SHORT ARTICLE

Mapping the seabed of the Colombian Caribbean: Proposal for a cartographic scheme of the underwater geomorphology of Colombia (South and Central Section of the continental margin)

Mapeando el fondo marino del Caribe colombiano: propuesta de un esquema cartográfico de la geomorfología submarina de Colombia (sección sur y central del margen continental)

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ABSTRACT

This paper shows the progress made in relation to the project to carry out submarine geomorphological and structural mapping of Colombian maritime territory, which started with the design of a cartographic grid divided into 22 charts at a scale of 1:250 000. This paper presents the first two charts developed between the years 2020-2021. These charts were prepared with the use of bathymetric information, 2D seismic data, magnetic and gravimetric anomalies, and satellite data, all integrated in Geographic Information Systems (GIS). As a result, the geomorphological units that characterize the southern and central part of the continental margin of the Colombian Caribbean were published in two thematic charts numbered 1408 and 1409, as established in the cartographic grid designed for this purpose.

KEYWORDS: Submarine geomorphology, Caribbean, continental margin, Sinú, Magdalena Fan, bathymetry

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Resumen

Esta publicación muestra los avances obtenidos en el proyecto de mapeado geomorfológico y estructural submarino del territorio marítimo colombiano, el cual parte desde el diseño de un esquema cartográfico para el Caribe que se dividió en 22 cartas a escala 1:250 000. En este trabajo se avanza con la presentación de dos primeras cartas desarrolladas entre los años 2020 y 2021. La elaboración de estas cartas se realizó con el uso de información batimétrica, sísmica 2D, anomalías magnéticas y gravimétricas, y datos satelitales, todo integrado bajo herramientas de sistemas de información geográficas (SIG). Como resultado se obtuvieron las unidades geomorfológicas que caracterizan la parte sur-central del margen continental del Caribe colombiano en dos cartas temáticas enumeradas 1408 y 1409, acorde a lo establecido en el esquema cartográfico diseñado para tal propósito.

Palabras claves: *geomorfología submarina, Caribe, margen continental, Sinú, abanico del Magdalena, batimetría.*

Introduction

Solid understanding of the geomorphological environment of the seabed is key for maritime spatial planning, the designation of marine protected areas, the construction and operation of offshore infrastructure and the implementation of environmental monitoring programs (Micallef, Krastel & Savini, 2017). Collecting remotely sensed data to map the seabed is difficult due to its high cost; however, in the last decade, the General Maritime Directorate (Dimar), through the Center for Oceanographic and Hydrographic Research of the Caribbean (CIOH) and the National Hydrographic Service (SHN), has made efforts to strengthen its technological research capacities by acquiring sonar equipment, data from which helps to generate new knowledge about the deep seabed of the Colombian Caribbean and Pacific.

Dimar is responsible for producing the nation's nautical charts, in accordance with item 4 of Article 5° of Decree-law N°. 2324 of 1984, and items 2 and 6 of Article 2 of Decree N°. 5057 of 2009, whilst also complying with Chapter V "Safety in Navigation" (Dimar, 2021). Consequently, the CIOH has proposed the development of a grid of thematic charts of the geomorphology and structure of the country's maritime territory, consisting of 22 charts at a scale of 1:250 000. They are to be numbered under the 1400 series for the Caribbean, and will delineate and describe the geomorphological units of the seabed of the Colombian Caribbean.

This article presents the first fruits of the labor of developing the cartographic grid for the Colombian Caribbean Sea, according to color-coded geomorphological charts, which delineate the geomorphological units and trace fault lines in two sectors located between the departments of Córdoba and Atlántico. These maps provides bathymetric information with a 250 m resolution (single beam) on the continental shelf, and 10 m to 50 m resolution (multi-beam) for the continental slope and abyssal plain of the Colombian Caribbean; as well as the interpretation of 2D seismic lines acquired and processed in the framework of exploration projects of the National Hydrocarbons Agency (ANH), stored in its Exploration and Production Information Service (EPIS) database; satellite gravimetry and magnetometry information obtained from the SEEQUEN database, corresponding to regional models from Sandwell *et al*. (2014) and EMAG2 (v3); and the use of GIS for processing and managing geo-referenced information.

Study area

Thematic Charts 1408 and 1409 cover the maritime territory of five departments of the Colombian Caribbean (Fig. 1), with a total coverage area of approximately 33 027 km². The coastline shown in Submarine Geomorphology Chart 1408 extends from the coast of the department of Córdoba, near Bahía Rada, to the coastal area near Galerazamba, in the department of Bolívar; its maritime zone or submerged area extends out to a depth of 3 300 m, according to the bathymetry acquired and processed by the CIOH. For its part, Chart 1409 covers from the coast of Galerazamba, in the department of Bolívar, where it borders Chart 1408, to the vicinity of Tasajera, Magdalena; the marine territory shown in it reaches a maximum depth of 3 700 m.

