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Geomorphological characteristics of the Southwest waters of Vietnam

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ABSTRACT

Based on the principle of origin, the Southwestern coastal topography of Vietnam is divided into 32 geomorphological units. Coastal and island topography consists of 9 geomorphological units belonging to 4 topographic groups: (i) terrain with the common erosive origin, (ii) plants of marine origin, (iii) mixed river and sea origin, and (iv) waste of biological origin - river and sea. The seabed topography consists of 23 geomorphological units belonging to 3 topographic groups (i) topography of marine origin; (ii) economics of river and sea origin; (iii) marsh-sea accumulation terrain. The topography of a small part of the coastal continent and most islands were formed in the Quaternary period, and the rest of the continental coastal topography and the entire seabed surface of Southwest Vietnam was developed in the Quaternary period, from late Pleistocene to Holocene.

Keywords: Southwest coastal region of Vietnam, geomorphological unit, geomorphological principle.

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INTRODUCTION

The study area is located in the Southwest coastal region of Vietnam (SWCRVN) within the coordinates of 7º48'00"–10º40'00"N latitude and 102º09'20"–105º21'00"E longitude. The North borders Cambodia, the South borders the East Vietnam Sea, the East is the Kien Giang, Ca Mau, and Bac Lieu provinces, and the West borders the Gulf of Thailand. The coastal region is of particular importance in terms of national security and defense because it is the frontline position of the country but also an area rich in natural resources, biodiversity, and vibrant economic activities. Therefore, the Vietnam State has been and is being invested in all aspects, including investigation projects, studies on natural conditions, planning, and natural resources in service of socio-economic development and protection of national sovereignty.

Based on field trips' documentation compiled by the authors in the years 2004–2019; combined with analysis of maps (charts), remote sensing images, analysis of geological-geomorphic conditions, hydro-meteorological conditions, water mass dynamics, and inheriting previous analysis results, published works; this study has established the Geomorphological Map of SWCRVN at the scale of 1:250,000. The map was created according to the principle of origin and introduced the basic features of the area's geomorphological features and the history of geomorphological development during the Late Pleistocene-Holocene period.

MATERIALS AND INVESTIGATION METHODS

Materials

Materials used in this study include:

Materials were collected during the survey trips on the topics that the authors participated in in the period 2004–2019 [1, 2].

References are related to projects [1, 3], topics [2], and research works [4, 5].

Maps, charts, remote sensing images, and scientific publications are from [1].

Based on the synthesis and analysis of documents of previous studies and the results of direct surveys of the authors' group when implementing topics and topographic maps, charts, satellite images, and other relevant documents.

Principles for establishment of geomorphological map

Currently, in the world, there are many classification tables of coastal and seabed geomorphology [6–9]. The unification of the principles of geomorphological mapping has so far been a big challenge both in terms of approach and method [10]. In this study, the authors use the principle of origin, based on the concept of "surfaces of the same origin", introduced in 1965 by scientists of the former Union of Soviet Socialist Republics' Institute of Geological Sciences introduced in 1965 [9], to divide geomorphic objects. On the map, surfaces of the same origin are shown by background color and separated by boundary lines. Dotted and dashed lines represent the material composition of surfaces. Proportional and out-of-scale symbols represent morphological-dynamic factors such as tectonic faults or alluvial flows.

GEOMORPHOLOGICAL CHARACTERISTICS OF THE SOUTHWEST COASTAL REGION OF VIETNAM

Overview of the geomorphology of the Southwest East Vietnam Sea

The topography of the Southwest marine area has a hierarchical nature, as seen in the area with a depth of over 50 m in the seabed on the east coast of the Gulf of Thailand to an altitude of 565 m on the top of the pagoda, in the Ham Ninh Mountain range, Phu Quoc (Figure 1).

