetry of the year 2000. These directions were selected with the intention of covering the slope of the Pasacaballos shallows and observing the differences in depths on each side; there are similar sedimentation patterns in profiles A and C, with depth decreases of up to 10 m (Figures 4A and 4C). However, in profile B, located at the front of the Canal del Dique, a strong sedimentation is observed that generates a delta progradation of approximately 600 m, with depth differences of up to 20 m (Figure 4B).

Sedimentary analysis

The sediments collected in Cartagena Bay were classified by GRADISTAT software according to grain size, and it also analyzed the sorting, asymmetry and kurtosis. In the samples collected in Cartagena Bay, a predominance of mud sediments is observed with 65.26% of samples classified in this size range (4φ to 10φ); followed by 31.10% sand particles (-1φ to 4φ) and only 3.64% gravel ($\varphi < -1$). This distribution highlights the prevalence of fine sediments in the area, with an average grain size of 5.08 φ, fluctuating between -2.36 φ and 9.85 φ.

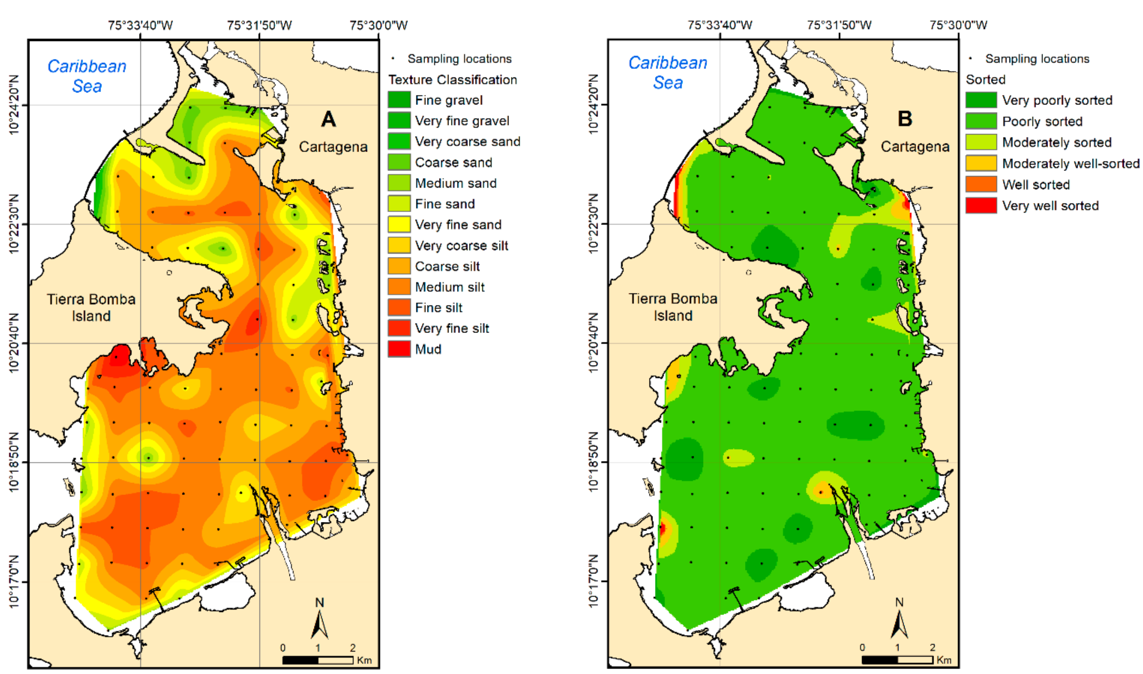
The sorting of the collected sediments is classified from very well sorted to very poorly sorted, with a predominance of poorly sorted sediments ($\varphi = 1.46 \pm 0.61$). In addition, 35 % of the collected samples evidence symmetry ($-0.1 \leq \varphi \leq 0.1$), with an average asymmetry value of 0.05 ± 0.28. Finally, the kurtosis value classified the sediments from very platykurtic to extremely leptokurtic, with a mean kurtosis of 1.30 ± 1.51 (Table 4). Figure 5 shows the distribution of these variables in the bay.

Table 4. Texture characteristics of the surface sediments in Cartagena Bay.