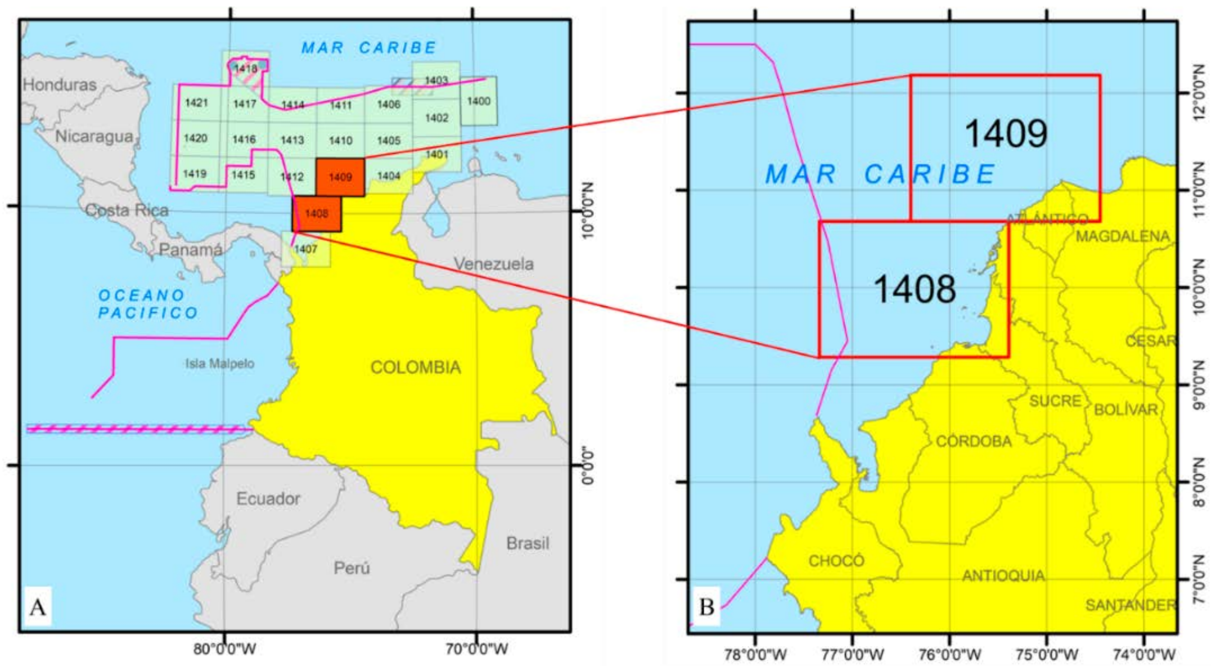

Figure 1. (**A**). Distribution of the cartographic grid for the submarine geomorphology of the Colombian Caribbean: 22 charts at a scale of 1: 250,000. (**B)** Geomorphological Charts 1408 and 1409.

General geological aspects of the mapped area

In terms of its geological context, the mapped area is located in the zone of influence of the South Caribbean Deformed Belt, which, in its southern section, is forming the Sinú accretionary prism on the seabed, as a result of the compressional interaction between the Caribbean plate and the South American plate (Veloza *et al*., 2012). To the north we can find the River Magdalena fan structure, and then reach the Sierra Nevada de Santa Marta mountain range, where the Santa Marta, Bucaramanga and Oca faults have an influence (Cediel, Shaw & Cáceres, 2003). On the mainland, the predominant structural provinces are: the Sinú and San Jacinto fold belts, the Plato Geofracture, and the Sierra Nevada de Santa Marta (Carvajal, 2012). The width of the continental margin, marked at the 200 m isobath, varies, being approximately 79.70 km in a straight line from Coveñas, but thinning towards the northern section. It is also possible to observe different processes associated with dykes, channels with important mass transport phenomena (Rangel-Buitrago & Idárraga-García, 2010), as well as areas of predominantly steep slopes, mainly forming canyon walls and important discrepancies in the relief (Vinnels *et al*., 2010).

The Magdalena Fan, most of which can be found in Chart 1409, extends off the coast of the department of Atlántico with a radius of 181.22 km. This area is not precise, since this data is obtained from the change in bathymetry observed in the analyzed data, but it is included in what is mapped and partially presented in this geomorphological chart. However, based on the geophysical data, the total section of the Magdalena fan has been divided into the upper, middle and lower fan. This suggests that it extends out to depths of approximately 4 500 m in its lower section, a zone in which changes in relief are scarce in comparison with the continental slope (Idárraga-García *et al*., 2019).

Methodology

In order to present the characteristics of the submarine relief, geomorphological mapping was carried out in the area of coverage beginning in 2020, applying the workflow designed by the authors for developing thematic charts (Fig. 2).