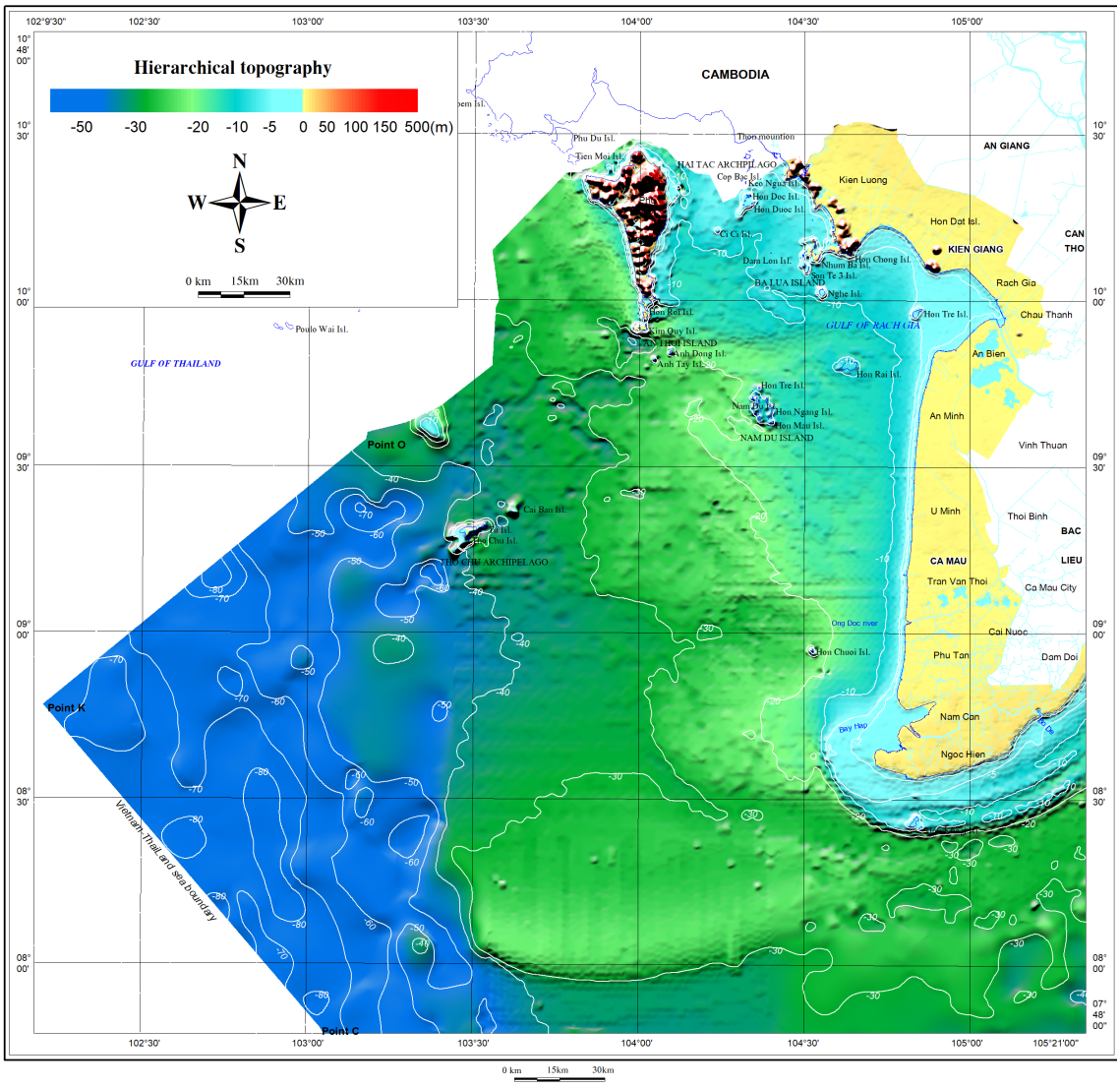


Figure 1. Geomorphology of the SW waters of Vietnam

Coastal continents and islands

Vietnam National Park has a coastline of about 450 km. The continental coastal topography is a low plain, strongly dissected by many estuaries, with no residual hills and mountains. The area is an accretionary part of the coast, and the speed to the sea is about 10–15 m/year. From Cape Ca Mau to Rach Gia, the beach runs Northeast Southwest. From Ca Mau cape to Rach Gia, the coast runs in the direction of the meridian with the lowest curvature; the coastal continent is a low, flat plain. The shoreline from Cai Nuoc to An Bien is very straight; the bending coefficient is 0.8, and accumulation activities bring the coastline to the sea at a speed of 5–10 m/year. From Rach Gia to the Vietnam-Cambodia border, the coast runs Northwest-Southeast. The shoreline from Rach Gia to the western tip of Cay Duong bay has an average bending coefficient of 0.5, with a moderate and weak accretion activity; in some places, erosion occurs, such as Chau Thanh and Nui Dat cape. The shoreline from the west of Cay Duong bay to the border, the winding coastline, alternating with sea-protruding capes composed of eroded

bedrock, are beaches with moderate and weak accumulation rates.

