El Bohío Suplemento Especial

El Bohío Suplemento Especial, Vol. 6 No.1, diciembre de 2022. ISSN 2226-6798

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Coastal study on Holbox Barrier Island: mapping exercise and geomorphic review of a touristic hotspot in the Yucatán Península, México

Presentación

Nos complace presentar en este Suplemento Especial El Bohío, los resultados del estudio realizado por un variado grupo de autores, pertenecientes a varias instituciones científicas, los cuales nos ofrecen valiosos resultados.

"Estudio costero en la isla de Barrera Holbox: ejercicio de mapeo y revisión geomórfica de un punto turístico en la península de Yucatán, México"

La compilación de la información de esta investigación científica, que tenemos el gusto de presentar en este Suplemento, esperamos sea de amplia y efectiva utilidad para el conocimiento y Manejo Integrado de las Zonas Costeras de nuestras regiones y países, los cuales cada vez requieren con más urgencia de documentación esclarecedora que esté dirigida a lograr resultados palpables y loables en la gestión de los ecosistemas costeros con una mirada ecosistémica.

Este estudio sobre los órdenes geomórficos en la península de Yucatán nos permite comprender ciertos procesos formativos terrestres que nutren la biodiversidad, la pesca y los servicios ecosistémicos en la isla Holbox en México, un punto turístico mundial con sobrepoblación humana. Se estudiaron doce localidades, utilizando drones que permitieron obtener fotografías que validan remotamente el litoral. Este ejercicio de mapeo facilita la interpretación de los procesos sedimentarios en la erosión, comparándose con datos de transectos submarinos, auxiliando a modelar las zonas para preservar las pesquerías y las características geográficas de las condiciones costeras que forman Holbox. Los resultados complementan el conocimiento de la zona, y su impacto en las pesquerías.

Sin pretender que esta entrega, sea un tema agotado, creemos que su publicación será una invitación al pensamiento colectivo, un acicate al desarrollo de nuevos profesionales los cuales buscan en experiencias como esta, el inevitable camino de lo andado y la visión aguda, de trazar nuevos derroteros, y lograr en esta disciplina impactos meritorios para las condiciones actuales y futuras que se nos puedan presentar.

Sirvan estas palabras como invitación a la lectura de este interesante y riguroso trabajo científico y a dejar abierto caminos reales o virtuales de un debate productivo, que agradecerá profundamente la comunidad en su totalidad.

Nuestros respectos.

Comité Editorial El Bohío

Presentation

We are pleased to present in El Bohío Special Supplement, the results of the study carried out by a varied group of authors, belonging to various scientific institutions, which offer us a valuable result.

"Coastal study on Holbox Barrier Island: mapping exercise and geomorphic review of a touristic hotspot in the Yucatán Peninsula, México".

We hope the compilation of the information from this scientific research, which we are pleased to present in this Supplement, will be of broad and effective use for the knowledge and Integrated Management of the Coastal Zones of our regions and countries, which increasingly require more urgent of enlightening documentation that is aimed at achieving tangible and commendable results in the management of coastal ecosystems with an ecosystem perspective.

This study of geomorphic orders in the Yucatan Peninsula allows us to understand certain land-forming processes that nurture biodiversity, fisheries, and ecosystem services on Holbox Island in Mexico, a global tourist hotspot with human overpopulation. Twelve locations were studied, using drones for obtaining photographs that remotely validate the coastline. This mapping exercise facilitates the interpretation of sedimentary processes in erosion, comparing it with data from submarine transects, helping to model zoning, preserving fisheries, and the geographical characteristics of the coastal conditions that make up Holbox. The results complement the knowledge of the area, and its impact on the fisheries.

Without pretending that this delivery is an exhausted topic, we believe that its publication will be an invitation to collective thought, an incentive to the development of new professionals who seek in experiences like this, the inevitable course of what has been traveled and the sharp vision for tracing new paths, and achieve meritorious impacts in this discipline for the current and future conditions that may arise.

May these words serve as an invitation to read this interesting and rigorous scientific work and to leave real or virtual paths open for a productive debate, which the community as a whole will be deeply grateful for.

Our respects.

Editorial Committee El Bohío.

Original article

Coastal study on Holbox Barrier Island: mapping exercise and geomorphic review of a touristic hotspot in the Yucatán Península, México

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Abstract: The study of the geomorphic orders in the Yucatan Península helps us understand some of the formative processes on Earth that nurture biodiversity, fisheries, and ecosystem services on Holbox Island in Mexico, a global touristic hotspot with human overcrowding. This investigation details the coastal setting on linear, embayed, elongated, and lobate shorelines of the northern end of the peninsula, facing the Caribbean Sea and Gulf of México. The local case study considers the sand bodies and coastal landforms assigned to geomorphologic orders according to their extension and relationship to waves, tides, and anthropogenic geometries on the surface. Twelve localities were analyzed with drone photography to validate remote interpretations of littoral terrain for 170 sites, including satellite observations of lagoon, shallow soft bottoms, spits, back-barrier islands, channels, capes, narrows, cays, sea mouths, marshes, and mangroves. This mapping exercise links the reported sedimentary processes for erosion, supply, transport, and deposition in sedimentary environments, including ridges, troughs, inlets, and fans. The features traced on maps were compared to data from underwater transects. Geomorphic elements such as sandplains, lagoons, and estuaries predominate to the west of the barrier island. To the east, geomorphologies stand for ebb channels, mud, and tidal flat coasts. These maps help to model the zoning for preserving fisheries and geographic features of the coastal conditions forming Holbox. These results complement the order of elements in geomorphic units for barrier islands in ramp systems or peninsular platforms where natural factors or human activities can afflict the shapes of the terrain and the refurbishment of fishing grounds (n = 33).

Keywords: coastal geology, shoreline geomorphology, littoral interpretation, barrier-island interpretation, sedimentary environments, fisheries.

Estudio costero en la isla de Barrera Holbox: ejercicio de mapeo y revisión geomórfica de un punto turístico en la península de Yucatán, México

Resumen: El estudio acerca de los órdenes geomórficos en la península de Yucatán nos ayuda a entender algunos de los procesos formativos terrestres que nutren la biodiversidad, la pesca y los servicios ecosistémicos en la isla Holbox en México, un punto turístico mundial con sobrepoblación humana. Esta investigación detalla el litoral en líneas costeras con formas lineales, ensenadas, alargadas y lobuladas del extremo norte de la península, frente al mar Caribe y el golfo de México. El estudio de caso local considera los cuerpos de arena y las formas costeras asignadas a órdenes geomorfológicos según su extensión y relación con las olas, mareas y geometrías antrópicas en la superficie. Doce localidades fueron analizadas con fotografías de drones para validar las interpretaciones remotas del terreno litoral en 170 sitios, incluidas las observaciones satelitales de lagunas, fondos blandos poco profundos, puntas, islas atrás de la barrera (*back-barrier islands*), canales, cabos, angosturas, cayos, bocas de mar, marismas y manglares. Este ejercicio de mapeo se vincula con los reportes para los procesos sedimentarios en la erosión, el suministro, transporte y depósito en los ambientes sedimentarios, incluidas las crestas, depresiones, entradas y abanicos. Las características trazadas en los mapas se compararon con datos de transeptos submarinos. Los elementos geomórficos como llanuras arenosas, lagunas y estuarios predominan al oeste de la isla barrera. Al este, las geomorfologías representan canales de reflujo, lodo y costas con llanuras de marea. Estos mapas ayudan a modelar la zonificación para preservar las pesquerías y las características geográficas de las condiciones costeras que forman Holbox. Estos resultados complementan el orden de los elementos en las unidades geomórficas para islas barrera en sistemas de rampa o plataformas peninsulares donde factores naturales o actividades humanas pueden afectar las formas del terreno y la renovación de los sitios de pesca (n = 33).

Palabras clave: geología costera, geomorfología del litoral, interpretación del litoral, isla barrera, ambientes sedimentarios, pesquerías.

Introduction

Recent investigations of the coastal environment of the northeastern Yucatán Shelf during the Holocene have described how the disproportional affectations of natural elements in ecology intertwine with the increase in population (Appendini *et al*., 2012; Rankey *et al*., 2013; Neal, 2020; Rubio-Cisneros *et al*., 2018; Jaijel *et al*., 2018a). This study is based on coastal observations to develop an improved mapping and geomorphological model for complimenting the interpretations of Holbox Island for its protection.

We investigate the geometries of the landscape on the ground and sea using drone photography, coastal plan views, cartographic information, fisheries data, and remote sensing images by processing satellite imagery. The prior correlation among these littoral areas was based on studies on the general coastal sedimentary environments, depositional characteristics, and shoreline models, which broadly address their geomorphology for recognizing environments and physical processes (Boyd *et al*., 1992). This is an observational exercise that is short of grain size tests, sedimentary cores, stratigraphic markers, or geological samples. Limited information about natural phenomena and human trends in coastal areas makes it imperative to devise the interrelationship of both processes to discuss comparisons between these events and sustainable decisions.

This article aims to (1) document the forms of the landscape in the barrier island with more detail relative to public cartographic materials; and (2) provide additional data on depositional and biological environments to previous interpretations of geomorphological units of modern and ancient ramp systems, using concepts of coastal geomorphology, sedimentary geology, and marine ecosystems.

Coastal setting

The Precambrian-Paleozoic Maya Block (ca. 400 Ma to 1.2 Ga) is the basement of the Yucatan Peninsula in southeastern México (Weber *et al*., 2012). The basement block displaced south from a nearby position to the present rio Grande Embayment and turned counterclockwise to its current position, starting Middle Jurassic (144 Ma) to the Late Jurassic-Cretaceous time boundary (164 Ma). During the spreading of the Gulf of Mexico, marine transgression framed the deposition of cretaceous limestones, building a carbonate platform. In the Eocene, a marine regression began until our time, forming the coastal plain with its shelf and clastic shoreline (Campa and Coney, 1983). The Yucatan Shelf extends from the Campeche Bank on the west to the north and eastward from the peninsula shoreline (Figure 1). The low regional topography combines with stable tectonics over 125 000 years (Ward, 1997). A broad low-relief karst plain comprises the Yucatan Peninsula with a surficial off-lapping sequence of undeformed Miocene to Pleistocene carbonate strata and underlying older limestones, with a sizable freshwater aquifer. The Yucatan Peninsula is mostly karst limestone rivers, there are no clastics to erode, and much drainage is internal and underground (Beddows, 2004; Blanchon *et al*., 2009; Beddows *et al*., 2016). The barrier islands in the territorial seashore along the Atlantic Ocean and the Gulf of Mexico are the top portions of the youngest passive continental margin deposits.

Figure 1.- Map of locations of the coastal sites studied in the southeastern Gulf of Mexico, northern Yucatán Península. Geological tectonostratigraphic terranes from Campa and Coney (1983). *Ch* Chortis, *COA* Coahuila, *Gu* Guichicovi, *J* Juárez *Ju* Juchatenco, *M* Maya, *Mi* Mixteco, *O* Oaxaca, *SMO* Sierra Madre Oriental, *TMV* Trans-Mexican Volcanic Belt, and *XO* Xolapa. Ocanographic lables are from GEOBCO.

Holbox Island is a relatively young land portion (Early to Middle Pleistocene; Jaijel *et al*., 2018b) compared to the rest of the Mexican historical geology (ca. Precambrian: Proterozoic 1.7 Ga) that correlates in time to geologic events in the Caribbean regions, Figure 2 (Pindell *et al*., 2021). This barrier island belongs to the Quintana Roo state in México. It has a surface of 62 872 km^2 divided up by two municipalities, Lázaro Cárdenas and Isla Mujeres. This barrier island complex spans more than 60 km of coastline between the Gulf of Mexico and the Caribbean Sea. Holbox lies in the nearshore region of the modern carbonate ramp at the northeastern tip of the Yucatán Peninsula (Rankey *et al*., 2020). Holbox.

This low-energy Holocene carbonate ramp system comprehends landforms of a palustrine system with marsh, mangrove, muddy lagoon, barrier, islet, shoreface, and nearshore. In general, Holbox's ramp lacks any significant bathymetry or reef barrier to baffle wave energy, remaining open to waves from the north-northeast and northwest and easterly trade winds (Ward, 1997).

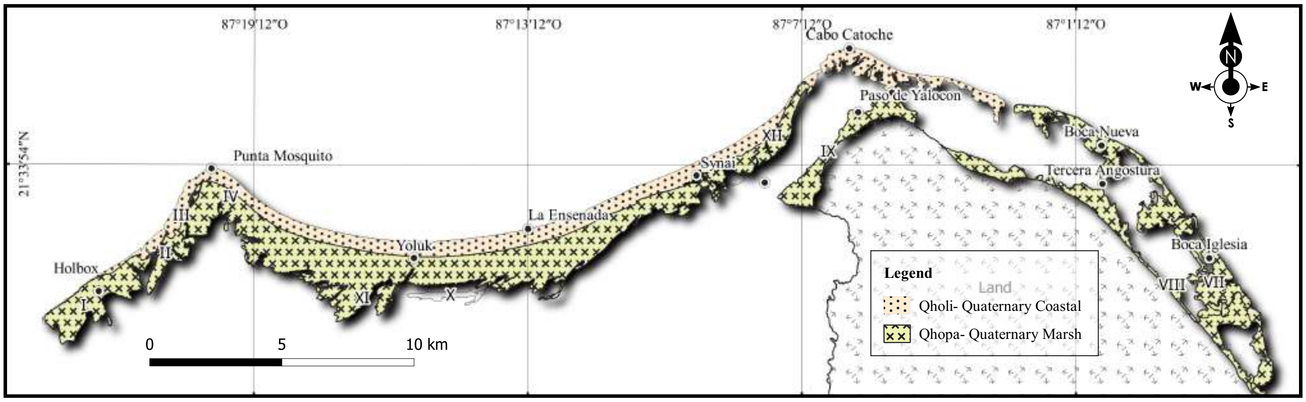


Figure 2.- Geological map of Holbox barrier island, reinterpreted from the *Servicio Geológico Mexicano* (2006).

On the seafloor, more than 200 km from Holbox, lies the Tulum Terrace, a northern termination of the Yucatan Shelf; both undersea features precede the Campeche escarpment to the deep abyssal plain of the Gulf of México. In the opposite direction, southeastern from Holbox lies the Yucatán Borderland. This tropical region is part of the shallow sea in the Mexican Exclusive Economic Zone. Holbox is in the Yum Balam Natural Protected Area, which aims to preserve the region's littoral environments and biodiversity (CONANP, 2022). The fishing and tourism in Holbox are set over a subtropical climate. These activities extend over the geographical areas that access sea-based shipping routes of the western Atlantic Ocean on the Caribbean and Gulf of México (Rubio-Cisneros *et al*., 2019).