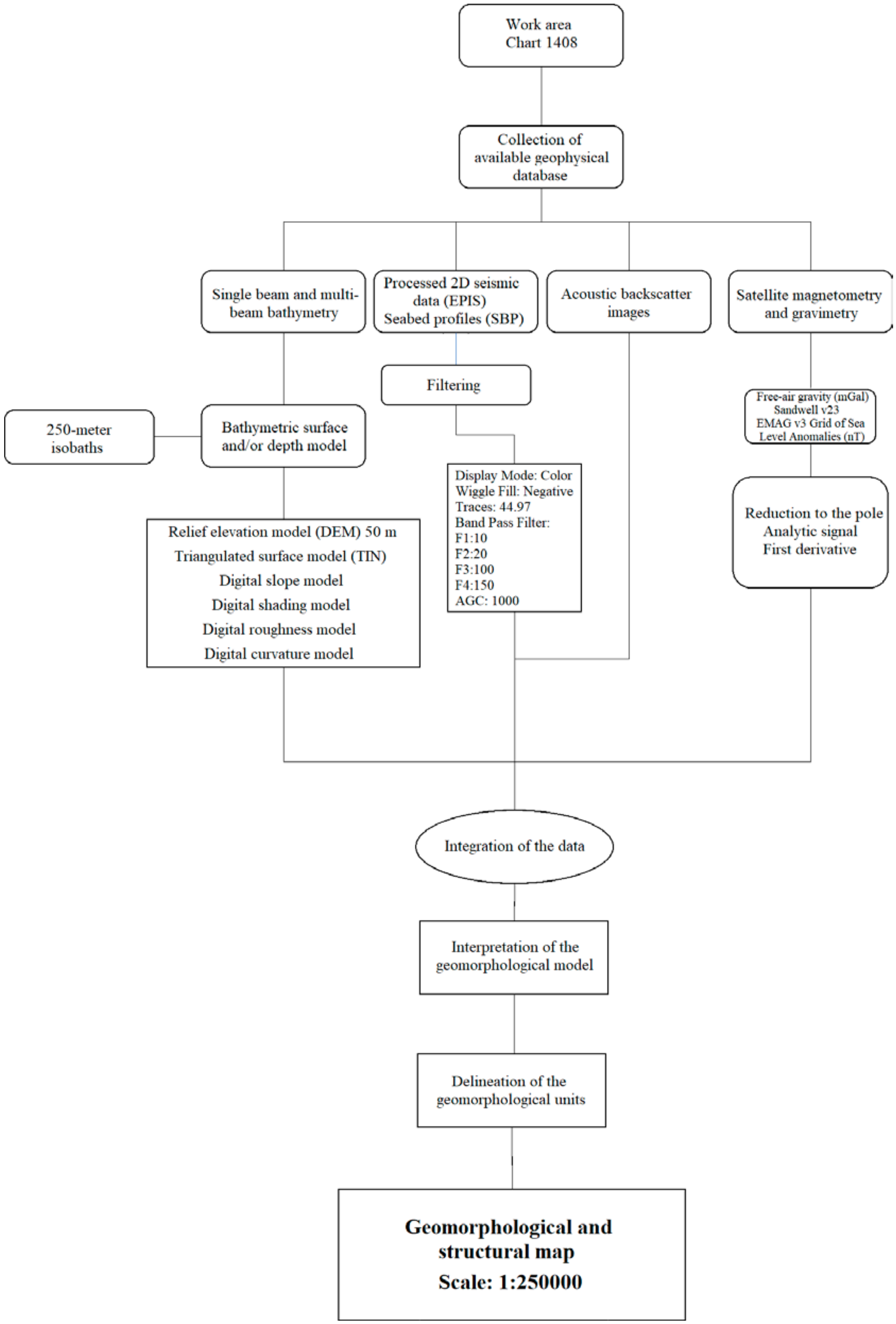

Figure 2. Methodological flowchart used for the elaboration of submarine geomorphology charts of the Colombian Caribbean Sea.

The methodology used was based on the criteria proposed by Micallef *et al*. (2017), which establish techniques and methods to identify and map underwater geoforms with the use of sonar. The main input for this work was the bathymetry provided by the CIOH, which was used to generate the digital depth models, giving a real 3D view of the seafloor. In addition to this information, seismic data was used to determine the deformation processes that gave rise to the configuration of the relief, such as uplifts, depressions, diapirs, landslides, lineaments and fault jumps, among others.

The gravimetry and magnetometry data correspond to a satellite data grid from the Sandwell *et al*. (2014) and EMAG2 (v3) models, respectively, in a section of the Caribbean that included the continental margin, with which regional structural lineaments and faults were identified. The seismic data was processed and, therefore, filters were applied to the images to aid their interpretation (Fig. 2). The interpretation was based on the free-air gravity (mGal) model. This model, based on satellite data, has a spatial resolution of ½ wavelength of 7 km (Sandwell *et al*., 2014); the magnetometry (EMAG2 v3) has a resolution of 2 arc-minutes and an altitude of 4 km above the geoid (Meyer, Saltus & Chulliat, 2017).

Raster images were generated from the depth model based on the surface, with a spatial resolution of 100 m in those areas with depths greater than 200 m. This 3D surface enables the identification of geoforms and underwater terrain features, with which each polygon was delineated. The digitized vector information was incorporated into a geodatabase, with a storage structure known as a feature dataset, which allowed the information to be standardized and the structures ordered according to the *esquema de jerarquización geomorfológica* (geomorphological hierarchy scheme) proposed by Carvajal (2012). In this way, the basic thematic information was obtained to enable the elaboration of the geomorphological map of the area.

The depth models made it possible to obtain digital representations of the underwater relief, from which variables such as slope, roughness, shading and transverse profiles, among others, were obtained. The data were integrated based on the lower resolution bathymetry in the continental shelf, but making maximum use of the possibility to identify structures in the zones of higher resolution in the slope and abyssal plain; therefore, based on the resolution of the data, it was considered prudent to perform the mapping at a scale of 1:250 000,

GIS Modeling

The first model obtained corresponds to the Digital Elevation Model (DEM), which, according to Olaya (2020), is the key piece of the geomorphometric analysis and is the digital equivalent of classic elevation mapping, represented by contour lines ranging from 10 m to 200 m depth on the continental shelf and from 200 m to 3 700 m from the slope to the abyssal plain. For this case, the DEM, the main input used in the other digital models, was obtained using the isolines or isobaths, and the resolution or cell size of the image depended on the distance between them.