Texture characteristics	Statistical parameters			
	Mean	Standard deviation	Minimum value	Maximum value
Grain size (φ)	5.08	2.55	-2.36	9.85
Sorting (φ)	1.46	0.61	0.04	2.87
Asymetry (φ)	0.05	0.28	-0.72	0.85
Kurtosis (φ)	1.30	1.51	0.58	10.63
Gravel (%)	3.64	12.57	0.00	100.0
Sand (%)	31.10	36.52	0.00	100.0
Mud (%)	65.26	40.60	0.00	100.0

We identified that sediment in the gravel size range is found only near the Bocagrande breakwater, and that these sediments were well sorted, symmetrical, and very platikurtic; while fine sediment is observed on the south coast of the island of Tierra Bomba, where poorly sorted, symmetrical and mesokurtic silts and clays are found. In other sectors such as the inner bay of Bocagrande, the Contecar dock, the Pasacaballos shallows and the coastal strip of Mamonal, sandy sediments are observed, with poor to moderate sorting and asymmetry towards the fine sediments. Meanwhile, in the Bocachica Channel there are sands with very poor to poor sorting, symmetry towards coarse grains, and which are leptokurtic. The rest of the bay is mainly composed of poorly sorted, symmetrical and mesokurtic muddy sediments (Figure 5).

The distribution of calcium carbonate content (%$CaCO_3$) showed that the area has a great influence of lithoclastic sediments, since 73% of the samples are in this classification, as they had less than 15% $CaCO_3$ content; this was followed by 13% of sediments classified as lithobioclastic and 10% as biolithoclastic. Only 4% of the samples were classified as bioclastic material, as they were more than 85% $CaCO_3$ (Figure 6).



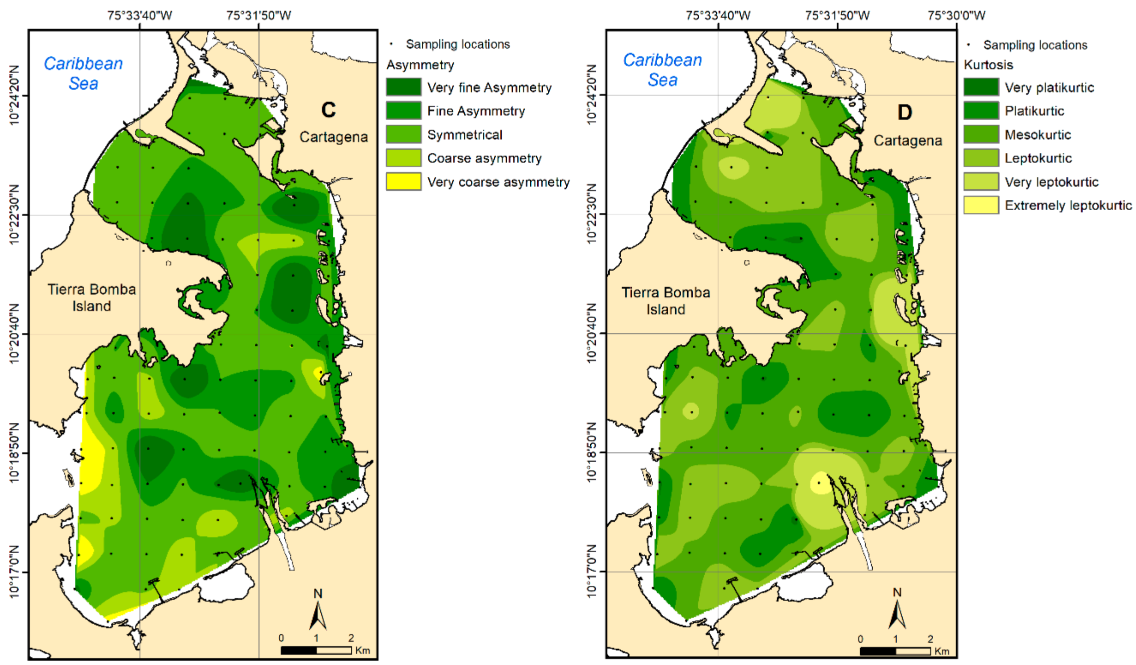


Figure 5. Visualization of the distribution of the texture characteristics of the surface sediments in Cartagena Bay.