Tectonics in the Caribbean, isostasy, eustatic, and other oceanographic factors raise sea level (Jaijel *et al*., 2018a). The Yucatán current that originates off the eastern flank of the Yucatán Shelf transports colder nutrient rich water to the wear into Holbox (16 to 20 °C). The regional Caribbean sea level marks a rise of ~1.5 m over the last 3000 years and a +6-m last interglacial coast in the northern part of the peninsula (Blanchon *et al*., 2009).

The water transport of upwelled and nearshore sediment strikes from east to northeast on the shallow ramp across the northern Yucatán Shelf. Other currents are related to longshore processes caused by daily easterly trade winds, coastal current drift, and northern waves. This region has varying cold fronts from November to March through April and a wet period from May to October (Jaijel *et al*., 2018a). The sediment transport to the west sustains the accretion of the longshore barrier spit in de Boca de Conil, the entrance to the Yalahau lagoon. Meanwhile, the surge of waves bordering the east of Holbox comes from the southeast without surpassing the 2 m in the height of curls. Locally, the waves approach the shore calmly, striking 144º to the west, 120º to the central section, and 100º to the east. The tides on the east of the Holbox barrier come from southeastern swells, striking the muddy flats on the coast, preserving the equilibrium of the shore owning to high sediment transport rates. The eastern coastal areas of Holbox have armor built from the groins, producing higher erosion rates than natural (Appendini *et al*., 2012).

The upwelled waters reach Holbox on the nearshore environment of the shallow ramp, producing a proliferation of biosiliceous and ubiquitous heterozoan or mixed heterozoan organisms. Upwelled water has variable chlorophyll levels, causing variable seasonal conditions. The local biota assemblage corresponds to carbonate sediment producers for biosiliceous deposits. The paucity of corals and coral reefs associates with the lack of nearshore oligotrophic environments in which chlorophyll levels are low.

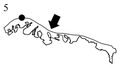
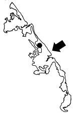
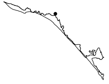
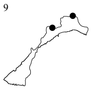
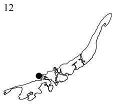
Most sediment is generally sand, silt, and mud are supplied locally from bottom currents and oceanic sources, and some clastic portion is likely aeolian (Neal *et al*., 2021). Holbox Island is a topographic barrier with beach ridges bounded to the south with a protected lagoon system. The lower-energy environment is restricted to form mainly on the island's lee side. Two main lagoons with shallow water parallel to the shoreline are located east and west, Laguna de Yalahau and Laguna de Boca Iglesia. The lagoons area is a patchwork of mangrove islands, tidal flats, hypersaline ponds, flooded forests, and narrow channels. Lagoon sediments vary in the northern and southern areas caused by a seasonal, easterly flowing current with a clockwise circulation pattern. The deposits in the north Holbox lagoon are coarser-sized sand transported from open water or washed from the barrier island consisting of molluscan coquina beach ridges (Logan *et al*., 1969). The southern area mixes sands and clay to silt-size muds made of calcite from foraminifera and algae (Brady, 1972). Some local watersheds with freshwater springs and groundwater discharge nutrients and sediments in runoff until they disperse into the back-barrier lagoons and coastal waters on Holbox Island (Luijendijk *et al*., 2020).

Methods

The study area includes well-exposed and laterally extensive geomorphological units, up to 35 km long and 2.0 km wide (Table 1). We performed a method to extract geographic data by the recognition of terrestrial and marine features for further description and characterization. We traced elements on the surface as points, lines and polygons using manual and optical observations, and site analysis, merged to marine and terrestrial data sources (Figure 3). Mostly, manual interpretation aided the mapping process by handpicking terrain features on satellite images and geographic representations; in addition, field observations from 2015 to 2017 on Holbox Island were also practical. This laborious data-processing activity has proven as effective as automated analysis for mapping the coastal morphologies (Schwartz, 2009). The criteria for mapping our inventory for describing the geometries include the extents, orientations, hierarchy of natural coastal forms, depositional contacts, sand bodies, lateral associated sedimentary deposits, civil structures, shore distribution, lithostratigraphy, marine biology surveys, watershed basins, and underwater transects sloping down the coastline for water bottom recognizance. All the information gathered was incorporated into a geographic information system.

Table 1.- Geomorphic features on Holbox Barrier Island.

Geomorphic features in Holbox Barrier Island

#	Location	Coastline and shoreline	Associated landforms	Descriptions and environmental interpretations (Supplementary Table 1)
1 	Holbox	Linear to embayed barrier	Accreted and discontinuous beach ridges	3rd-order feature, 5.6 km long, 1.5 km wide, Seaward shoreline shifting to shoreline retreat in downdrift sections, Sawtooth pattern forming anthropogenic shoreline steps. Dissipative shoreline with wide shallow inshore profile and restricted reflective domains near wave breakers.
	other: Punta Cericote, Punta Caracol, El Casco, Punta Cocos, Salina	Backshore	Berm	
		Foreshore	Barrier spit, Shoals	
		Nearshore	Transverse dunes	
		Back-barrier	Back bar lagoon and navigation channel	
2 	East Holbox *Malecon*	Embayed barrier	Shoreface mouth bypassing structures	3rd-order feature, 1.9 km long, 1.4 km wide, Sand removal near shoreface bypassing, where outflow incises berms, Variable shoreline shifts and segmented ridge formation. Dissipative and reflective shoreline with bars and troughs.
	other: West Punta Mosquito	Backshore	Berm, Washover terrace, Dendritic network, Aborted fluvial network	
		Foreshore	Shoreface bars, Subaqueous dunes, Swash bars, Shoals, Marginal channel, Troughs, Bar-bypassing, Subaerial levees, Rip current embayments.	
		Nearshore	Transverse dune	
		Back-barrier	Lagoon bar	
3 	Punta Mosquito	Elongated/Lobate barrier	Cuspate shore, Amalgamated beach ridges, Active or aborted channel mouth bypassing	3rd-order feature, 3 km long, 700 m wide, Prograding shoreface coastal development, Berm downdrift from mouth bypassing is removed or shifts landward, Wave-dominated estuary partly closed, Littoral drift starting from updrift section near the apex of the cuspate shore, and wash load from mouths bypassing, Losses of sand removed alongshore or washed over, Fluvial sand supply by and wave-dominated shoreface bypassing. Dissipative shoreline with weak rips and mild shoaling.
	other: Santa Teresa	Backshore	Washover sands and terrace, Spillover the lagoon, Dendritic network	
		Foreshore	Subaqueous barrier bar and sands, Swash bars, Channel bar, Subaerial levee, Sand flat, Mouth bars	
		Nearshore	Longitudinal bars	
		Back-barrier	Lagoon embayment	
4 	Ensenada	Linear barrier strandplain	Accreted beach ridges, Lineated depositional unconformities	3rd-order feature, 35 km long, 1.9 km wide, Longshore deposits of Molluscan sand, Littoral drift is predominant longshore transport between the nearshore and shoreface, coastal currents Sand ridges in linear coast pinch to the East in the mouth bypassing with back-barrier features like a marsh, Berm is segmented when near pinch outs of sand ridges at the downside of wave-dominated shoreface bypassing, Consistent advance of shoreface, Longitudinal waves in mid-section, and transverse dunes in East. Dissipative shoreline with a low berm and wide setup.
	other: San Manuel, Yoluk, Rancho Mil, Punta Lino, Synai	Backshore	Swale ponds, Desiccated barrier ponds, Backshore lagoon	
		Foreshore	Bar formation, Subaqueous barrier, Longshore bar, Crenulated dunes, Rip cell circulation, Longitudinal waves	
		Nearshore	Transverse dune	
		Back-barrier	Partly dissected by lagoon inlets, Back-barrier marsh	
		Lagoon	Lagoon islands	
5 	Cabo Catoche	Elongated/Lobate barrier	Arched coastline	3rd-order feature, 7.7 km long, 900 m wide, Berms downdrift from ria and estuary mouth bypassing shift landward or are removed, Shoreline generations shift to elongate/lobated morphologies, Successive barrier ridges form discontinuous bends from cuspate foreland, Mouths bypassing dissecting barrier, forming coastal inlet, Wave-dominated estuary with close partly open to a lagoon with a parallel shore, Removal of material prevails at wave and tide confluence near the lobate shoreline, Shoreface transgression, seaward accretion on the updrift section, Downdrift shoreface shifts landward, and mixes with wash load from mouths bypassing. Updrift groin deposition. Reflective and dissipative shoreline in the mixed energy system. Marsh networks reach the coastline from the back-barrier.
	other: Boca Santa Paula, Rancho Bonito	Backshore	Desiccated barrier features, Fluvial drainage, Swale ponds, Washover fan	
		Foreshore	Channel margin linear bar, Subaqueous levee, Groins	
		Nearshore	Shoal complex, Longitudinal dunes, and transverse dunes,	
		Back-barrier	Spillover lobes, Flood ramp, Marsh	
		Lagoon	Narrows	
6 	Boca Nueva	Embayed barrier	Estuary mouth bypassing, Ebb-Channel	3rd-order feature, 6.3 km long, 1.6 km wide, Landward shift of shoreface and invaded by intertidal flat near estuary mouths, Shoreface retreats landward near wash loads from inlets, and intertidal flats advance seaward, Open-ended shore in a lagoonal estuary of a mix of energy from tide and wave. Dissipative shoreline with a low berm, attached mud fans, and rips.
	other: Boca Limbo	Backshore	Washover fan, Fluvial drainage	
		Foreshore	Sandridge, Subaqueos levee, Sand fan, Flood-tidal delta, Rip current	
		Nearshore	Transverse and longitudinal subaqueous dunes	
		Back-barrier	Back bar lagoon, Tidal flat	
		Lagoon	Narrows	
7 	Boca Iglesia	Embayed barrier	Estuary mouth bypassing	3rd-order feature, 3.1 km long, 1.5 km wide, Tide-dominated coast, contributing to a regressive environment, Sand washed in from seafloor (Yucatan current), Foreshore removal to no deposition of beach, Mixed wave and tide estuaries, open-ended or partly closed with interdeltaic lagoon, and dendritic outline, Shoreline shifts landward, allowing ebb channel load to advance seaward, Reflective and dissipative beach cusps, Flood tidal delta flooring lagoon, bays, ria and estuary mouths, Growing spits accrete updrift, letting channel load wash downdrift, Dissipative shoreline with narrow to the low berm, and reflective domains in cusps and crescentic bars.
	other: Entrance to Boca Nueva, Cayo Cahum, Entrance to Boca Iglesia, Punta Arena	Backshore		
		Foreshore	Channel mouth and flood channels, Ebb channel and delta, Crescentic bar-cusps, Transverse dunes, Tidal flat	
		Nearshore	Linguoidal dune, Lunate dune	
		Back-barrier	Back bar lagoon, Tidal flat	
8 	Laguna Boca Iglesia	Marsh in mainland	Narrows	3rd-order, 14 km long, 800 m wide, Onshore waterlogged deposit bordering mainland and around the lagoon, Sand and mud are deposited by occasional waning current activity.
	other: Por adentro del río - Punta Cayo Ratón Tercera Angostura, Laguna Boca Iglesia, Río del Limbo	Back-barrier	Inner barrier marsh	
		Lagoon	Marsh islands	
9 	Paso de Yalikin	Marsh in mainland	Narrows	4th-order, 5 km long, 1 km wide, Onshore patchy are deposited in front of the cuspate foreland, Coalescence of the marsh is with interdistributary lagoons, Mainland ridges are in contact with waterlogged lands, Concave low-lying land extends out to a seaward point, Sand and mud are deposited by occasional waning current activity.
	other: Segunda angostura, Punta Chijaltun	Lagoon	Mud and mixed flats	
10 	West Punta Catalan	Back-barrier island	Inner barrier marsh	4th-order feature, 3.1 km long, 400 m wide, Marshland occupies inundated ridges from a major geomorphic feature of strandplain and another associated inner barrier marsh.
	other	Back-barrier	Inlets in standplain	
		Lagoon	Lagoon island and bars	
11 	Yoluk	Back-barrier muddy ridges	Saltmarsh	4th-order feature, 2 km long, 1.3 km wide, Occupies an interface between sandy ridges and intertidal flat, Some inner barrier marsh associated with waning current activity.
	other: Sabana Anegada	Lagoon	Marsh islands	
12 	Rancho Bonito	Back-barrier marsh	Narrows	3rd-order feature, 3.2 km long, 700 m wide, Marsh occupies inlets ads inundated swales between boundaries of sand ridges with mud from intertidal flat, and salty patches of marshes at the barrier, Sand and mud are deposited by occasional waning current activity.
	others: Angostura, Sinai	Back-barrier	Swale pond, Saltmarsh	
		Lagoon	Microbial mats	

Arrows depict the current orientation, and dots in the geomorphic elements represent the most nearby locality. For more information check map in Figure 4 in the article.