The digital models generated included: a slope model, which identifies the gradient or maximum range of change in the Z-axis for each cell; a shading model, in which a shaded relief is created, considering the angle of incidence of the light source; a curvature model, which provides information on the concavity or convexity of the surface; an aspect model, which provides the direction of the slope; and a roughness model, which denotes the irregularity or unevenness of the terrain.

By integrating the interpretations of the geophysical data (bathymetry, 2D seismic, acoustic backscatter, 2D SBP, and GIS tools) it was possible to produce a geomorphological map in two sections, at a scale of 1:250,000, corresponding to Thematic Charts 1408 and 1409. The nomenclature used to characterize the geomorphological structures was based on the geomorphological hierarchy proposed by Carvajal (2012). That work proposes the classification of zones or terrains according to the size and area they occupy, and the level of study, or scale, with which one wishes to work. Therefore, it proposes that each category constitutes a system, and the lower systems are contained within the upper ones.

For the case of this study, carried out at a scale of 1:250 000, the areas were classified into units. The unit is the individual geoform, homogeneous in their origin, generated by a geomorphological process of accumulation or erosion. To name each unit in the thematic table, the nomenclature containing the main formation process or environment (called 'region' in the hierarchy) was used, plus the initials of the name of the geoform. Thus, geomorphological units characterized as denudational, such as debris flow complexes (cfd), turbidity flow complexes (cft), slope deposits (dt), dykes (d) and landslides (dz), are prefixed with a capital D; geomorphological units characterized as morpho-structural, e.g., escarpments (e), depressions (dp), homoclinal ridges (sh), terraces (t) and mud volcanoes (vl) are prefixed with the capital letters MS.

Thus, it is important to mention the processes observed in this submarine geomorphological classification: Denudational (D), Marine (M), Coastal Marine (CM), Marine Denudational (DM), Marine Morpho-structural (MMS), Morpho-structural (MS); and we also mention the observed geoforms: Coral Area (ac), Channel (ca), Canyon (cñ), Debris Flow Complex (cfd), Turbidity Flow Complex (cft), Holocene Deposit (dh), Slope Deposits (dt), Landslide (dz), Dyke (di), Escarpment (e), Abyssal Plain (lla), Continental Shelf (pc), Homoclinal ridges (sh), Valley (v), Mud Volcano (vl).

Results and discussion

The thematic charts obtained are the result of the interpretation of geophysical variables (bathymetry, 2D seismic data, magnetometry, and satellite gravimetry) and their integration in GIS tools. The bathymetric information has a spatial resolution ranging from 15 m to 250 m, the latter in the shallowest areas such as the continental shelf. From this, relief elevation models (DEM), 3D visualizations, transverse profiles and GeoTIFF images were generated, and these were analyzed with GIS tools. These gave profiles with depth data, so isobaths for every 50 m and 250 m depth could be generated and added to the model.

Interpretation of satellite magnetometry and gravimetry

This data showed significant anomalous fields in the submerged accretionary prism and the Magdalena Fan. The most important gravimetric anomalies have values between 13.0 mGal and 80.4 mGal, and geomagnetic behavior between 21.9 nT and 94.09 nT; with elevated values closer to the fan structure, and with negative or low anomalies towards the abyssal plain of the Caribbean basin (Fig. 3).

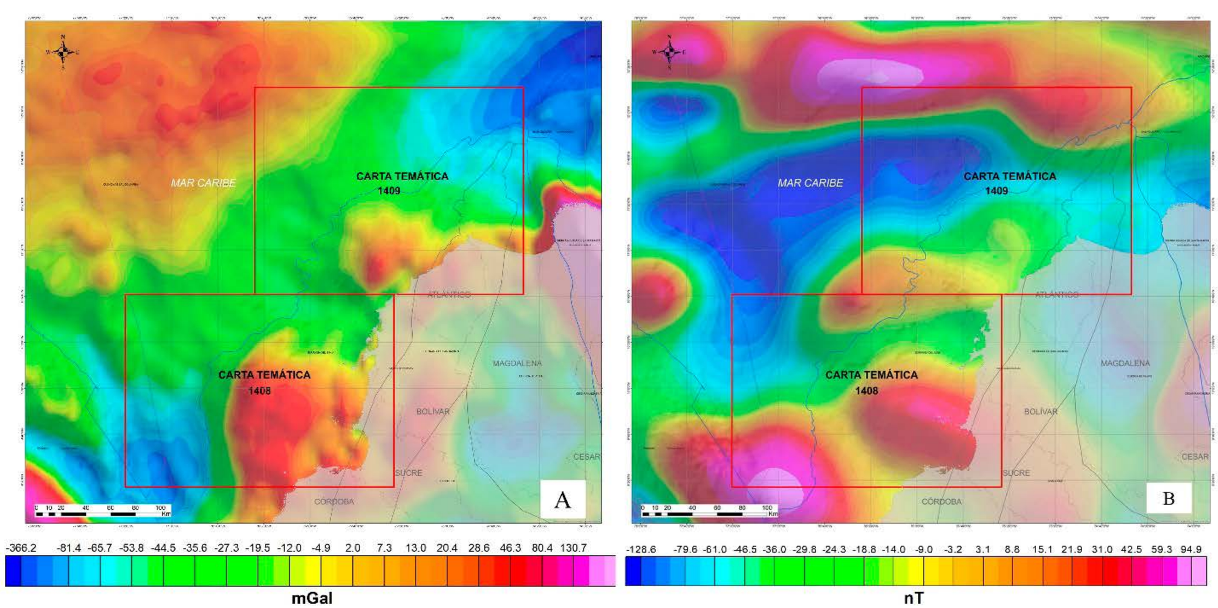

Figure 3. (**A**) Free-air gravity anomalies, Sandwell model; (**B**) EMAG v3 sea level magnetic anomaly. Grid taken from the SEEQUENT database. https://public.dap.seequent.com/