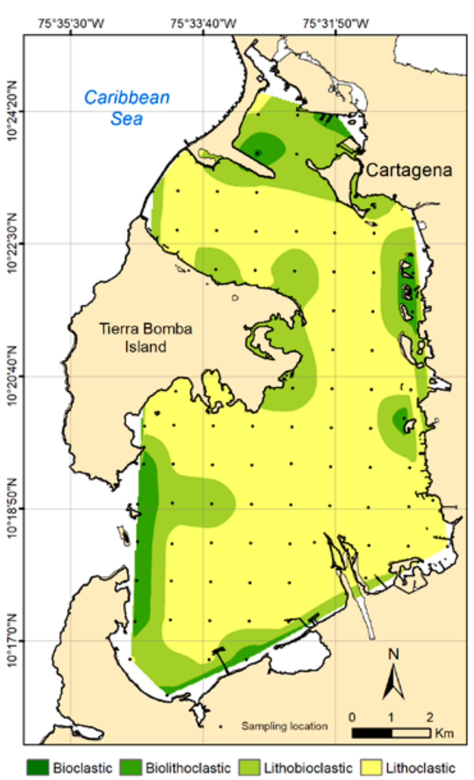


Figure 6. Visualization of the distribution of the composition of the surface sediments of Cartagena Bay.

The biolithoclastic and lithobioclastic material is mainly distributed in coastal areas such as the inner bay of Bocagrande, the coastal strip between Contecar and Mamonal docks, the coast of Barú Island, Ciénaga Honda and the northeast of Tierra Bomba Island. There is also a grouping of this material in the Bocachica channel. The rest of the areas of Cartagena Bay are characterized by lithoclastic sediment (Figure 6).

Discussion

Cartagena Bay is considered an estuary due to the presence and influence of the Canal del Dique, a man-made structure that generates fluvial inputs in the area (Lonin, Parra, Andrade and Thomas, 2004). This structure was built in colonial times with the objective of directly connecting the Magdalena River to the bay (Bell-Lemus, 1989). Since then, the canal, its mouth and some sectors have been constantly dredged to ensure the navigability of the areas and the economic stability and functionality of the ports of the city of Cartagena (Andrade *et al*., 2004; Lonin, Parra, Andrade and Thomas, 2004; Restrepo *et al*., 2013). Thus, it follows that the main bathymetric changes during the studied period could have been caused by dredging in the study area and by the sediment load contributed by the Canal del Dique and the ensuing alteration of the sedimentary dynamics of the bay, mainly in the Pasacaballos shallows.

The Canal del Dique represents a fluvial contribution with the transport of fine terrigenous sediments (0 - 31 μm) (Lonin and Giraldo, 1996). According to Tosic *et al*. (2018), historical records indicate an average flow of 397 $m^3\ s^{-1}$ during the years 1984-2000 and an increase to 508 $m^3\ s^{-1}$ during the period 2000-2010. Similarly, the sediment load before 2000 was 16135 ton day^{-1}, and increased to 23906 ton day^{-1} during the period 2000-2010. In addition, a sedimentation rate of 0.7 - 0.8 cm yr^{-1} was estimated at the mouth of the channel. This sediment of fluvial origin has reached and impacted the coastal ecosystems of the bay, as well as areas with the presence of coral reefs, generating an impact on these ecosystems (Restrepo, Escobar and Tosic, 2018).

According to bathymetric comparison studies previously conducted by Andrade *et al*. (2004), the greatest differences in depths are observed at the front of the Canal del Dique, since a deltaic type environment has developed in recent decades, generating an accumulation of sediments up to 22 m thick. This is consistent with what was observed in this study, where bathymetric profiles showed a decrease of up to 20 m in depths around the mouth of this channel (Figure 4B).

Previous studies of Cartagena Bay by Mora *et al*. (2018) report mud and gas emanations, evidencing diapiric activity and the presence of fluid and gas seeps. In this research, multibeam bathymetry from 2020 was used to identify, quantify and georeference 42 Mud Volcanoes (VD) in the central and southern area of the bay (Figure 7A), which are geoforms that can cause a change in the sedimentary facies due to their contribution of muddy material.