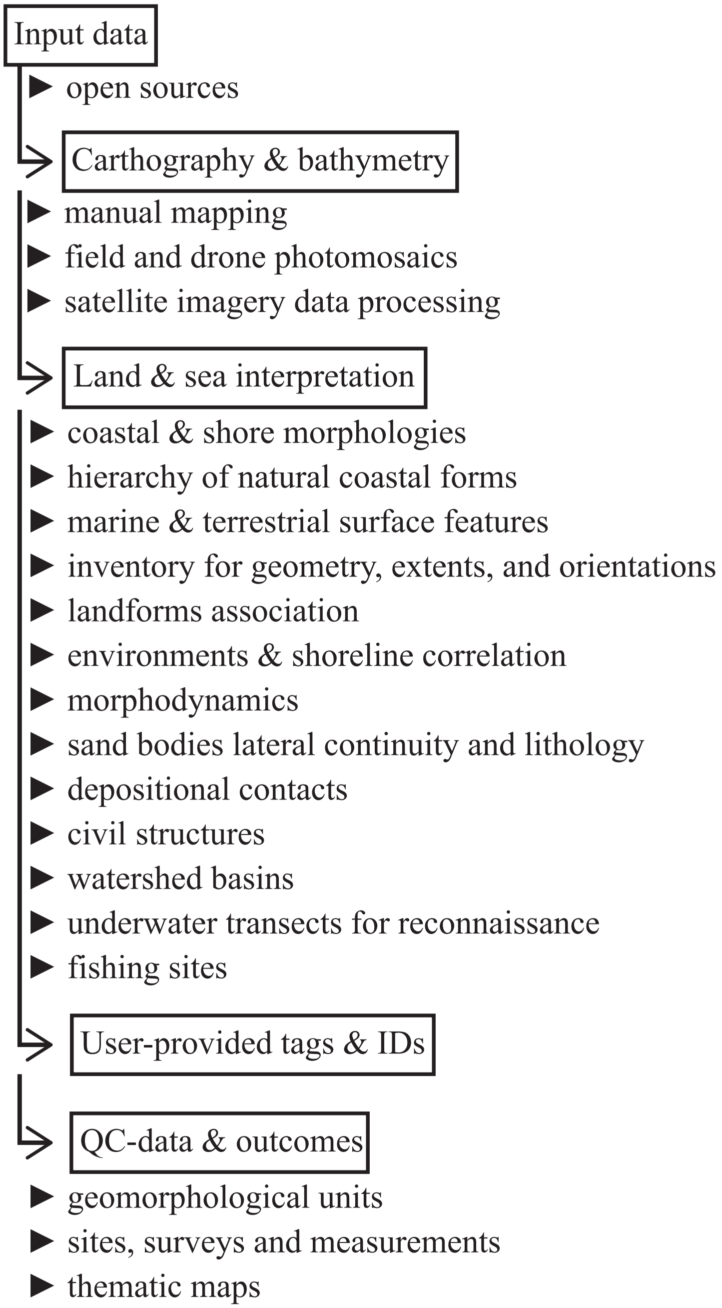


Figure 3.- Workflow for the recognition of geologic structures.

We describe 12 major geomorphic units and over 160 different site observations in interpretative maps (Figures 4, 5, 6, and 7). The maps are in the Universal Transversal Mercator (UTM) 1984 datum, and the map projection system is the WGS-1984 Universal Transversal Mercator Zone 16N. Maps created using the Free and Open Source QGIS. The geometries delineated on the coast in Holbox were correlated with research on the geomorphology of reported barrier islands and their equivalent sedimentary environments (Davis, 1994). The observations consider the structure and position of the coastal setting, and the interface between sea and land. This work is limited to surface features, some of which are measured with aerial tools. Drone photomosaics guided the correlation of morphologies with analogs for mapping major and minor features in the littoral, using the principles of coastal geomorphology (e.g., Bird, 2008; Table 2 and Supplementary Figure 1). Furthermore, when available, detailed observations of land or sea were incorporated from processing satellite imagery.

Table 2.- Hierarchy of geomorphological features used in this study.

Order	Geomorphological unit
1	Related to global tectonics, continental coasts, and peninsulas
2	Deltas, shelves, cuspate coasts, coastal plains, and carbonate ramps
3	Coastal barriers, shorelines, strandplains, estuaries, lagoons, rias, channel mouths, and marshes
4	Coastal foredunes, spits, embayments, channels, sand ridges, shoals, and dune complex
5	Beach berms, cusps, shore platforms, flats, dunes, sand bars, washover terrace, inlets, narrows
6	Runnels, swash bars, washover fans, groins, swale ponds, and shore lagoons
7	Current ripples

Modified from Bird, 2008.

The terminology for describing and interpreting littoral landforms, current association, processes for shoreline equilibrium, and depositional sedimentary environments follows Boyd *et al*., (1992, 2006) and Schwartz (2009). For our interpretations and discussion, complimentary coastal geomorphic relationships in barrier islands consider the environmental analysis in physical oceanography from Reineck and Singh (1986), Perillo (1996), Reading (1996), Arche (2010), and Neal *et al*., (2021). For the definition of sand geometries, we use the work of Wright and Burchete (1998), Huddart and Stott (2010) and Davis and Dalrymple (2012) in coastal landsystems, carbonate ramps, and tidal morphodynamics. Some opportunities included in the method were high-resolution imagery and free datasets. Remote sensing was performed by processing satellite-derived images LiDAR-Light Detection and Ranging, Sentinel, and by staking data in Google™ Earth Pro and Planet Labs applications. For larger-scale surface coastal mapping and limiting dry and wet areas, we analyze the Sentinel-2 satellite data for extracting the normalized difference water index (Jiang *et al*., 2021; see map results in Supplementary Figure 2).

Some of the map information for the corresponding cartographic and bathymetric features belong to the *Servicio Geológico Mexicano*, the *Instituto Nacional de Estadística y Geografía* (INEGI), the European Space Agency (ESA), Spalding et al. (2007), General Bathymetric Chart of the Ocean's, Gazetteer of Undersea Feature Names Version: 4.3.1 –GEBCO Compilation Group (Tozer *et al*., 2019), UNEP-WCMC and IUCN (2021 a, b), Hernández Santana *et al*., (2017), Ryan et al. (2009), Carbotte *et al*., (2004), Luijendijk *et al*., (2020), Sayre *et al*., (2019), and WAVEWATCH III (2019). All spatial data on fishing grounds, related ecological habitats, and ecosystem services were followed after Rubio-Cisneros *et al*., 2018 and 2019. Mangroves and land use were referenced from Simard *et al*., (2019) and *Comisión Nacional para el Conocimiento y Uso de la Biodiversidad* (CONABIO), respectively. A basic correlation of data assisted our proposal for the conservation of the barrier island after associating the reported geomorphic units, fisheries, number of species, human impact, and natural processes (deposition, erosion, wave or tide energy).

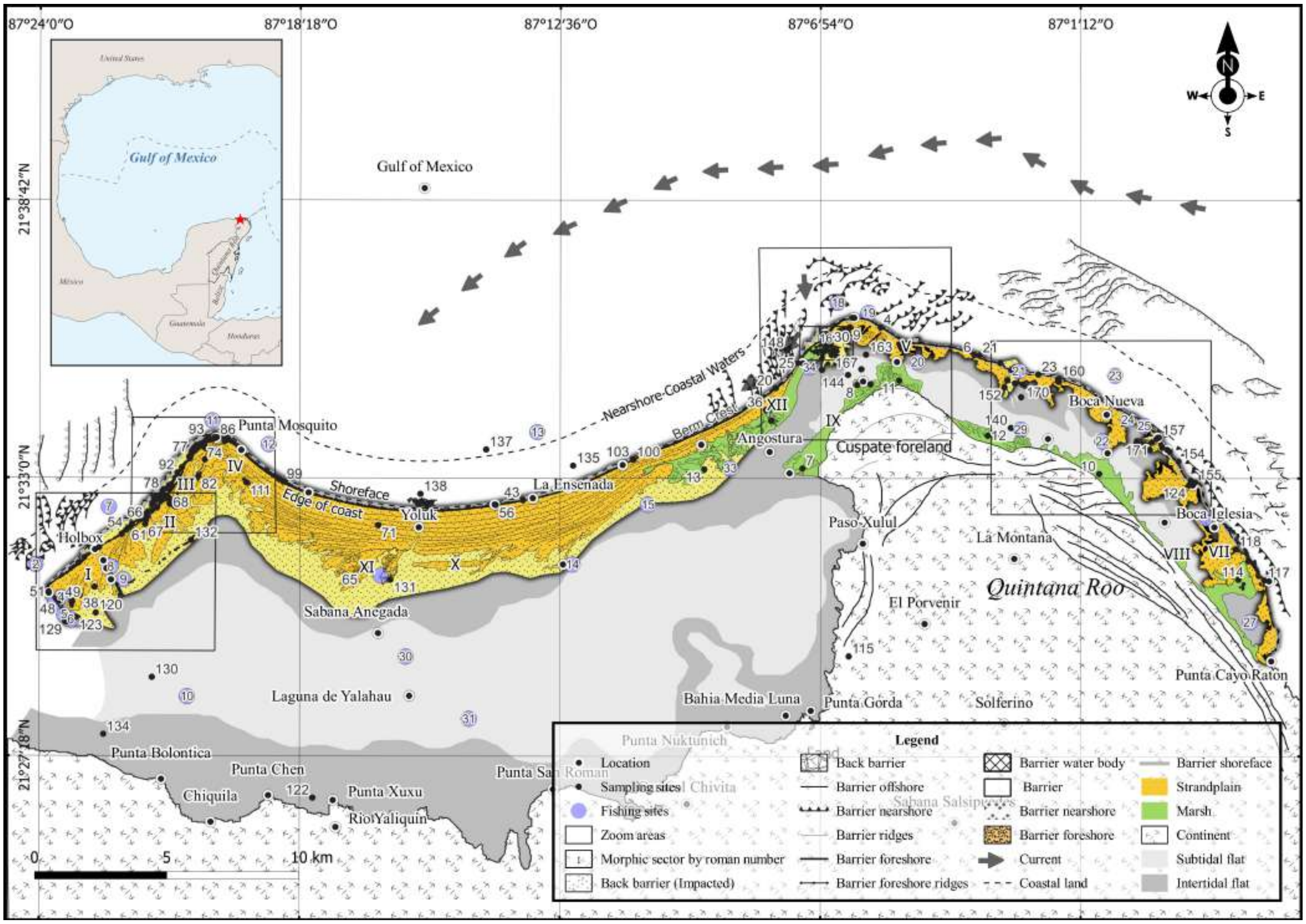


Figure 4.- Geomorphological map of Holbox Barrier Island. The most significant features appear while others can be seen in more detail for each map representing the zoom areas (Figures 4 through 7). The 12 morphic sectors in roman numerals are described in ascending order in Table 1. The 34 Fisheries are listed in Table 3. Any other of the 171 sampling sites are in Supplementary Table 1 (information available upon request to the corresponding author). The coverage for drone photography is available in Supplementary Figure 1. Datum: Universal Transversal Mercator (UTM) 1984; projection: WGS-1984 Universal Transversal Mercator Zone 16N.

Table 3.- Correlation between geomorphic features and historical fishing sites.

#	Fisheries		Geomorphic features												
		ID*	*Barrier (from west to east)*							*Back-barrier (seaward)*					
			1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	
1	Entrance to the lagoon	7	■												
2	Bajos	37	■												
3	Punta Cocos	104	■												
4	Punta Casco	30	■												
5	Punta Ciricote	31	■												
6	Isla Pasión	39	■												
7	Frente a costa de Holbox (*downtown*)	57	■	■	■										
8	Muelle por la Caleta	66	■												
9	La Caleta	16	■	■											
10	Canal - tubería en Laguna Yalahau	80	■												
11	Punta Mosquito	20			■	■									
12	Santa Teresa	67			■	■									
13	La Ensenada	26				■									
14	Punta Catalán	55				■									
15	Punta Lino	98				■									
16	Boca Santa Paula	43					■								
17	Cabo Catoche	36					■								
18	Manchones de Cabo Catoche	52					■								
19	Cuevas de Cabo Catoche	77					■								
20	Segunda Angostura	45					■								
21	Boca Limbo	50					■	■							
22	Boca de Angostura	42						■							
23	Las Bocanas	14					■	■	■						
24	Cabo Catoche - Punta Cayo Ratón	62					■	■	■						
25	Boca Nueva	21						■	■						
26	Boca Iglesia	40							■						
27	Laguna Cayo Ratón	78							■						
28	Punta Cayo Ratón	32							■						
29	Por adentro del río - Punta Cayo Ratón	65					■	■	■	■	■			■	■
30	Laguna de Yalahuau	34	■	■	■	■					■	■	■	■	■
31	Raíces de manglar por todo el río	64	■	■	■	■	■				■		■	■	■
32	Los Islotes	23				■						■	■		
33	Synai	69												■	■
34	Rancho Bonito	44												■	■

Fisheries' ID are from Nadia et al. (2018). Geomorphic features are described in Table 2 in the document. Supplementary Table 2 keeps a record of species at fishing sites.

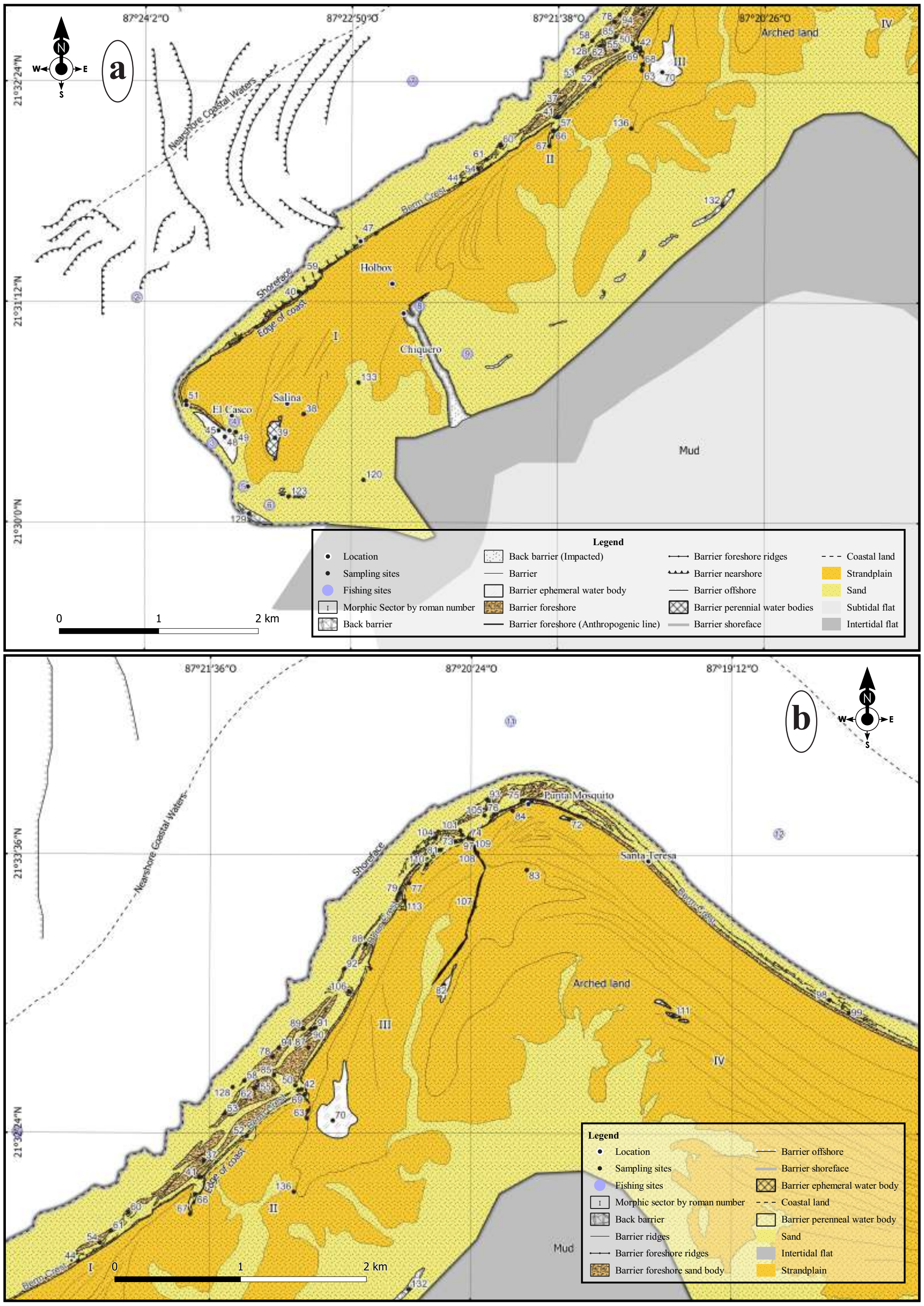


Figure 5.- (a) Representation of Holbox pier on a linear barrier (I) in the associated localities of punta Cericote, punta Caracol, El Casco, punta Cocos, and Salina (Table 1). Other geomorphic sectors around are embayed barrier (II). (b) Map for the localities in the arched geomorphology in punta Mosquito (III). The lobated shoreline shares a common boundary to the west with the embayed barrier (II) and a linear barrier with strandplain to the east (IV). Complementary data in Table 2. See Figure 4 for spatial reference of this map. Explanation of the sampling sites is given in Supplementary Table 1.