The gravimetric and geomagnetic interpretation, determined by the textural changes of the images, allowed the identification of three basins clearly differentiated by the behavior and distribution of the anomalies. Figure 3A, corresponding to free air gravimetry, shows high anomalies in the continental margin, at the previously mentioned points, and low anomalies towards the deep zone of the abyssal plain, from where the figures increase towards the NW, in the direction of the Cayos Basin. A similar trend is observed in the magnetometry (Fig. 3B); however, the highest anomalies identified are located in the southern part of the continental margin, while the low magnetic anomalies are found towards the Caribbean Basin. An important feature is the coincidence of the high gravimetric and magnetic anomalies in the area of the Sinú Deformed Belt, in the southern part of the mapped area, which takes up a large proportion of the map.

2D seismic interpretation

In the mapped zones there are two important structures: the Magdalena Fan in the north, and in the south the accretionary prism that forms part of the Sinú Deformed Belt. The continental platform narrows to the north of the chart, with evidence of coral units visible in the bathymetry. Structurally, there are important uplifts and depressions in the seabed, as well as processes related to the sedimentary activity of the Magdalena Fan (Fig. 4).

The superposition of the sub-bottom information, obtained with seismic and bathymetric data, enabled the identification of channels generated by sediment flow (Fig. 4), mainly on the continental slope; as well as the presence of large-scale cross-stratification in the slope cross-section (Fig. 5). These seismic lines belong to the section of chart 1409 corresponding to the Magdalena Fan.

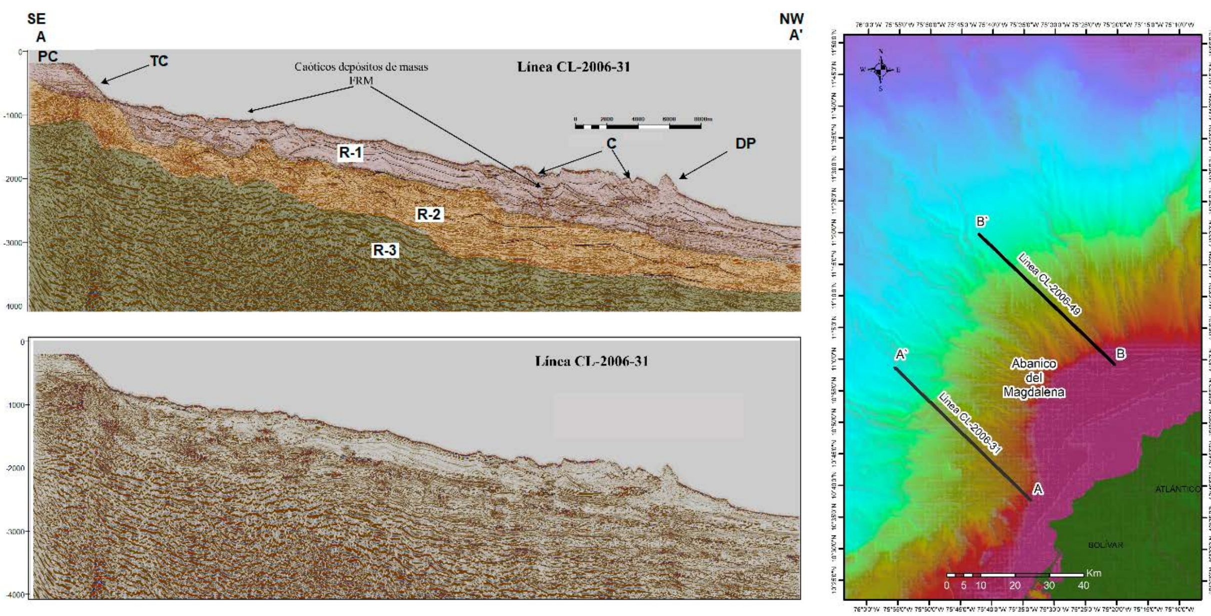

Figure 4. The A-A' cross-section shows the sedimentary deposits of the Magdalena Fan, represented by seismic reflectors that show signs of chaotic deposition in R-1 and R-2, which are associated with mass movement phenomena (FRM) and marked diapiric activity. Reflector R-3 corresponds to the basement rock in the zone. PC: continental platform, TC: section of the continental slope, C: channel, DL: Mud Diapir.