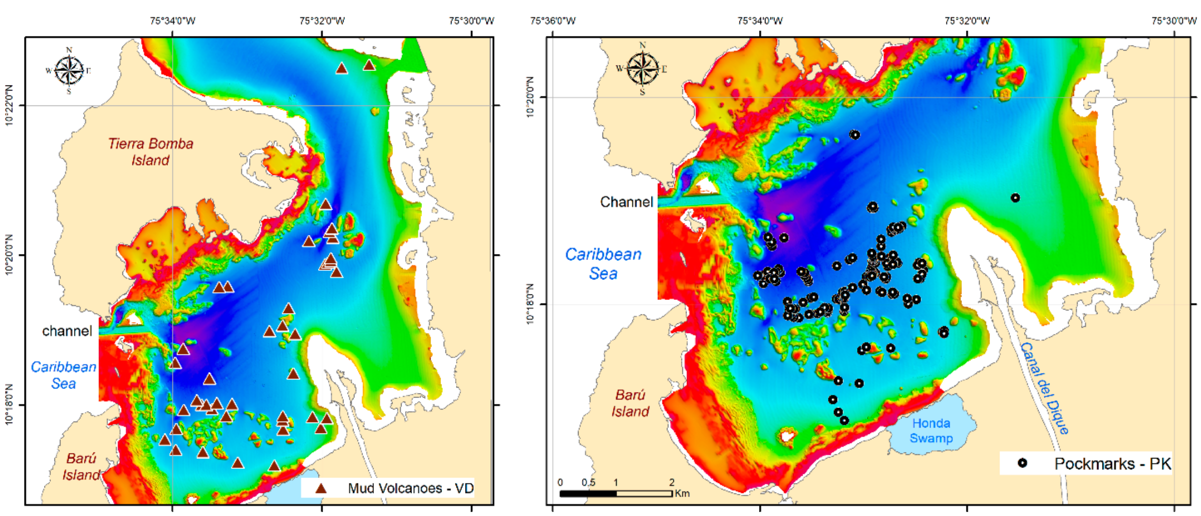


Figure 7. Location of Mud Volcanoes (VD) and Pockmarks (PK) in Cartagena Bay.

Additionally, this study identified a total of 151 Pockmarks (PK) (Figure 7B), which are characterized as circular depressions that are located mainly to the south of the bay, with diameters between 20 and 40 m and variable depths, ranging from 0.60 m to 3 m. Mora *et al*. (2018) propose a possible structural control in the depth of the Pockmarks, because they identified them clustered or aligned at 3 m depth. However, in this study there is no evidence of a trend in depths that could confirm the possible structural control proposed by those authors. We do not rule out the proposal of Mora *et al*. (2018), due to the fact that some existing depressions could be being covered by sediments coming from the Canal del Dique and would not be observed.

Studies related to the characterization of the bottom sediments of Cartagena Bay have concluded that the distribution of its sedimentary facies has changed in recent decades (Vernette, 1978; Andrade *et al*., 2004; Restrepo *et al*., 2013; Franco, Restrepo, Sanabria and

Gutiérrez, 2013). Authors affirm that the $CaCO_3$ content has decreased throughout the bay and in the southwestern zone the grain size has also decreased; they suggest the increasing contribution of sediments from the Canal del Dique and the oceanographic conditions of the area as the main causes of these variations (Franco, Restrepo, Sanabria and Gutiérrez, 2013).

Thus, the calcareous sediments present in the bay are being covered by terrigenous sediments transported by the channel, which is playing a fundamental role in the sedimentation of the area (Restrepo *et al*., 2013). The %$CaCO_3$ figures observed in this study back up this idea, as only 4% of the samples collected were classified as bioclastic material, while 73% have a lithoclastic composition.

Additionally, it is important to emphasize that this study shows a trend of calcareous sediments with larger grain size in the area of the Bocachica Channel (Figures 5A and 6), which suggests that the dredging carried out in the sector removes the terrigenous material transported by the Canal del Dique and exposes the sandy calcareous material at the bottom. This is supported by the fact that in the sectors near the coasts of the islands and the ports, where erosion and dredging occur, a higher prevalence of this calcareous material is also observed, compared to the rest of the bay.