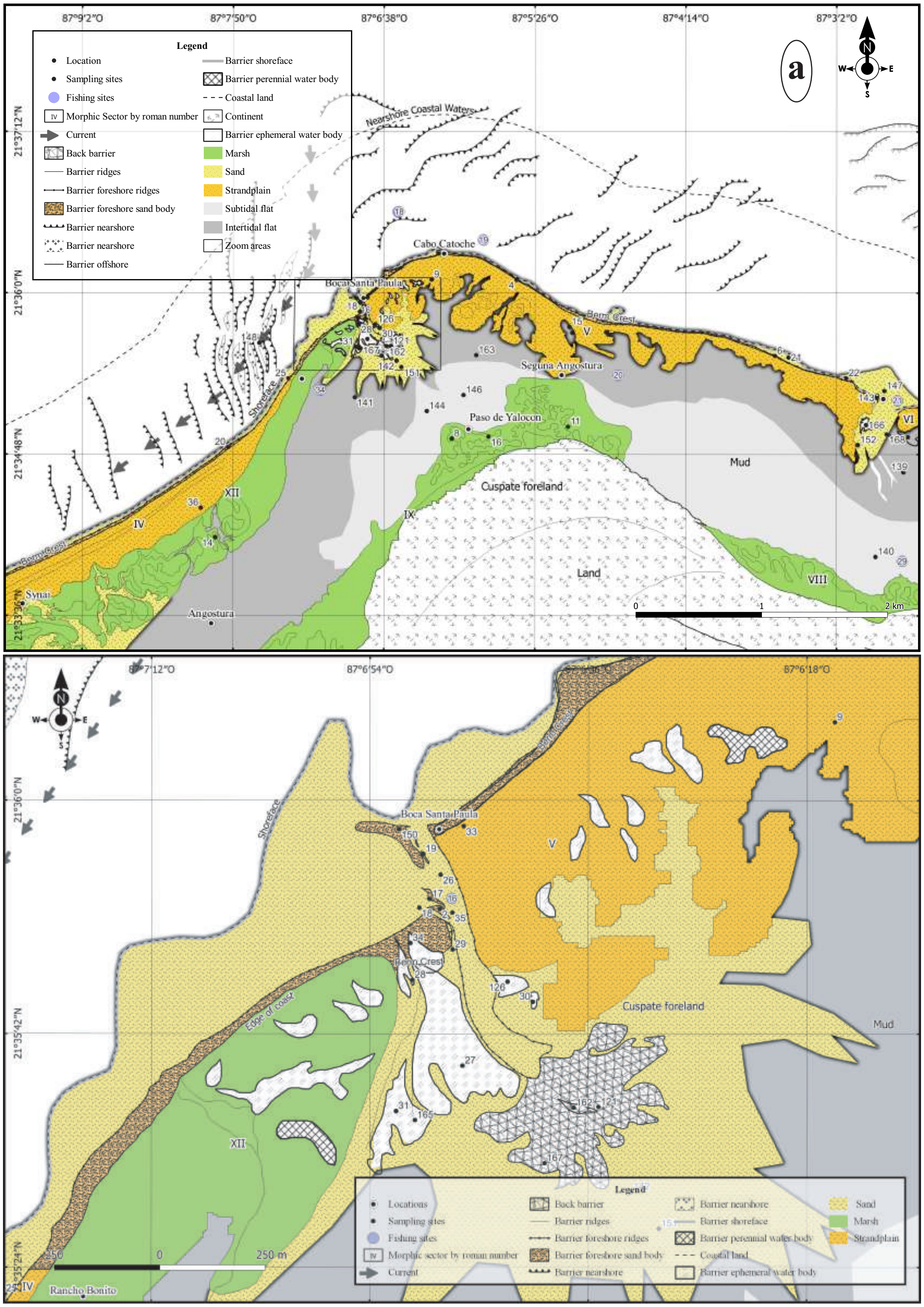


Figure 6.- (a) Diagrammatic representation of the elongated geomorphology (V) in the fishing ground cabo Catoche, also near boca Santa Paula and Rancho Bonito (Table 1). The cuspate barrier is in proximity to barrier geomorphologies' of linear shoreline with strandplain (IV), embayed shoreline (VI), lagoon Boca Iglesia (VIII), narrows at Paso de Yalakin (IX), and back-barrier marsh in Rancho Bonito

(XII). (b) Record in detail the zoom area inside Figure 6a over the Boca Santa Paula river mouth in the locality cabo Catoche. The characteristics of the terrain are sand bodies emplaced inward of the back-barrier and a patchy definition of the marsh and strandplain. See Figure 4 for spatial reference of these maps. Further geomorphological and fishing grounds are described in Tables 1 and 3. The sampling sites are described in Supplementary Table 1.

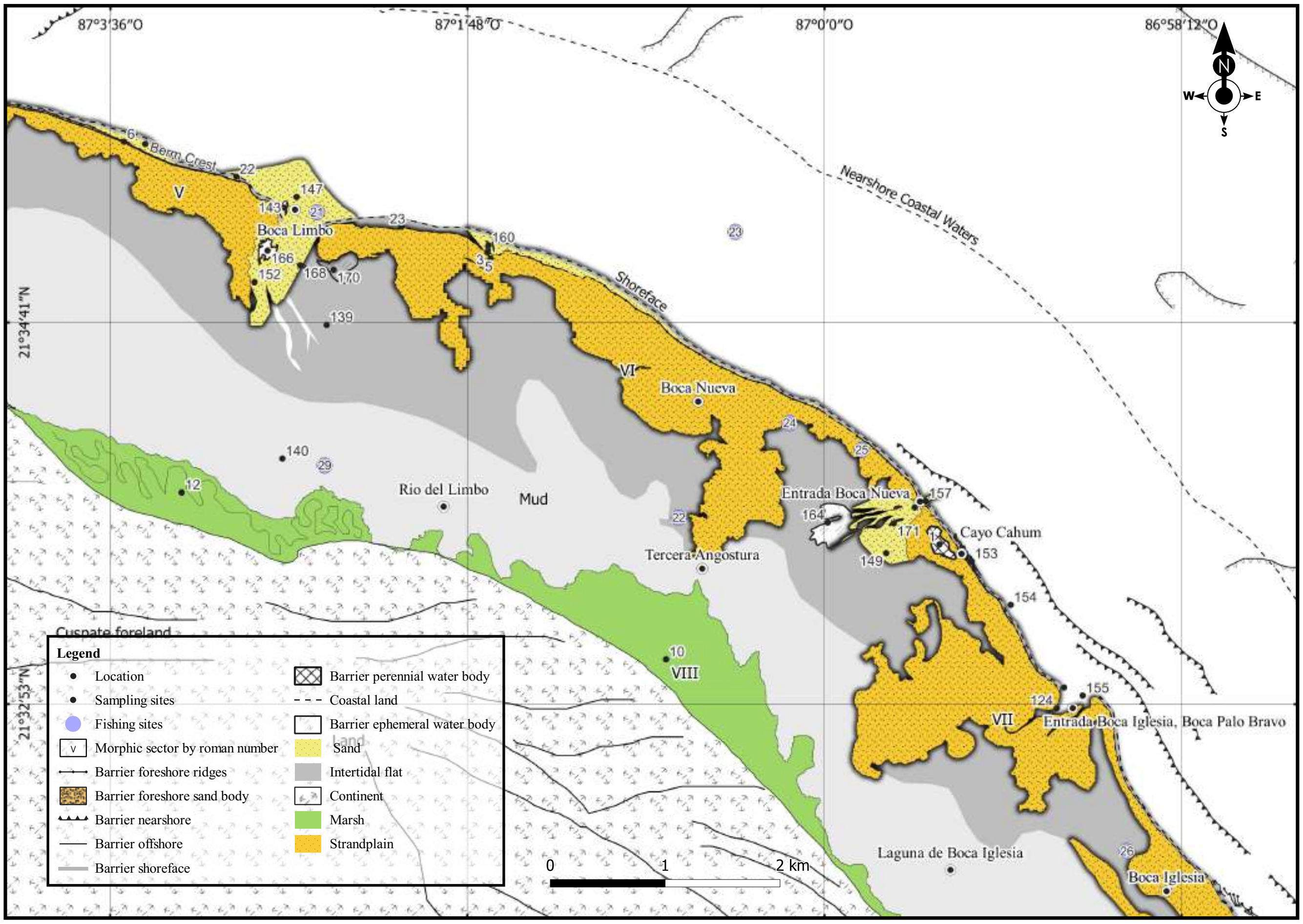


Figure 7.- Plan for showing the layout of the embayed barrier shorelines in localities Boca Nueva (VI) and Boca Iglesia (VII; Table 1). See Figure 4 for the geographical reference of this map. The geomorphologies of the back-barrier relate to the narrows and marsh in the boca Iglesia lagoon (VIII). Key for fisheries identification (ID) in Table 3. The sampling sites are explained in Supplementary Table 1.

Geomorphological descriptions

The general shape of the landscape and individual features on the coast of Holbox island were grouped into three main geomorphic patterns. The coastline and shoreline have linear, embayed, elongated, and lobate geometries, besides extra geometric units in the back-barrier. A summary of geomorphology is given in Table 1. The descriptions are for the geometry of near-surface landforms (Supplementary Table 1). The explanations are broad to distinguish types of shorelines.

Linear barrier shorelines

Beaches in linear barriers are exposed to waves and partly protected by a natural headland or engineering structures (Table 1). The linear shoreline forms sandplains with beach ridges. The currents flow parallel to the shoreline. The surface of the shore in linear shorelines has 5.6 km to 5 km in length and 1.5 km in breadth. From Holbox village to 15 km offshore, the gradient of this depositional ramp measures a maximum in degrees of 3.9 % and a mean slope of 0.4 %. The backshore is flat, occupied by the native settlers, fishers, and tourists on the west of the barrier island, but primarily uninhabited for the eastern territory. These sections of the shoreline are partly vegetated with mangroves or set aside marshes.

Sand forms on the beach range in height and can be traced laterally for kilometers (Figures 4 and 5a). These features are asymmetrically shaped into a series of coastal-parallel sandy elements. Each major ridge is 100 to 200 m wide and separated by shallow troughs. In plain view, extensive depositional discontinuities truncate the beach ridges and divide the sandplain into sets of beach ridges. Beach ridges are made up of medium-to-coarse-grained skeletal fragments (Anthony and Aagaardc, 2020).

Near Holbox Island and east of the jetty or *Malecon*, the features on the littoral are distributed successively trending obliquely to the shoreline, their orientation is east-west and step ocean ward (northward) over a regional gently seaward dipping ramp. Mangroves grow seaward and mudflats on the backside of the linear shoreline that borders the Yalahau lagoon. These dense natural mangroves occupy the shoreline on fine sediment substrate close to the concave apex of the ensenada-bay. Some of these linear shorelines near Holbox downtown have changed over land uses, passing on to deforestation of the green coverage (Figure 8a and b).

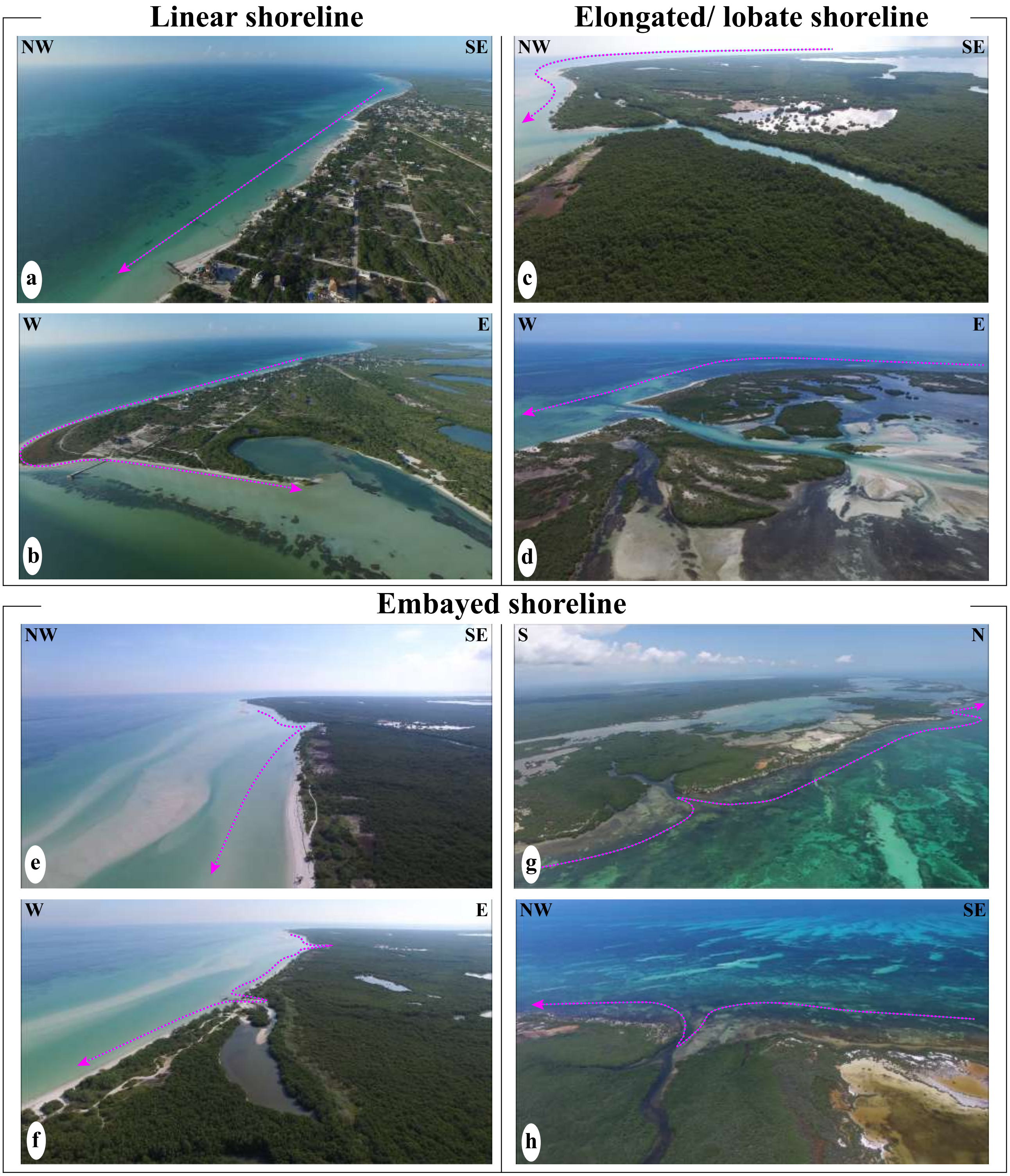


Figure 8.- Photos from shorelines with linear, embayed, or elongated geometries. a) linear shoreline in Holbox with groins, b) barrier spit in punta Cocos and punta Casco west from Holbox, c) cuspate shoreline in punta Mosquito, d) elongated or lobate shoreline in cabo Catoche, e) and f) embayed shorelines east from Holbox and west from punta Mosquito, g) and h) embayed shorelines in boca Iglesia.