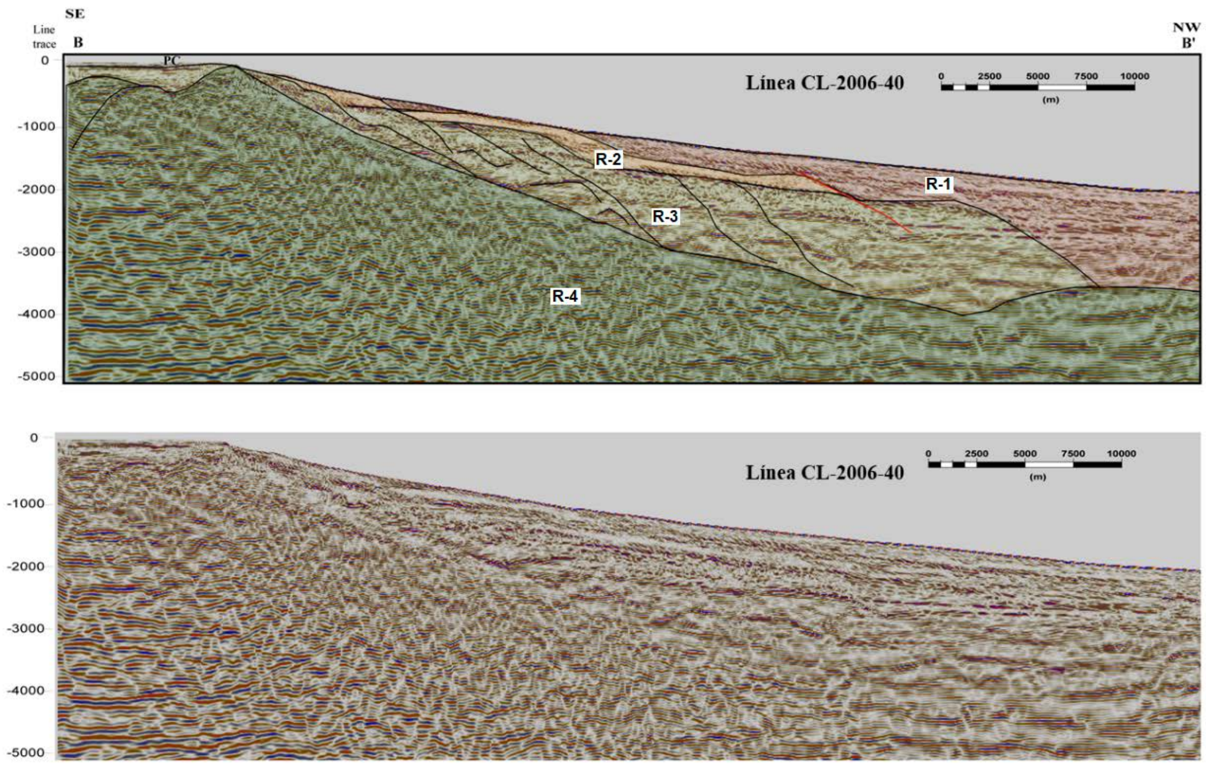

Figure 5. Seismic reflectors R-1, R-2 and R-3 show regional scale depositional processes, with discontinuous reflectors, suggesting faulting and displacement of layers. The last reflector, R-4, is associated with the basement rock in the area.

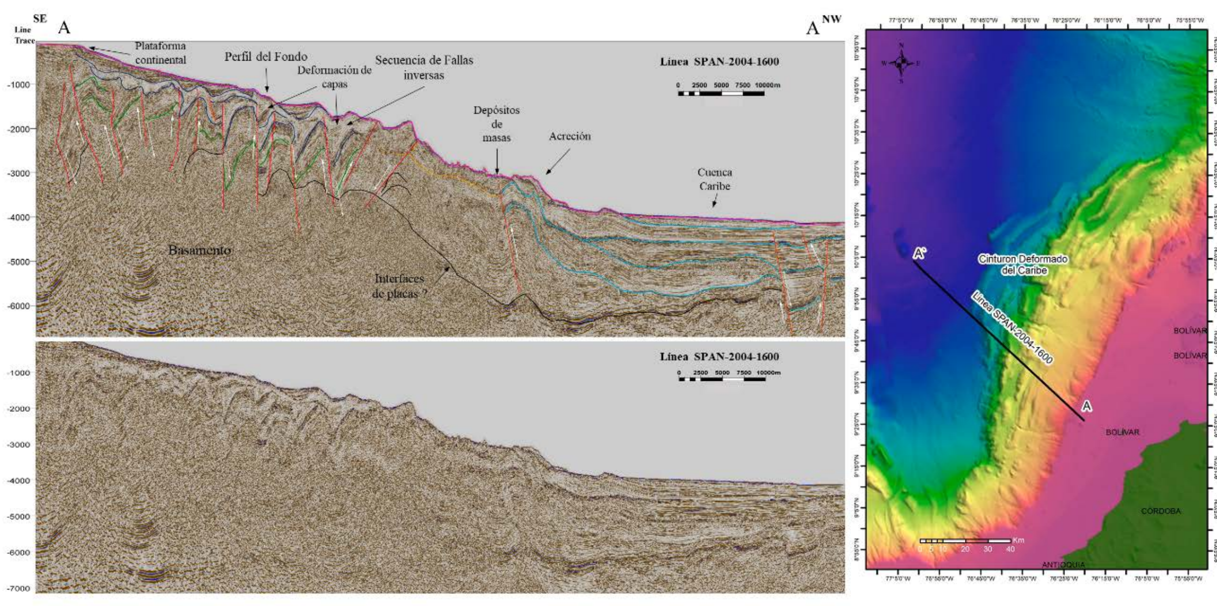

Figure 6. The seismic reflectors are discontinuous thrusts and deformed towards the slope, showing a sequence of reverse and normal faults and mass deposits, along with accretion of the oceanic plate in the Caribbean basin. The A-A' line corresponds to the southern section of Chart 1608.