Finally, the sediment distribution of Cartagena Bay may be altered due to the presence of anthropic structures, such as the Bocagrande breakwater and the Canal del Dique. This is because these structures influence the distribution of facies, mainly due to the contribution of terrigenous sediments from the Canal del Dique, as previously mentioned by Andrade *et al*. (2004). In this study, it was determined that the sediment size distribution in the bay is dominated by muddy material from the Canal del Dique, deposited mainly at its mouth and in the central zone of the bay, while sands are found mainly in the sediments of the Bocagrande beach and sectors near the coast.

Conclusions

According to the evidence of this study, the morphological evolution of the bottom of Cartagena Bay may be affected by three main factors. Firstly, there are clear changes in the depths of the areas used for the access of ships, such as channels and docks. Taking into account the information reported by the Port Captaincy of Cartagena for the years 2005 and 2010, it can be said that this anthropic intervention directly influences the depth of the different areas of the bay and represents an alteration in its morphology.

Secondly, there is the presence of mud volcanoes and Pockmarks, identified mainly to the south of Cartagena Bay. These geoforms cause characteristic morphogenetic changes that are evident in the area where they occur and in turn alter the sedimentary facies due to their muddy content. Finally, the anthropic intervention that the Cartagena Bay has suffered, such as the presence of the breakwater and the Canal del Dique, accentuate the changes observed in the distribution of the sediment facies identified in the bay.

The Canal del Dique is a fluvial contribution that represents a sediment load of 23 906 ton day^{-1}, which is reflected in the predominance of terrigenous sediments in the Cartagena Bay. The distribution obtained from the sediment characteristics reveals that 65% of the sediments are classified in the mud size range and 73% have a lithoclastic composition. In addition, the sediment load transported by the Canal del Dique defines the relief shape and depth of the Pasacaballos shallows, where the shallowest depths were found in the last study.

Bibliography

Andrade, C.; Arias, F.; Thomas, Y.F. (1988). Nota sobre la turbidez, circulación y erosión en la región de Cartagena (Colombia). *Bol. Cient. CIOH,* 8: 71-82. https://doi.org/10.26640/22159045.29

Andrade, C.; Thomas, Y. F.; Lonin, S.; Parra, C.; Kunesch, S.; Ménanteau, L.; Andriau, A.; Piñeros C.; Velasco, S. (2004). Aspectos morfodinámicos de la bahía de Cartagena de Indias. *Bol. Cient. CIOH*, 22: 90-104. https://doi.org/10.26640/22159045.131

Bell-Lemus, G. A. (1989). El Canal del Dique 1810-1840: el viacrucis de Cartagena. *Boletín Cultural y Bibliográfico,* 27(21):15-23. Recuperado de: https://publicaciones.banrepcultural.org/index.php/boletin_cultural/article/view/2585

Blott, S. J.; Pye, K. (2001). GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth surface processes and Landforms,* 26(11):1237-1248. https://doi.org/10.1002/esp.261

Díaz, J. G.; Serrat, J. F. (2019). La Escollera de Bocagrande en Cartagena de Indias (Colombia): una obra maestra de la ingeniería española en ultramar (s. XVIII). In: *Actas del Undécimo Congreso Nacional de Historia de la Construcción: Soria,* 9-12 octubre 2019 (pp. 459-468). Instituto Juan de Herrera.

Dirección General Marítima, Capitanía de Puerto de Cartagena. (2010). *Dragado de ampliación del canal de acceso de la Bahía de Cartagena-Sector Bocachica entre las abscisas del proyecto K0+330 al K1+620.* Dimar-CP5.

Franco, D. A; Restrepo, J. C., Sanabria, N. Y; Gutiérrez, J. C. (2013). Caracterización y distribución de facies sedimentarias en la bahía de Cartagena, Colombia. *Boletín de Geología,* 35(1):43-53. https://ri.conicet.gov.ar/handle/11336/6632

Klingebiel, A.; Vernette, G. (1979). Estudio batimétrico y sedimentológico en la plataforma continental entre Cartagena y la desembocadura del río Magdalena (Colombia). *Bol. Cient. CIOH,* 2: 55-70. https://doi.org/10.26640/22159045.8

Lonin, S. A.; Giraldo, L. (1996). Influencia de los efectos térmicos en la circulación de la bahía interna de Cartagena. *Bol. Cient. CIOH,* 17: 47-56. https://doi.org/10.26640/01200542.17.47_56