Embayed barrier shorelines

Beaches on embayed barrier shorelines align to the coast with a subparallel to asymmetrical trend, forming a curved or embayed shoreline (i.e., locality of East Holbox *Malecon*; Figures 4, 5a and b). The berms have low relief that follows the concave shoreline and separates the sub-environment of the foreshore from the backshore. The backshore and foreshore pass transitionally to the nearshore, extending irregularly. Some low sloughs partition the barrier island into subdivisions of 1 km in length. Back-barrier dendritic networks cut the barrier island, connecting lagoons to the sea. Some small channels partly dissect the bar without breaching the sea. Mangroves grow in these fluvial passages. The coast in these geomorphic features outlines a series of concave shorelines with inlets (Figure 8g and h). The backshore is a narrow and flat area. The berm extents uneven for dozens of meters but generally is absent or intersects with fluvial networks. Shallow brackish water lies near the mangrove fringes and updip in the lagoon (i.e., locality boca Iglesia).

Elongated/Lobate barrier shorelines

This beach face juts from the shoreline, forming an elongated/lobate barrier. This locality is the farthest north extent of a cuspate foreland on the Yucatán Península. This landform aligns discontinuously forming a curvy shoreline and distributes unevenly near to shallow sloughs (i.e., localities of punta Mosquito and cabo Catoche; Figures 4, 5b and 6; Table 1). The elongated/lobate barriers vary from 3 to 7 km long and less than 1 km wide. The backshore is a flat area with vegetation. Locally, it has overflowing and connects the back lagoon with the sea. The berm comes to an end near the sloughs. The beach has some detached breakwaters and groins at the apex of the elongated/lobate barrier or near mouth bypassing. The lobate and cuspate barrier in front of cabo Catoche develops near the remains of cemented hardgrounds or the upturned sedimentary carapace of the bound strata lying on bottom of the nearshore sea floor, at the place of convergence for wave and tidal currents (Figure 9a; see "bedrock high" in Neal *et al*., 2021).

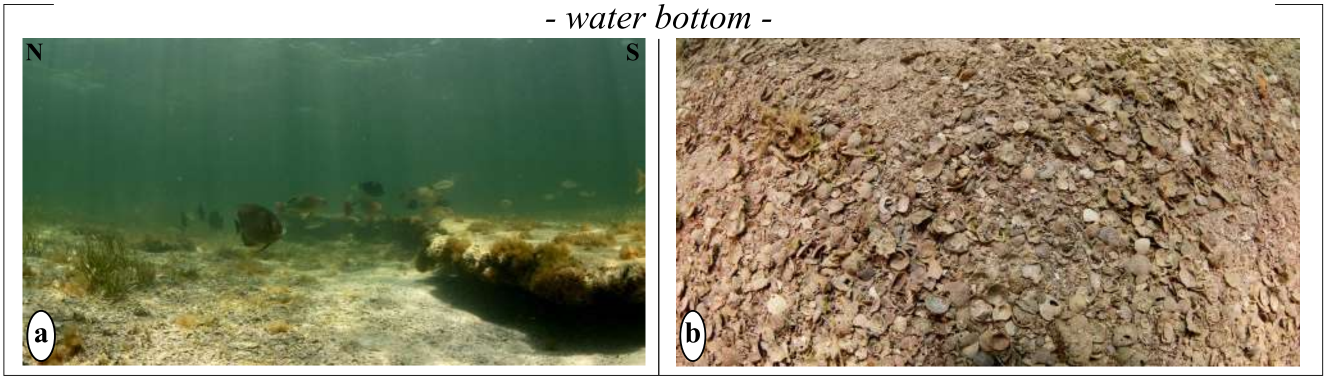


Figure 9.- Photos of the seafloor a) shallow-water sea bottom made of molluscan sand and gravel, and b) hardgrounds or sedimentary bedrock with cuspate geometry, which contours relatively parallel to the lobate barrier in cabo Catoche (Neal *et al*., 2021 for data).

Back-barrier island units

The barrier is separated from land by lagoons distributed parallel to the shore; this water body is up to 300 000 km^2. Some shallow channels dissect the western part of the lagoon. Some permanent inlets allow for the connection of the lagoon with open seawater. Narrow passages form in the lagoon between the back-barrier and the rest of the lagoon sectors. The lagoon area has a consistent shallow depth updip and near mangroves fewer than 2.0 m. The lagoon area is deeper toward the center and north of the open ocean.

Geomorphological interpretations

The coastal geometries in Holbox relate to wave and tidal forces or mixed-energy that commonly occurs in microtidal (tidal range ≤2 m) or mesotidal areas (tidal range 2–4 m). The interpretation of the geometry of near-surface landforms is for their origin processes (Supplementary Table 1). All major elements in Holbox are geomorphic features comprising lower-order elements, as described below. Variations in the forms of the elements are third-order features but do not develop higher series further (Tables 1 and 2). The interpretations are for two general environments, transgressive and regressive shorelines. A correlation between the geomorphic feature and locations with fishing sites is in Table 3. In the supplementary Table 3 is a list of fishing sites with their species in correlation to the main geomorphic patterns.

Linear barrier shorelines

The sand bodies that accrete seaside toward the shelf and a lagoon on the landside are sedimentary features of barrier islands (Reineck and Singh, 1986). The linear shorelines in Holbox are formed by the processes of littoral drift and swash-backwash. Beach face sub-environments in linear barriers are foreshore, and nearshore. The linear sandplains accretes beach ridges, like in the structures on the foreshore (i.e., localities of Holbox and La Ensenada; Figures 4 and 5a). The gentle beach face in linear shorelines breaks waves seaward on a broad surf zone. The surf and breaker zones are distributed parallel to the shoreline. Littoral drift occurs by predominant currents between nearshore coastal waters and the advancing shoreface. The longshore currents in the surf and breaker zones mix with wave energy and the low angle of approaching waves. Interaction of the nearshore currents with the surf zone creates unidirectional sediment transport on the shoreline. Most sediment on beach ridges accretes directly from wave power and current activity from the nearshore (Caladesi and St. Vincent islands in Hine, 2008). The net tendency in this environment is to straighten the shoreline progressively.

The backshore, foreshore, shoreface, and nearshore are superimposed following the general alternation of shoreline elements, locally dissected by the 4th-order embayments or third-order geomorphic features (Table 2). The backshore comprises 6th-order elements that are distributed in areas of backshore lagoons, swales, and desiccated barrier ponds. Ordinary berms are 5th-order elements that accrete to the shoreface. The berms divide the backshore and foreshore and pinch out 4th-order elements such as in estuarine channels.

The beach ridges on a plain with swales lay on the northeastern Yucatan Peninsula. 4th-order landforms accrete ridges, bars, and troughs as a rhythmic topography, that terminate in barrier spits to the west on the foreshore. These landforms shape the series of coast-parallel asymmetrical strandplain.

They were created during the last interglacial shoreline in the late Pleistocene (~120 k yr. B.P.) when the sea level was higher than present by ~6 m (Blanchon *et al.*, 2009). The barrier has ancient successions on the backside, and younger beach ridges accrete seaward.

The discontinuities in beach ridges represent the changes in sediment supply that distributes on the shoreline. Ridges form by landward migration and rise of breaker bars, isolating the former beach face and creating a depression between ridges for shallow water or wet areas. The ridges migrate landwards and infill the runnel immediately up-beach. During the accretion of ridges, swales and berms form, responding to waves of fair-weather periods. The accretion of the beach ridges in the imagery progrades west barrier in sets of beach ridges and terminates in island spits (aka "Punta" locations in Holbox; e.g., Nauset Beach, Chatham Harbour inlet in Reading, 1996; St. Joseph Peninsula in Schwartz, 2009). The images and maps show a series of offlapping beach ridges in areas that have been built seaward even in historical timescales (Neal *et al.*, 2021). Beach ridges in these linear barrier shorelines with marine sediment supply from wave power are regressive, with a seaward shift in position of the shoreline to the west. The succession of these ridges has shifted southward and westward at historical rates of 10 m/yr. The sets of individual beach ridges on Holbox barrier island turn into a complex, which has changed over time. These features range to 5 or more meters above sea level, and their elevation distance correlates with the height of measured sample cores and seismic data (Jaijel *et al.*, 2018a). These stratigraphic markers have an estimated age of formation of 712 ± 32 cal yr, 1571 ± 40 cal yr. B.P. 449 ± 25 cal yr. dates to ~1300 yr. (Jaijel *et al.*, 2018b). Other landforms, such as berms, form into bars if migration shifts to the shoreface. The topography is leveled off as the beach face deflates whenever storm periods occur on the coast. As storm conditions decrease, the ridges reform and the cycle renews.

Shoals in the shoreface accumulate alongshore near Holbox Island and east to the *Malecon*. This sub-tidal part on the beach face consists of 5th-order structures trending obliquely to the shoreline, like nearshore bars and subaqueous barriers. Each succession of beach ridges builds up from the last ridge (Figures 8a and 8b). The nearshore presents 5th-order transverse dunes. The nearshore extends from the uppermost shoreface to the foreshore areas.

The natural processes for the removal and supply of sand are risks to the landscape of the island and increase with anthropogenic activities to build canals, shoreline barriers, and groins. These groins disturb the littoral drift and shelter wave action where sediment intercepts for deposition (Figure 8a). Sediment is continually added to this environment during fair-weather periods. The wave-induced bottom surge is directed landward, depositing sediment in the upper part of the beach face removed during swash-backwash. Alternatively, the barrier island remains stationary and thickens. These longitudinal wave-induced nearshore currents accumulate sediment on the upstream side of the groins. The shoreline of the jetty or *Malecon* in Holbox directs wave currents obliquely to the barrier and retains sediment transport (Pawleys Island in Steele *et al.*, 2001). Locally, groins and detached breakwaters produce indented shorelines to intercept littoral drift, which erode and need mitigation.

Currently, the barrier island faces unplanned urban development and questionable land use. Some field observations in 2022 denote the growing construction of houses and hotels near in the coastal area of Holbox town, where erosion was already an issue when this study started in 2017. Besides, the soil in Holbox is compacting, mostly on unpaved roads. The increasing number of golf cars, motorcycles, all-wheel-drive vehicles, and small trucks compact the soft sandy paths (Rubio-Cisneros *et al.*, 2018). The limited soil for water adsorption during rains leds to massive floods and puddles (Supplementary Figure

3). Puddles have a residence time of weeks, which causes water pollution and local traffic disorders for mobility around the streets. In addition to the predominant basinal processes on the barrier island, subsidence is also responsible for shoreline shift (Jaijel *et al*., 2018a, b).

The linear barrier shorelines include the fishing sites near the entrance to laguna Yalahau, Bajos, Punta Cocos, punta Casco, punta Ciricote, isla Pasión, and in front of Holbox (downtown), punta Mosquito, Santa Teresa, La Ensenada, punta Catalán, and punta Lino (Figure 5a and Table 3). The ecology on the historic fishing grounds of the linear barrier includes species such as sharks, sea turtles, rays, groupers, snappers, soft coral, sawfish, barracudas, grunt-southern king croaker, mullets, corvinas, sea cucumber, snooks, sea snail, lobster, bonefish, tripletail, mojarras, shrimp, horseshoe crab, Florida stone crab, manatee, and Florida pompano (Supplementary Table 2).

Embayed barrier shorelines

The environment of the embayed barrier in the west of Holbox Island is a wave-dominated estuary and a place for longshore currents. Beach face sub-environments occur variably in embayed barriers from landward to seaward. In general, an embayed barrier is a 3rd-order geomorphic feature, 1.9 km long and 1.4 km wide (Table 1). The sub-environments distribute accordingly with the subparallel to asymmetrical trend of the curved or embayed shoreline. On the west side of the barrier island, sand deposits and grooves cap the beach face.

The sub-tidal zone of the beach face is sand bars following the shoreline trend. Here the shoreface and swash bars on the foreshore are discontinuous. Bars on the foreshore accrete collectively, but unconformities interrupt this rhythmic topography. The set of bars is broken as the ridges and trough intercalate. Some of these bars are transverse to the shoreline. Sediments prograding seaward are visible in drone photos (Figures 8e and f). The slanted waves approaching the shoreline migrate the shore swash bars through littoral drift, routing downdrift the mouth bypassing. Most of these landforms are disrupted bodies of sand that extend seaward and occupy sinuous sedimentary environments or represent realms that disperse sediments. Locally, ria outflows cutting the sedimentary features on the foreshore. A broad supratidal "marsh" extends landward from the lagoons, consisting of carbonate sediment.