The southern section of the mapped zone consists of successive continuous uplifts and valleys oriented in a NE-SW direction, dissected by channels associated with a system of reverse or thrust faults. This folding is evident towards the most distal part of the coastline, where it meets the abyssal zone, where the continuity of the deformation front is inferred, while some covered normal faults can be identified towards the platform and in the middle of the deposit. The latter extends to the abyssal zone within the Colombia Basin (Fig. 4).

This zone is affected by normal faults towards the coastline and reverse or thrust faults towards the boundary between the platform and the continental slope; on the latter, the important folding of the southern Sinú Deformed Belt can be identified (Fig. 6).

Continuing to the NE, the Sinú Deformed Belt reappears. This folding, a product of the deformation processes in the area, was defined as a homoclinal ridge, due to the configuration of the layers, which in turn are separated by valleys and dissected by channels corresponding to the fallen blocks of the sector (Fig. 6). In this area, diapiric activity is more evident, as there are protuberances associated with mud volcanoes. This area is also affected by the Bucaramanga-Santa Marta sinistral fault system, which extends from the continent (Cediel *et al.*, 2003) to the submarine part of this area. This system generates satellite normal faults that affect the area where the continental shelf narrows.

Finally, the thematic charts (Fig. 7) show the geomorphological units using a color code, which is given in detail in Table 1 and Annex 1.

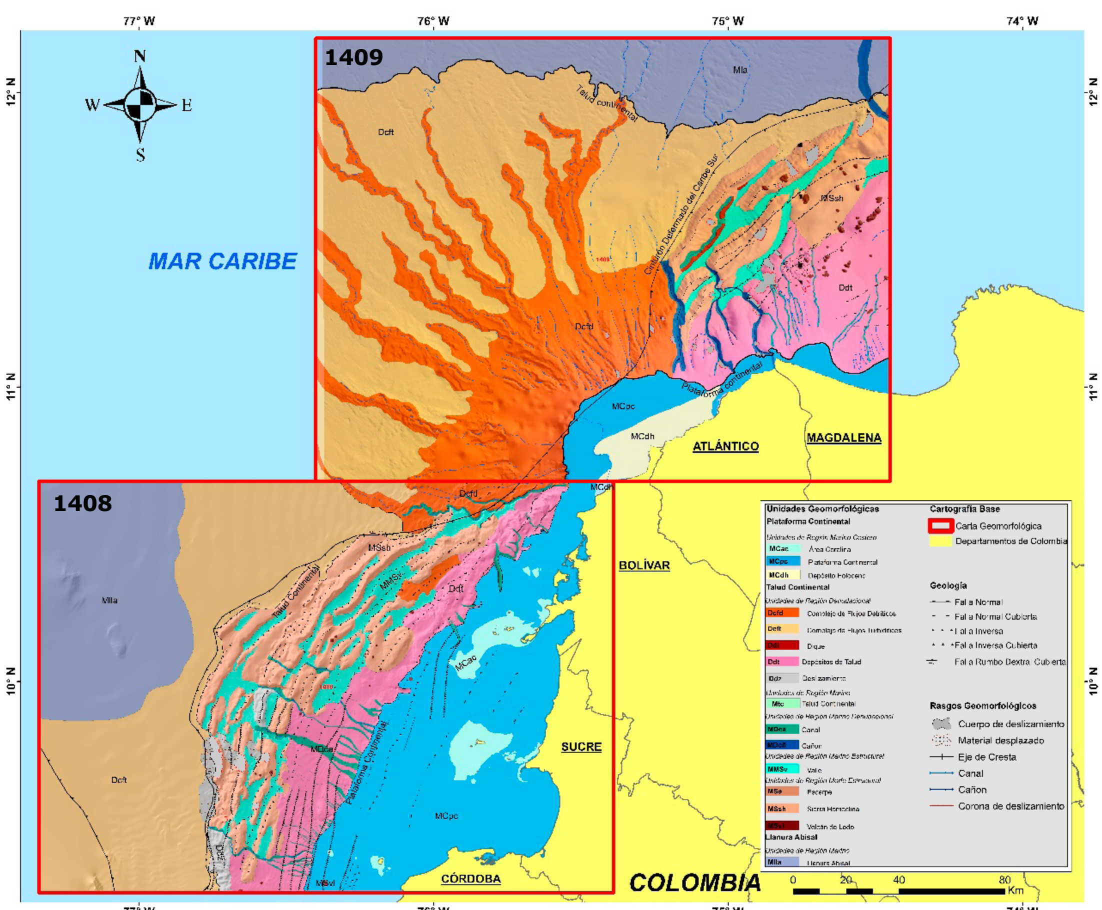

Figure 7. Charts nos. 1408 and 1409, showing the geomorphological units of the Colombian Caribbean on a scale of 1:250 000.