Lonin, S.; Parra, C.; Andrade, C.; Thomas, Y. F. (2004). Patrones de la pluma turbia del Canal del Dique en la Bahía de Cartagena. *Bol. Cient. CIOH,* 22: 77-89. https://doi.org/10.26640/22159045.130

Molares, R. (2004). Clasificación e identificación de las componentes de marea del Caribe colombiano. *Bol. Cient. CIOH,* 22:105-114. https://doi.org/10.26640/22159045.132

Mora, H.; Carvajal, J. H.; Ferrero, A.; León, H.; Andrade, C. A. (2018). Sobre emanaciones de gas natural y la evidencia preliminar de subsidencia en la bahía Cartagena de Indias (Colombia). *Bol. Cient. CIOH,* 37(2):35-51. https://doi.org/10.26640/22159045.2018.448

Padilla N.; Villanueva E. (2020). *Distribución del sedimento de fondo de la Bahía de Cartagena.* Recuperado de: Repositorio Universidad del Norte.

Pulido, D. A.; De Lisa, A.; Viteri, D.; Guzmán, R. (2013). Determinación de los datums de referencia vertical con fines hidrográficos para la Bahía de Cartagena. *Bol. Cient. CIOH,* (31):175-190. https://doi.org/10.26640/22159045.258

Restrepo, J. C.; Franco, D.; Escobar, J.; Correa, I. D.; Otero, L.; Gutiérrez, J. (2013). Bahía de Cartagena (Colombia): distribución de sedimentos superficiales y ambientes sedimentarios. *Latin american journal of aquatic research,* 41(1), 99-112. https://doi.org/10.3856/vol41-issue1-fulltext-8

Restrepo, J. D.; Escobar, R.; Tosic, M. (2018). Fluvial fluxes from the Magdalena River into Cartagena Bay, Caribbean Colombia: Trends, future scenarios, and connections with upstream human impacts. *Geomorphology,* 302:92-105. https://doi.org/10.1016/j.geomorph.2016.11.007

Rueda, J. G.; Otero, L. J.; Pierini, J. O. (2013). Caracterización hidrodinámica en un estuario tropical de Suramérica con régimen micro-mareal mixto (Bahía de Cartagena, Colombia). *Bol. Cient. CIOH,* 31:159-174. https://doi.org/10.26640/22159045.257

Sibson, R. (1981). *A brief description of natural neighbour interpolation. Interpreting multivariate data.*

Smith, R.; Taft, G. (2000). Legal Aspects of the Continental Shelf, in Peter J Cook, and Chris Carleton (eds), *Continental Shelf Limits: The Scientific and Legal Interface online* end. Oxford Academic. https://doi.org/10.1093/oso/9780195117820.003.0007

Tosic, M.; Restrepo, J. D.; Lonin, S.; Izquierdo, A.; Martins, F. (2018). Water and sediment quality in Cartagena Bay, Colombia: Seasonal variability and potential impacts of pollution. *Estuarine, Coastal and Shelf Science,* 216, 187-203. https://doi.org/10.1016/j.ecss.2017.08.013

Udden, J. A. (1914). Mechanical composition of clastic sediments. *Bulletin of the Geological Society of America,* 25(1): 655-744. https://doi.org/10.1130/GSAB-25-6555

Vernette, G. (1978). Cartografía de los fondos en la plataforma continental: estandarización de los criterios sedimentológicos. *Bol. Cient. CIOH,* 4: 3-13.

Vernette, G.; Buitrago, J.; Campos, N.; Llano, M. (1977). Variaciones morfológicas de las costas de la Bahía de Cartagena a partir del siglo XVI. *Bol. Cient. CIOH,* (1):21-40. https://doi.org/10.26640/22159045.5

Vernette, G.; Lesueur, P.; Klingebiel, A. (1984). Evolución morfológica y sedimentológica de la flecha litoral del laguito (Bahía de Cartagena). *Bol. Cient. CIOH,* (5): 3-23. https://doi.org/10.26640/01200542.5.3_23

Wentworth, C. K. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology,* 30(5): 377-392. https://doi.org/10.1086/622910