Embayed barriers east of Holbox are 3rd-order geomorphic features, extending from 3.0 to 6.3 km long and approximately 1.6 km wide. The beach face is higher in order than other 3th-order elements. Beach face sub-environments on these coasts accrete asymmetrical to the shoreline by accumulating clastic elements. The sandy elements are exposed to tides on gently curved beaches, with irregular forms near channels, bays, and estuarine mouths (i.e., localities of Boca Nueva and Boca Iglesia; Figures 4 and 7; Table 1). The upper part of the beach face is subject to most currents, causing shorelines to break and bypass currents. The shoreface shifts landward, while local intertidal flats near rias advance seaward to the sub-tidal zone. Most inlets form with channel elements of sand bars and fans on the shoreface. The spacing between the inlets subdivides the barrier island into segments of 1 to 3 km in length. In the absence of berms and a restricted backshore, the beach face stands unprotected against local inundations on the barrier. The back-barrier lagoon has fairly consistent depth trends in its intertidal and subtidal zones.

Sediment is transported seaward along the gently dipping shoreface to the west. Locally, percolation is limited by the uneven breaking of sediment swash against the irregular extent of the beach face. The sand geometries on the shoreface are transgressive bars, troughs, dunes, and shoals. The removal of sediments from the shoreface is done by waves or by residual motion from tide and upwelling from the sea. Embayed barrier shorelines are dissipative shorelines due to the considerable degradation of sand deposits, occasionally by the action of rip currents and outflow in channel mouths.

Estuarine shores develop where shorelines are broken or bypassed by the estuarine channels, forming embayments and mixing intertidal sediments. These areas are subject to temporal fluctuations in fair-weather waves and episodic storms. The bypass of the shoreface is another estuarine configuration of its channel, where the outflow removes sand and causes a berm incision. Dendritic outlines and short-lived fluvial passages cut the barrier, supplying sediment from the lagoon and letting a sediment-laden or stormwater enter the lagoon (i.e., localities East Holbox Malecon, punta Mosquito, and near cabo Catoche). Some levees along the ria indicate sand deposits related to this rise in the water table. The estuarine channel dredge sandy substrates out of dense natural mangroves. This removal of muddy sediment causes mangroves to degrade and widen the nearby area with no vegetation.

Embayed shorelines east of the Holbox barrier island are associated with regressive systems. Tidal conditions prevail on these shorelines and relate to the rise and fall of currents (microtidal or mesotidal) that shape the intertidal zone in eastern Holbox. Tides generate landforms by moving water between the sea and the coastal plain, lagoons, and estuaries through inlets and distributary waterways. Tidal inlets develop estuary mouths bypassing tidal prisms and flats that flood into and out of lagoons. This section of the barrier now has a beach and a low to narrow berm. The intertidal zone on the foreshore is exposed to most tides and the daily swash of the waves. Both waves and tides during tropical depressions alter the shape of embayments, producing changes in the depositional environments (Jaijel *et al*., 2018b). The embayed barrier shoreline south of boca Iglesia shifts landward, consisting of inlets up to the locality cabo Catoche. In the east, tidal inlets cut the barrier island, connecting the sea with the restricted interdistributary bays and lagoon. The inlets, marshes, and tidal flats with shallow depths are unprotected from weather conditions. In these shallow exposures, water can reach hypersaline conditions during the dry season (Jaijel *et al*., 2018a).

The eastern section of the barrier island is a dissipative shoreline, shifting rip currents, reflecting cusps and crescentic bars. The shoreline forms from the steady tide and aligns with the crest lines of the waves that arrive. As tidal currents emerge from the inlets, sand and fine sediment expand with flow deceleration to form ebb- and flood-tidal deltas. Currents from channels, ebb, and floods deposit sand bodies. The ebb currents concentrate in the deep-central channel, and flood currents in the marginal channels. Locally, the inlets have ebb-tidal deltas that mold these seaward mouths. When the ebb flows, the sediment escapes onto the shelf, but a reduction in the supply of sediment to the sea induces the landward migration of sand deposits into the mouths. The inlets are generally flood-dominated channels of consolidated clay substrates. When the waves approach the lateral margins of the tidal inlets, they remove material alongshore. With wave action, beach spits accrete alongshore by drifting and scouring off the updrift margin of the tidal inlet (e.g., Georgia embayment in Reading, 1996). Deltaic deposits with material that migrates opposite to the eastern tidal current are near boca Iglesias. Here the inlets become symmetrical if the wave advances to the shoreline but curve asymmetrical if the wave transports obliquely alongshore. The waves create swash bars that flank the tide-dominated channels (e.g., Monomoy Island in Reading, 1996).

Where inlets on the eastern barrier island form elongated sand bodies scattered along the shoreface, the tides are strong on the shore and have low wave power. Storm berms accrete aside mouth bypassing behind the shoreface. Locally, tide concentrates the current in a single flood-tidal channel or through channels dissecting a ramp with lobe-shaped sand bodies. The lobe-shaped flood-tidal delta interfingers with the shoreface deposits at the inlet mouth, forming a broader sand accumulation. Sediment deposition at flood tidal deltas builds a series of overlapping fans or spillover lobes near the lagoonal mouths (i.e., locality Entrada Boca Nueva). These lobes and fans have dozens of meters in length and width. Ebb spits protect these inlet environments. The tidal channel extends seaward, prograding with transverse dunes on the nearshore and beyond (Essex River in Schwartz, 2009; Spiekeroog island in Davis and Dalrymple, 2012). The tidal channel integrates into the backward marsh and forms dunes on the sea.

Washover fans on embayed shorelines are geomorphic elements constituted by sand accumulations deposited over the barrier, back-barrier, mouths of inlets, and into the lagoon. These fans are caused by sheet flow during high tide and storm periods on embayed barriers. Washover fans also occur on the backshore near swale ponds after seawater overflows above the barrier (Horn Island in Schwartz, 2009). Channels erode the scattered eolian dunes and some beach ridges capping the beach face. These landforms mask the flat of the barrier and can be dissected by rias. Washover fans can superpose in deposition, forming a composite structure that obstructs passageways flooding the barrier. Washover processes are locally frequent in the north of these eastern embayed sections. Despite their limited expression, washover fans are more likely to occur in microtidal lagoon environments. They associate with temporary inlets that evolve into flood-tidal deltas at the east of the study area, which spread as the inlet migrates (Moslow & Heron, 1978).

The coastal environments on embayed shorelines east of Holbox barrier island are the habitats for sea turtles, groupers, snappers, corvinas, snooks, lobsters, and manatees (Supplementary Table 2). Embayed shorelines cover the historic fishing sites in front of Holbox (downtown) and La Caleta (Figures 4, 5a, and b; Table 3).

The embayed shorelines in the west of the Holbox barrier island incorporate the historical fishing sites of Boca Limbo, Boca de Angostura, Las Bocanas, cabo Catoche - punta Cayo Ratón, boca Nueva, boca Iglesia, laguna Cayo Ratón, and punta Cayo Ratón (Figure 7 and Table 3). The species associated with this coastal environment are sea sharks, turtles, groupers, snappers, Florida pompano, sawfish, barracudas, sea cucumber, sea snail, and lobster (Supplementary Table 2).

Elongated/Lobate barrier shorelines

These littoral forms mold from preexisting rock outcrops, headlands, sediment supply, and currents. This landform comprises the sub-environments for eolian dunes, backshore, foreshore, and nearshore. These are broadly aligned discontinuously to the curvy shoreline and distribute unevenly near-to-mouth bypassing (i.e., localities of punta Mosquito and cabo Catoche; Figures 4, 5b and 6; Table 1). Elongated/lobate barriers are 3rd-order geomorphic features and laterally extensive. These curved beaches range in size from 3rd- to 4th-order.

Longshore currents on the nearshore and processes in the surf zone supplement wave transportation in the elongated/lobate barrier. The sediment on the beach at the convex formation of cuspated shorelines comes from shoaling and waves breaking (Cape Canaveral in Hine, 2008; Dungeness in Schwartz, 2009). This process from offshore removes the sediment on the beach (Reading, 1996). The transfer of sandbanks accumulates sediment at the landward termination of the sand deposit. Locally, wave refraction creates the arched coastline oriented SW 37º prograding to the west in Holbox (i.e., the locality cabo Catoche).

The sediment transported into the water column is fine sediment and mud, including heterozoan biota related to the upwelling of cool nutrient-rich water on the Yucatán Shelf. The sediment in suspension attenuates wave or tide energy, preventing coastline erosion on elongated/lobate shorelines. Unconsolidated bottoms and shoals around cabo Catoche protect the coastline from shifting or elongating the lobate shoreline. The tide in storm periods causes the advance and retreat of swales and berms. Locally, berms can shift their relief toward the shoreface or get breached. When waves break on the shoreline, sediment escapes onto the shelf through sloughs, developing sand ramps at the lagoon entrance, especially during flooding and stormy seasons. These local conditions create wave-dominated estuaries partly open to a lagoon with a parallel shore and channel margins with linear bars.

The backshore is vegetated by the mangroves and with desiccated clastic features in its flat surface. The local drainage intertwines across ridges and troughs. The berm separates the backshore sub-environment from the foreshore with no tracks near estuarine mouths. Other landforms on the surface and back of the barrier island are lobe-shaped sand units with fan geometries, forming at the mouths of channels and inlets (Figure 10).

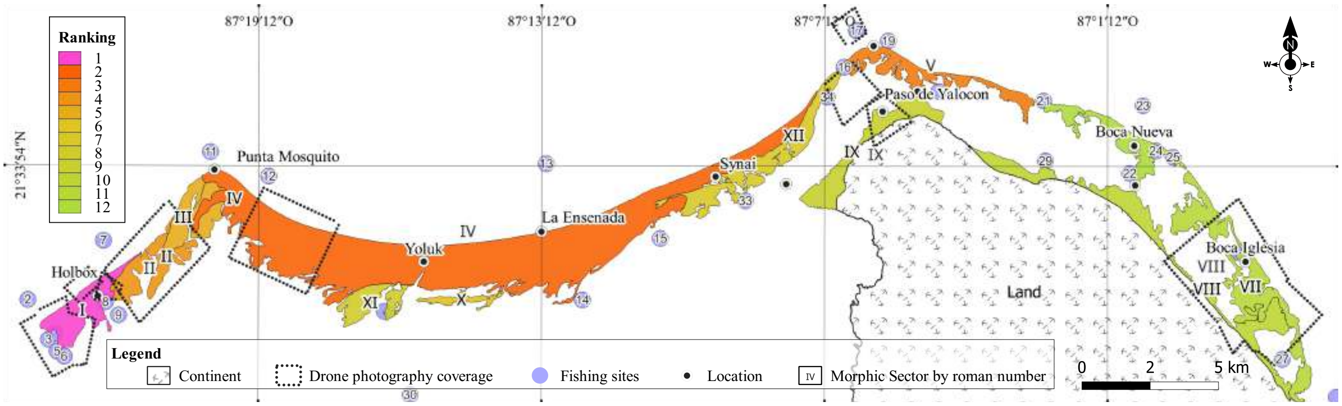


Figure 10.- Holbox Barrier Island map of indicating the level of protection to preserve the 12 morphic sectors based on the reports on deposition, erosion, wave or tide energy, number of species per fishing ground, and human impacts; the color is based on the ranking by the sum of all variables. The morphic sectors are in roman numerals and in Table 1.

The absence of passageways to accommodate landward-directed storm waves and wind-forced currents causes floods and washover elements. The berm is compromised when these overflows occur. Swales, washover fans, and lagoons develop in the spillover zones. These areas represent supratidal environments inundated by the high tides and storms that carry sediment landward as spillover deposits that advance into the barrier's back and back-bar lagoon. Washover fans are lobe-shaped sand units that can overlap fans from different sources. These fans produce an irregular apron of sand that forms a back-barrier flat, which projects into the lagoon (Reading, 1996). Washover fans are formed by sheet flows when sediment eroded from the seaward side of the barrier transfers to the lagoon during storm periods. A composite washover fan represents a significant breach through the barrier island and can be reopened by later storms (McGowen and Scott, 1975). Subtle scour surfaces of the sand separate the individual washover units. Washover channels occupy the entrance of some inlets or mouths of channels.

Elongated/lobate shorelines are dissipative transgressive systems with rips and shoals. Sedimentary deposits traverse the shoreline under wave circulation from the east. In the shoreface occur bars obliquely to the cuspate shore. A subaqueous sand barrier accompanies the sub-tidal zone of the beach face whenever the shoreline straightens. The sand landforms on the shoreface accrete seaward on the updrift section. At cabo Catoche, the ocean currents from Rancho Bonito remove material along the coast to the west (Figure 6). The near-offshore areas are protected by the remains of reefs, rock caves and rias. This geomorphic element progrades offshore under continuous sediment supply, stable sea level, and low to moderate subsidence. However, the removal of the sediment along the beach may be at times trending contrary to the main littoral drift, producing unconformable accretion of ridges.

Although the elongated/lobate barrier's geomorphic feature is a product of a transgressive system, it occurs in a zone where wave and tide currents convey, creating a seaward shift in position of the shoreline (i.e., locality east of cabo Catoche). Here the mixing of processes accretes sand, forming variants of the shoreline in length. Locally, the most northern wave-dominated of these geomorphic features has beach ridges built of sand interspersed with muddy tidal lagoon deposits swept into the sea by occasional water rise. Locally, the mix of wave energy in the northeastern parts conveys regressive tide-dominated elements such as inlets fringed by mangroves. These indented tidal coastlines with marshy areas and minor sandy beaches occur eastern Holbox.

The shoreface shifts landward on the downdrift side, mixing the wash load from estuarine mouths. Mud calcite concentrates in suspension or settles with some biosiliceous fragments on the lower shoreface (Figure 9b; see Neal *et al.*, 2021). Although corals are notably absent in the locality, allochthonous organic-rich fragments occur at the bottom of the water near the shoreface.

Landforms in the foreshore accrete subparallel to the coast, alternating asymmetrical ridges and troughs. Locally, landforms on the foreshore, like swash bars accrete unconformably and migrate, widening the arched shore. The ridges migrate seaward to fill the runnel and incorporate sediment supplied from estuarine channels. The apex in the elongated/lobate barrier is part of the transgression of sand ridges that accommodate successions of bent ridges and estuaries from the mainland. The ridges pinch out on the sandplain in the barrier.