Table 1. Proposed nomenclature for the 229 geomorphological units delineated in the two geomorphological charts

	REGIÓN / PROCESO	UNIDAD GEOMORFOLOGICA	NOMENCLATURA DE UNIDAD	NÚMERO DE UNIDADES
CARTA TEMÁTICA 1408 Cinturón deformado del Sinú	MARINO COSTERO	Área Coralina	MCac	18
	MARINO DENUDACIONAL	Canal	MDca	40
	DENUDACIONAL	Complejo de flujos de detritos	Dcfd	2
	DENUDACIONAL	Complejo de flujos turbidíticos	Dcft	2
	MARINO COSTERO	Depósito Holoceno	MCdh	1
	DENUDACIONAL	Depósitos de Talud	Ddt	22
	DENUDACIONAL	Deslizamiento	Ddz	8
	MARINO	Llanura Abisal	Mlla	1
	MORFO ESTRUCTURAL	Sierra Homoclinal	MSsh	21
	MARINO MORFO ESTRUCTURAL	Valle	MMSv	13
	MARINO MORFO ESTRUCTURAL	Volcán de Lodo	MSvl	31
				Total de Unidades: 159

	REGIÓN / PROCESO	UNIDAD GEOMORFOLOGICA	NOMENCLATURA DE UNIDAD	NÚMERO DE UNIDADES
CARTA TEMÁTICA 1409 Abanico Río Magdalena	MARINO DENUDACIONAL	Canal	MDca	8
	MARINO DENUDACIONAL	Cañon	MDcñ	4
	DENUDACIONAL	Complejo de flujos de detritos	Dcfd	1
	DENUDACIONAL	Complejo de flujos turbidíticos	Dcft	1
	MARINO COSTERO	Depósito Holoceno	MCdh	1
	DENUDACIONAL	Depósitos de Talud	Ddt	2
	DENUDACIONAL	Dique	Ddi	1
	MORFO ESTRUCTURAL	Escarpe	MSe	1
	MARINO	Llanura Abisal	Mlla	1
	MARINO COSTERO	Plataforma Continental	MCpc	3
	MORFO ESTRUCTURAL	Sierra Homoclinal	MSsh	6
	MARINO MORFO ESTRUCTURAL	Valle	MMSv	5
	MARINO MORFO ESTRUCTURAL	Volcán de Lodo	MSvl	36
				Total de unidades: 70

Conclusions

We identified 229 geomorphological units in charts 1408 and 1409, which correspond to structural and denudational processes associated with the environments of the platform and slope of the continental margin; these include homoclinal ridges, slope deposits, mud volcanoes, etc., as well as linear geomorphological features, such as channels and canyons.

We also identified mass movements and plotted the tectonic features observed in the 2D seismic data associated with normal, reverse and strike-slip fault lineaments.

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Author contributions

Conceptualization: Y.S.; methodology: Y.S.; software: Y.S., M.C., E.G.; visualization: M.C.; analysis: Y.S.; data curation: D.S., O.A., D.D., J.U.; writing and preparing the original draft: Y.S., M.C., E.G.; writing, checking and editing: Y.S. All the authors have read and accepted the published version of the manuscript.

Bibliography

Carvajal, J. H. (Ed.). (2012). *Propuesta de estandarización de la cartografía geomorfológica en Colombia.* Servicio Geológico Colombiano. Bogotá. 83 pp. https://doi.org/10.32685/9789589952825

Cediel, F.; Shaw, R.; Cáceres, C. (2003). Tectonic assembly of the northern Andean Block. 2003. En: Bartolini C., R. Buffler y J. Blickwede (Eds.). *The Circum-Gulf of Mexico and Caribbean: Hydrocarbon habitats, basin formation and plate tectonics, AAPG Memoir 79: 815-848*. https://doi.org/10.1306/M79877C37

Dirección General Marítima. (2021). *Esquema de Cartografía Náutica Nacional.* Cuarta actualización. Dimar. 89 pp. Bogotá.

Idárraga-García, J.; Masson, D.; García, J.; León, H.; Vargas, C. (2019). Architecture and development of the Magdalena Submarine Fan (southwestern Caribbean). *Marine Geology,* 414: 18-33. https://doi.org/10.1016/j.margeo.2019.05.005

Meyer, B.; Saltus, R.; Chulliat, A. (2017). *EMAG2v3: Earth Magnetic Anomaly Grid (2-arc-minute resolution).* Version 3. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5H70CVX

Micallef, A.; Krastel, S.; Savini, A. (Eds.). (2017). Submarine geomorphology. Springer. 556 pp. https://doi.org/10.1007/978-3-319-57852-1

Olaya, V. (2020). Sistemas de información geográfica. *Un libro libre de Víctor Olaya.* volaya.github.io/libro-sig/index.html

Rangel-Buitrago, N.; Idárraga-García, J. (2010). Geología general, morfología submarina y facies sedimentarias en el margen continental y los fondos oceánicos del mar Caribe colombiano. En: INVEMAR (Eds.). *Biodiversidad del margen continental del Caribe colombiano,* 29-51.

Sandwell, D.; Müller, R.; Smith, W.; García, E.; Francis, R. (2014). New global marine gravity model from Cryo-Sat-2 and Jason-1 reveals buried tectonic structure. *Science,* 346: 65-67 https://doi.org/10.1126/science.1258213. PMid:25278606

Veloza, G.; Styron, R.; Taylor, M.; Mora, A. (2012). Open-source archive of active faults for northwest South America. *GSA Today,* 22(10): 4-10. https://doi.org/10.1130/GSAT-G156A.1

Vinnels, J.; Butler, R.; McCaffrey, W.; Paton, D. (2010). Depositional processes across the Sinú accretionary prism, offshore Colombia. *Marine and Petroleum Geology,* 27(4): 794-809. https://doi.org/10.1016/j.marpetgeo.2009.12.008

Annex 1 - Details of the geomorphological units and base cartography of Charts 1408 and 1409 showing the geomorphological units of the Colombian Caribbean Sea at a scale of 1:250 000.