The breaker zone extends to the inner shelf where the tracts of biogenic structures end near cabo Catoche. A bar complex covers the nearshore and extends over the downdrift side. The nearshore has longitudinal bars that extend over the beach face, where waves break on the outer bar to reform and break again on the inner bar. Locally, the nearshore presents transverse dunes and a shoal complex. The nearshore in the northern regions of the barrier island gets protection by the relief of the sea bottom, creating low-energy conditions. These local subtidal bathymetric heights are north of the barrier island (i.e., in front of cabo Catoche). Seagrass beds grow in some of these subtle elevated spots.

Mangroves and marshes in lobate to elongated shorelines near the coast are exposed to the removal and progradation of the sandy substrate, making vegetation appear fragmented or in mosaics (aerial photographs: Figure 8c and d). Locally, washover fans cut off mangroves, which is possibly seasonal adversity.

Elongate and lobate shorelines include the historic fishing sites in front of Holbox (downtown), punta Mosquito, Santa Teresa, Boca Santa Paula, cabo Catoche, Manchones de cabo Catoche, Cuevas de Cabo Catoche, Segunda Angostura, Boca Limbo, Las Bocanas, and cabo Catoche - Punta Cayo Ratón (Figures 4, 5b, and 6; Table 3). In coastal environments with elongated and lobed shapes inhabit sharks, whale sharks, sea turtles, rays, groupers, snappers, sea cucumber, sawfish, barracudas, snooks, sea snails, and lobster (Supplementary Table 2).

Back-barrier island lagoon and marshes

The Yalahau lagoon is sustained by tide-dominated processes surpassing the barrier rather than wave-dominated, which is restricted to the beach and shoreface (Neal *et al*., 2021). The lagoon is in contact with the back-barrier. It holds landforms of 4th- and 3rd-order, which do not exceed 5 km long and 1 km wide (i.e., localities of Yoluk, west punta Catalán, Rancho Bonito, Paso de Yalikin, and Laguna Boca Iglesia; Figure 4 and Table 1). Fine sediments constitute the wetlands, ponds, ridges, fans, and inlets in contact with the lagoon. A network of intertidal channels dissects muddy areas in the western lagoon. Mangroves dominate the intertidal and subtidal zones of the shallow lagoon. The narrows are passageways periodically flood when seawater enters the lagoon (i.e., the Angostura, Segunda Angostura, and Tercera Angostura localities).

The *angosturas* are narrows at geomorphic geometries where tide energy is plausibly related to their formation. These areas are relicts of what may have formed when the lagoon breached laterally shallow fine-grained deposits, connecting restricted interdistributary bays, flood-tidal deltas, ebb channels, or inlets. The *angosturas*, narrows, and other sites connecting through waterways were not closed but related to Holbox Lagoon's evolution since the estimated flooding phase occurred at ~1550 yr B.P. The long-term response to sea level fluctuations is a natural phenomenon that accounts for the restriction of wáter in the lagoon. Other water bodies, such as bays and inlets, especially in the back-barrier, appear to be formed or inundated synchronously in a few hundred years, between ~2000 yr. B.P and ~1550 yr B.P. The water table for this regional phenomenon reached its current level around 950 yr B.P, revealing the rise was not linear and might have had high-low fluctuations and abrupt changes (Jaijel *et al.,* 2018b).

The brackish water system in the lagoon lacks significant fluvial input (e.g., Great Sound in Posamentier and Walker, 2006). The lagoon connects hydrodynamically with the open ocean; enough for sediment transport from the sea to get into the lagoon, even though it may stagnate for months and be restricted from seawater (i.e., localities boca Conil, boca Nueva, boca Limbo, boca Santa Paula, and punta Mosquito).

Starting from the spit punta Caracol in Holbox, the lagoon entrance to the southeast is a depositional zone for submerged sand bodies visible in aerial photos and satellite images. The progressive accumulation of clastic deposits at this entrance can stop boca de Conil from supplying seawater to the lagoon for months (fisherman *personal communication*).

Landforms such as washover fans, smaller ephemeral water bodies, and saline flats surpass the lagoon as the shoreface retreats landward. The rising sea level removes sediment from the upper shoreface and transports it to the lagoon. The subtropical and humid climate in the supratidal region of northwest Yucatán produces sparse salt marshes instead of sabkhas in the backed zone, with buildups of microbial mats, desiccation cracks, pools, springs, and wetlands.

The back-barrier lagoon has a consistent depth in the intertidal and shallow subtidal deposits. The intertidal flats and salt marshes extend over the lagoon, and mangroves nourish where the intertidal channels dissect the barrier leaving muddy and saline substrates (Jaijel *et al*., 2018b). It has shallow bottoms near the mangrove fringes in the margins of inlets and updip. Embayments inside the lagoon incorporate marshes on the shallower sections. The mangroves fringe thins out and disappears as the tide action increases along the coastline. The mangroves border the land-water interface in laguna de Boca Iglesias and rio Limbo. In boca Iglesia, on the backside of the shoreline surrounding laguna de Boca Iglesia, mangroves accumulate muddy sediment after tides. The fraction of calcite mud in the lagoons comes from in situ mud-producers, local bioerosion (Matthews, 1966), and is transported from the northern higher-energy offshore (Appendini *et al*., 2012). Calcite mud concentrates in suspension or settles with some biosiliceous fragments in the lagoons. The removal of sandy and muddy substrate fragments mangroves and interrupts their recovery.

The historic fishing sites on the back-barrier in Holbox are Laguna de Yalahuau, inside the shallow slough near punta Cayo Ratón, Raíces de manglar por todo el río, Los Islotes, Synai and Rancho Bonito (Figure 4 and Table 3). The species living in the coastal environment of back-barrier are sharks, sea turtles, groupers, snappers, soft corals, sawfish, barracudas, mullets, corvine, snooks, sea cucumber, sea snail, lobster, shrimp, horseshoe crab, Florida stone crab, bonefish, tripletail, manatee, dolphin, Florida pompano (Supplementary Table 2).

Discussion

We examine the coastline of Holbox, a Caribbean barrier island in northeastern Yucatan with notable categories of littoral geometries and fishing resources. This geographical area is vulnerable to the distribution of land, water, and populations after climate phenomena, rising sea levels, hurricanes, coastal erosion, sediment deposition, loss of vegetation, floods, shifting low sloughs, or human activities (Blanchon *et al*., 2009; Schwartz, 2009; Jaijel *et al*., 2018a; Tereszkiewicz *et al*., 2018). Given the challenge of correlating the anthropogenic and natural conditions with the causal processes of landforms in Holbox, this work presents equifinal interpretations for the origin, setting, and stages of formation, which can help in the characterization of the Yum Balam protected area and in resource management in barrier islands on ramp systems or over similar peninsular formations (Goudie, 2004; Vázquez-Lule *et al*., 2009; de Oliveira *et al*., 2019).

We interpret four main geomorphic features considering principles in geology and related marine sciences for anchoring sedimentary observations and landforms created in a coastal environment under regressive and transgressive marine conditions, under a predominant seaward shift in the position of the shoreline. Since the morphology and orientation of geometries in the terrain formed by sand are highly variable across the coast, both sedimentary and biological environments are complex when examined in a local shore dynamic and require further study. Offshore, subaqueous dunes and widespread current ripples are less common as seen in the aerial photos or scuba diving, suggesting that the bedload portion may not be markedly alongshore in water deeper than ~2.0 m. This geomorphology is suitable for correlating ecological conditions and markers from sedimentological analysis, like facies and paleoenvironmental discriminations or paleoclimate variabilities among coastal peats like marshes, tidal flats, salt marshes, beach deposits, shelf, and deeper coastal surroundings (Jaijel *et al*., 2018a; Neal *et al*., 2021).

Natural causes and anthropogenic interventions

Regional boundaries frame Holbox barrier island on a geological basement (Precambrian-Paleozoic Maya Block), a Cretaceous carbonate platform, an overlying coastal plain of carbonate sequence with its Miocene to Pleistocene shelf, and the last interglacial clastic shoreline. The island opens offshore as its underlying carbonate strata extends onto a gently dipping ramp capped by a shoreline depositional system. Since the Holocene transgression, Holbox has migrated landward across the low-energy carbonate ramp that makes the Yucatan Shelf.

From the eastern margin of Holbox on the Caribbean, the barrier extends kilometric sand ridges following longshore currents until arching the trend of the bar to the west. The barrier shifts landward from the elongated/lobate shoreline in boca Santa Paula west of cabo Catoche by forming a linear coast that widens up in the La Ensenada locality. The sandplain bends inland from the deposition of a beach ridge complex following littoral drift to the Santa Teresa locality west of punta Mosquito. In the apex areas, wave-dominant sea mouths occur, allowing the back-bar lagoon to meet the sea. The elongated/lobate shoreline in Punta Mosquito lengthens landward to the west as sediment supplies from eastern estuarine mouths and currents. The central-west section of the Holbox barrier island is made up of an embayed shoreline until it shifts southwest to a linear shoreline in the town of Holbox. The shore in Holbox village is fed by the longshore transport, which shifts the upper shoreface during transgression, or the lower shoreface when the sea level falls (e.g., Reading, 1996; Posamentier and Walker, 2006). The island progrades with trade winds from the east in the circulation of tropical weather throughout April to September. However, cold fronts arrive from the northwest heading southeast from October until they shift to stormy conditions in March (Cahuich-López *et al*., 2020; Neal *et al*., 2021). The most western end of the barrier island presents recurved sandy spits in punta Cocos, Punta Caracol, and punta Cericote that turn to strike the southeast.

The promontories with lobate geometry in the barrier of Holbox Island belong to a primordial estuarine or tidal delta on the coast, while low sloughs are partly associated with the formation process. The coastline in Holbox barrier island tends to straighten and lacks the protuberances of most deltaic coasts for some reasons: (i) fluvial input is reduced and much drainage is internal and underground through the karst limestones; (ii) coastal plain is supplied primarily from marine sources by longshore transport, (iii) to a lesser extent sediment supply comes from numerous small closely spaced rias, rather than by a single slough; and (iv) wave processes sustain a transgression following the Yucatán littoral drift, meeting with an upwelling zone where tidal incursion arrives from a much steeper seafloor possibly from Bottom Ekman (e.g., Reading, 1996; Rankey *et al*., 2020, Estrada-Allis *et al*., 2020; Anthony and Aagaard, 2020). The increasing thermo-hyaline currents from upwelled waters are basinal reworking like in other barrier islands, this process makes the ocean supply of sediment undertake waves and tides (Rankey *et al*., 2021).

During the Holocene, the seaward shift in the deposition of the shoreline on the Yucatan Shelf possibly had an incipient estuary or a tidal delta forming distributary mouth bars, with a marsh on its back, beach ridges to the west, and an interdistributary bay in the east of what is now Holbox Island. Eventually, delta lobes were abandoned, leading to an erosional headland with flanking barriers distributed in front of the preexisting headland. As waves approach, the barriers shift into a barrier island, leading to a non-deltaic shoreline shifting in the position of the shoreline to the west and a back-barrier.

The curved platform is produced by the continuous swell waves diffracted from the tip of a headland, combined with wave refraction and a nearshore current circulation system on the lee of the headland. Shoreline in cabo Catoche presents breakwaters shelter wave action where sediment intercepts for deposition. The coastal infrastructure can eventually affect natural resources in historical fishing sites near biogenic structures and mangroves habitats, even causing beach erosion.

Holbox deals with human overcrowding by people visiting and moving to live on the island. Humans have modified the landscape of onshore and offshore coastal areas due to transportation, construction, fishing, and tourism (Tran 2006; Rubio-Cisneros *et al*., 2018, 2019, 2022). The barrier island faces social conflicts related to land tenure, fisheries overexploitation, illegal fishing, the increasing use of unsustainable practices to generate electricity, and the production of excessive trash, among other socio-environmental threats. All these activities shift the orientation of the shoreline and its morphology. The risks are over the ecosystem services for fisheries and tourism (Port Phillip Bay in Schwartz, 2009).

Human coastal activities and natural phenomena in Holbox impact historical fishing sites reported associated with linear geomorphologies. These impacts also threaten fishing sites in elongated/lobate shorelines and to a lesser extent the eastern embayed barrier shorelines plus the back-barrier geomorphic units (Figure 10). The shorelines on Holbox Island with a higher sum of impacts from humans and nature are candidates for restoring beaches, designing recreational sites for environmental tourism, or nourishing habitats. Sectors of greater extension like Ensenada include more fishing sites and species, while other remain remote to the east in boca Iglesia. In contrast, sectors protected at the back-barrier with lesser species or not related to fishing sites are less important for protection against natural or human impacts. Actions in shoreline remediation can help preserve the ecological interactions needed for the succession of coastal ecosystem services. Shore protection is an adaptation for sediment management strategies and coastal developments (Cooper *et al*., 2007).

The areas with mangroves losses are also a cause for beach erosion downcoast (i.e., localities Holbox *Malecon*). Mangroves and associated vegetation diminish current flow and wave action. This vegetation colonizes areas that have become more sheltered due to the growth of sand bars, spits, or barriers along the coast. These features in mangroves are identified aerially and can improve our understanding of their vital conditions. Further landscape details in Holbox will disclose the extent of dense natural mangroves, degraded mangroves, fragmented mangroves depicted as mosaics, mangroves deforestation areas, or clear-felled mangroves converted to other uses.

The measures to protect shifts in the coastline and impacts on the ecology require the conservation of coastal landscapes in Holbox, integrated with the socio-ecological and economic values by observations in the most touristic areas (e.g., cabo Catoche; video from Rubio-Cisneros, 2019).

Regionally, in the rest of the coastal area in Quintana Roo, there is an equally urgent need to create stable, safe, and healthy beaches for human societies to coexist with nature.

Conclusions

This study in the northern Yucatán Península describes geomorphic features that have been little studied on the tropical Holbox Barrier Island. The coastal landforms comprising the coast are linear, embayed, and elongated-to-lobate shorelines formed on a modern shelf and ramp sea after the last Holocene sea transgression (Late Pleistocene ~120 k yr. B.P.). The macroscopic view of the coast shows a shoreline over a moderately stable and low-gradient coastal topography divided into backshore, foreshore, nearshore, and back-barrier with marsh, mangrove, muddy lagoon, and barrier-islet environments. Tides approach eastern geometries, creating flood-tidal deltas, ebb channels, and inlets. Meanwhile, the northern geomorphological features accrete easterly as the waves arrive landward under fair-weather conditions, pushed by the prevailing seasonal weather, like the upwelled current trajectory or north cold fronts. Littoral forms are from settings with wave energy but limited tidal range, and to lesser extent sediment that moves from continental regions. The supply of sand to the shoreline by littoral drift and upwelling produces sand accumulation, sediment removal, and transportation on micro-mesotidal beaches. Smooth beaches make dissipative shorelines, and reflective shorelines form inlets on convex shorelines or concave promontories of sand with an irregular shoreface. The geomorphic characteristics of this barrier island are impacted by natural beach transformation, but mostly by unplanned urban development. The cross-correlation of field data and cartographic methods proves a model presenting the forms in the landscape that need sustainable protection for Holbox´s environments.

Acknowledgments

The authors are thank to the Rufford Foundation, United Kingdom, for a research grant to Dr. Nadia Rubio, which allowed developing fieldwork on Holbox Island from 2015 to 2022. The authors are grateful to the fishers and their families for their warm hospitality and support for our research. Special thanks to fisher Miguel Zapata and his wife Etelvina Mogel, and son Julio Zapata for helping us at the field. Also, we give special thanks to fisher Vicente Caceres for supporting our investigation on the island. We thank the authorities from the *Comision Nacional de Areas Naturales Protegidas* (CONANP), *Área de Protección de flora y fauna Yum Balam* for their support to our activities on the island. We appreciate *Alianza Kanan Kay* for the extension in the science of this work. Tha authors thank Marine Biologist Erik Higuera for collaborating on this project with drone photography, as well as to the anonymous reviewers.

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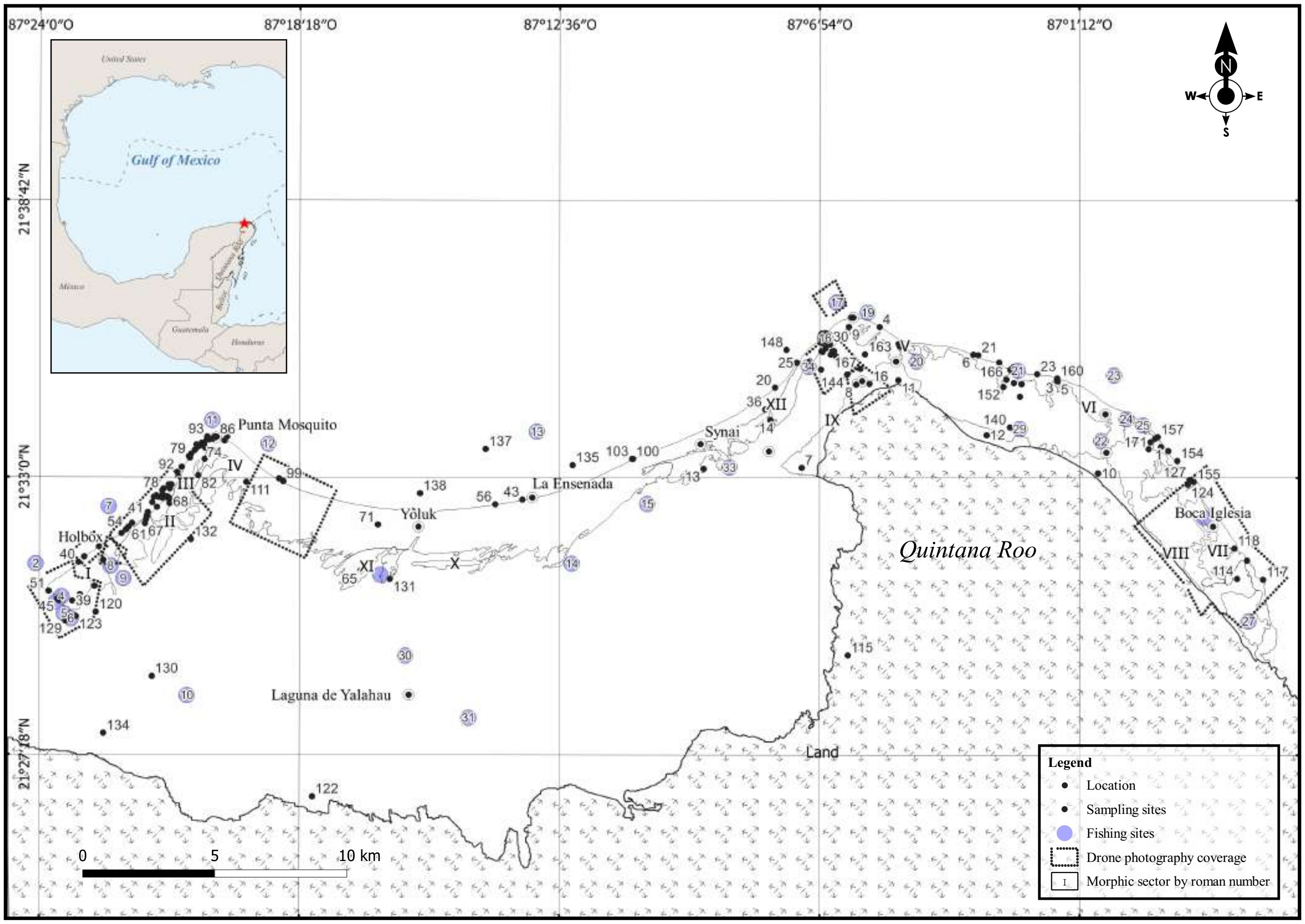
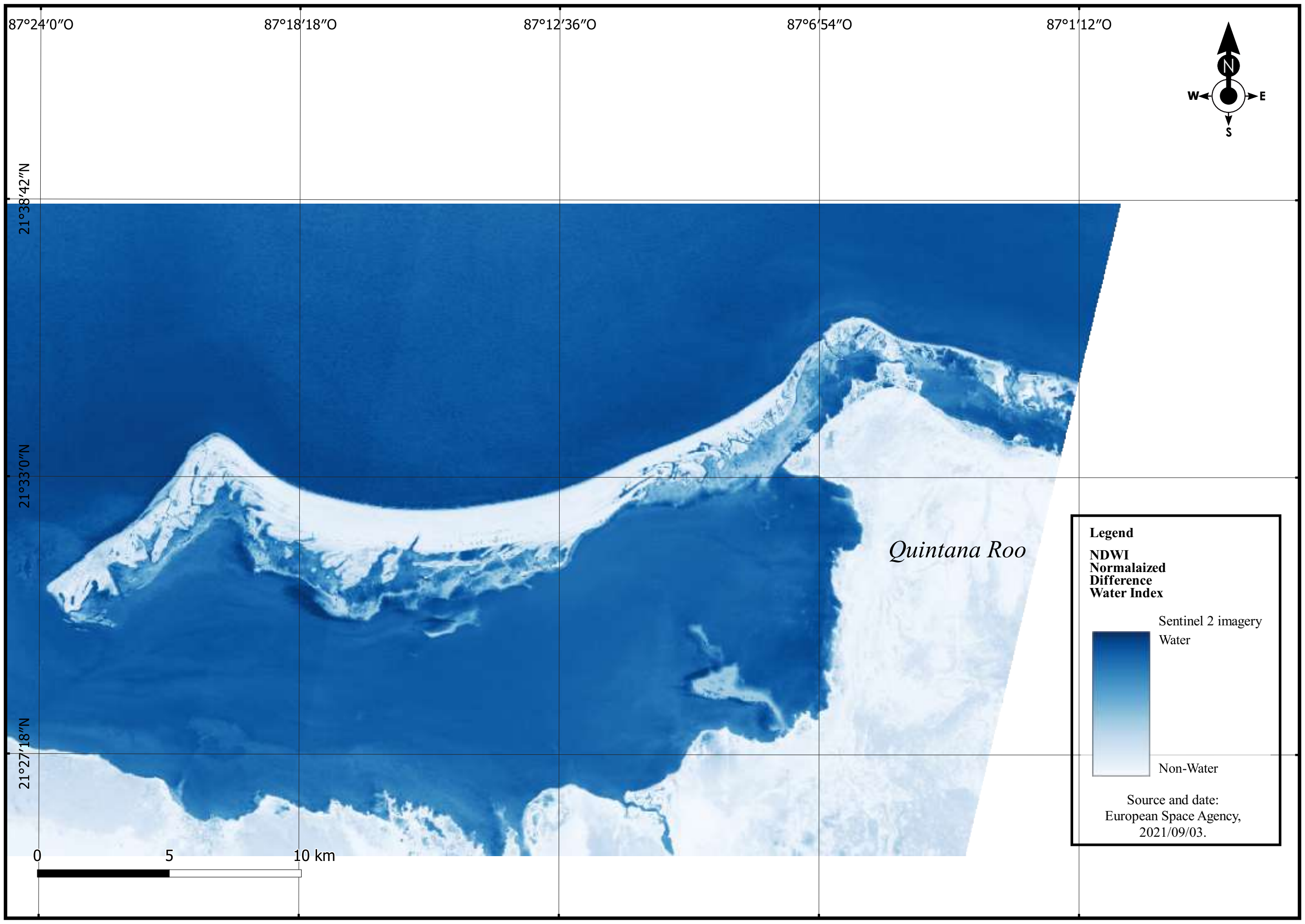
Supplementary data



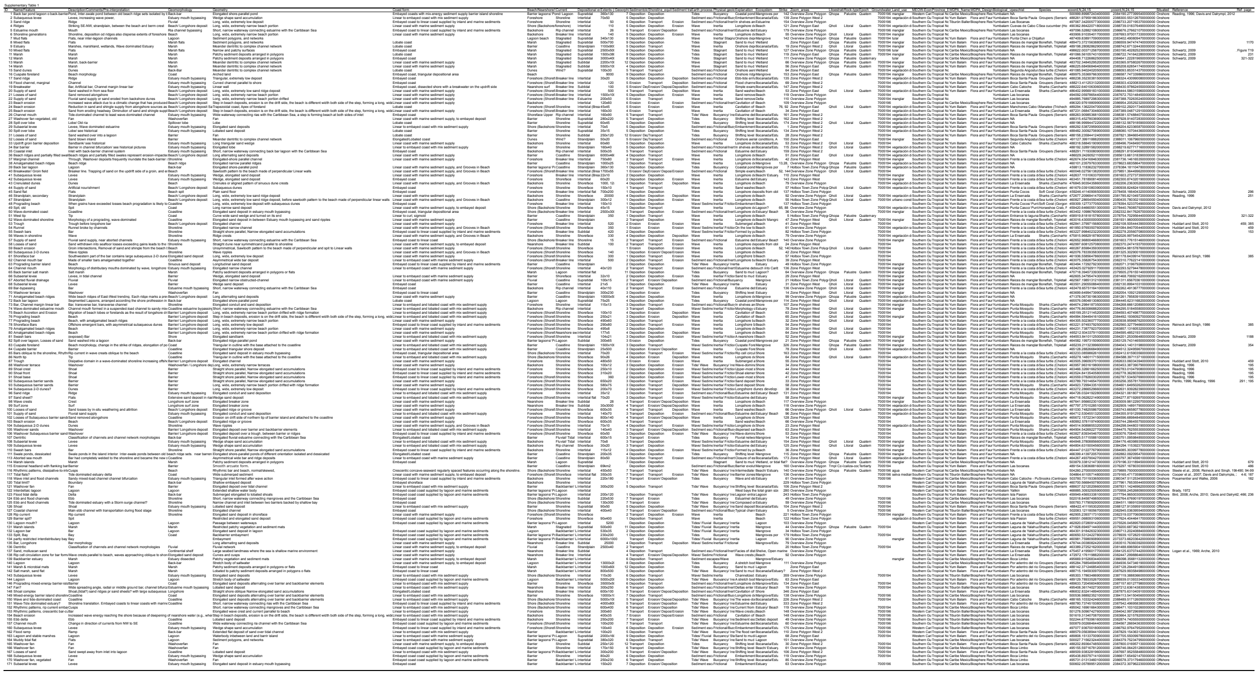
Supplementary Figure 1.- Drone photo coverage in the study of Holbox Island.



Supplementary Figure 2.- Water extraction by the normalized difference water index (NDWI) in the study of Holbox Island.

Supplementary Figure 3.- Flooding in Holbox community areas and downtown.

Supplementary Table 1.- Geomorphological survey of Holbox.



Supplementary Table 2.- Geomorphic features are corresponding to fishing sites. Fisheries' ID are from Nadia *et al*., (2018).

Supplementary Table 2

#	Geomorphic feature and its corresponding fishing sites	(n)	Species (n)
1	Bajos, Canal- tuberia en Laguna Yalahau, Entrance to Laguna Yalahau, Frente a costa de Holbox, Isla Pasion, La Caleta, Laguna de Yalahuau, Muelle por la Caleta, Punta Casco, Punta Ciricote, Punta cocos, Raices de manglar por todo el Río	12	60
2	Frente a costa de Holbox, La Caleta, Laguna de Yalahuau, Raices de manglar por todo el Río	4	29
3	Frente a costa de Holbox, Laguna de Yalahuau, Raices de manglar por todo el Río	3	37
4	La Ensenada, Santa Teresa, Laguna de Yalahuau, Los Islotes, Punta Catalán, Punta Lino, Punta Mosquito, Raices de manglar por todo el Río	6	70
5	Boca Limbo, Boca Santa Paula, Cabo Catoche, Cabo Catoche- Punta Cayo Ratón, Las Bocanas, Manchones de Cabo Catoche, Por adentro del Río- Punta Cayo Ratón, Raices de manglar por todo el Río, Segunda Angostura	9	27
6	Boca de Angostura, Boca Limbo, Boca Nueva, Cabo Catoche- Punta Cayo Ratón, Las Bocanas, Por adentro del Río- Punta Cayo Raton	6	12
7	Boca Iglesia, Boca Nueva, Cabo Catoche- Punta Cayo Ratón, Laguna Cayo Ratón, Las Bocanas, Por adentro del Río- Punta Cayo Ratón, Punta cayo raton	7	18
8	Boca de Angostura, Laguna Cayo Ratón, Por adentro del Río- Punta Cayo Ratón, Raíces de manglar por todo el Río	4	
9	Laguna de Yalahuau, Por adentro del Río- Punta Cayo Ratón, Punta Chen a Chijaltun, Raices de manglar por todo el Río, Segunda Angostura	5	
10	Los Islotes, Laguna de Yalahuau	2	22
11	Los Islotes, Laguna de Yalahuau, Raices de manglar por todo el Río	3	25
12	Laguna de Yalahuau, Por adentro del Río- Punta Cayo Ratón, Raices de manglar por todo el Río, Rancho Bonito, Synai	5	24

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Quien no se resuelve a cultivar el hábito de pensar, se pierde el mayor placer de la vida.

Thomas Alva Edison
(1847-1931) Físico e inventor estadounidense.