The morphology of the islands is quite complicated, the hierarchical properties are apparent, and the levels can be distinguished: 0–6 m, 10–15 m, 20–25 m, 30–50 m, 50–150 m, and 150–500 m (Figure 1). In Phu Quoc island, most of the area is mountainous terrain. Many places have a monoclinic form created by erosion, exposing the sedimentary basement rocks of the early Cretaceous (K_1pq) Phu Quoc formation. They are strongly affected by exogenous processes, especially human activities, such as leveling and construction of urban areas, exploitation of forests and construction materials, renovating beaches to welcome tourists, etc.

Bottom of the sea

The topography of the seabed is quite complex, different between the Eastern and Western areas of Ca Mau cape.

The topography of the seabed East of Ca Mau cape can be divided into three steps: Steps at a depth of 0–10 m have a relatively flat and gentle surface, especially in part near Hon Khoai island there are arc-shaped underground dunes located at a depth of about 5 m; Steps at a depth of 10–20 m, inclined to the south; Steps at depths greater than 20 m with a complex convex surface.

The bottom topography of the Western area of Ca Mau cape has a distinct hierarchical nature that can be divided into two steps: Step at a depth of 0–15 m; the surface is quite gentle and flat. The step is at a depth of 15-(-40) m; the surface is quite complicated, clearly differentiated in depth, rough and convex, and there are ancient riverbeds and ancient shorelines.

Surfaces of the equivalent origin

Based on the principle of origin, it is possible to divide the Southwest Sea of Vietnam into 32 surface types of identical origin as follows (Figure 2).

Surfaces of the equivalent origin in coastal continents and islands

Group of surfaces of synthetic abrasive origin

Synthetic erosion-accumulation surface, altitude 150–500 m, undivided Quaternary age (pdQ)

This surface covers the tops and slopes of mountains and mountain ranges in the Phu Quoc island district, with an area of about 23 km^2. The bedrock that makes up this surface is the Early Cretaceous sediments of the Phu Quoc Formation (K_1pq), composed of gritty sandstone containing white pebbles layered diagonally and granular, gritty, gray sandstone. The morphology of the slope is elongated; the longitudinal profile is diverse and concave. The gradient is from 5–40^o, and the average height is 150–500 m. Ham Ninh Mountain range with peaks of different heights: Pagoda at 565 m high, Vo Quai - 478 m, Chop Chai - 283 m, Cay Khe - 203 m, Ong Dieu - 162 m, and Ham Ninh - 376 m; Duong Dong Mountain range with peaks: Dien Tien at 207 m high, Suoi Da at 222 m, etc.

The process of general erosion with the role of flood sedimentation predominates. The flow rate drops suddenly when the flood flows from the mountain slopes to the foothills or from the mountains to the low plains, causing the sediment to be deposited very quickly, forming a detrital cone. The accumulation process creates a characteristic conical or fan-shaped detrital cone due to the temporary flow in the flood season.

The detrital cone comprises two types of sediments, the accumulative boulder sediments, and the accumulative clay deposits. Sediment has a different grain size, from coarse to fine, poor selectivity and roundness, and a gradual decrease in flow rate:

Top part: pebbles, medium-grained pebbles, sometimes coarse-grained, poorly rounded, low selectivity, unclear layering.

Sometimes a single oblique sublayer is encountered with an inclination angle of 10 to 150 downstream.

The middle part: small-grained pebbles and sandy gravel belonging to the bed facies of the proluvia. Selectivity and rounding are better than alluvia-type oblique layering, and organic remnants are almost absent.

Bottom part: clay-clay with poor selectivity mixed with many sand mixtures. This section contains many plants remains.

The erosion, transportation, and accumulation process by temporary flows on the slope's surface create an eroding topography with characteristic sedimentary formations. The place of appearance is usually not far from the bedrock, so the composition is similar to that of the remnant facies and weathered crust, but the sediment has a typical overlapping and divergent structure.

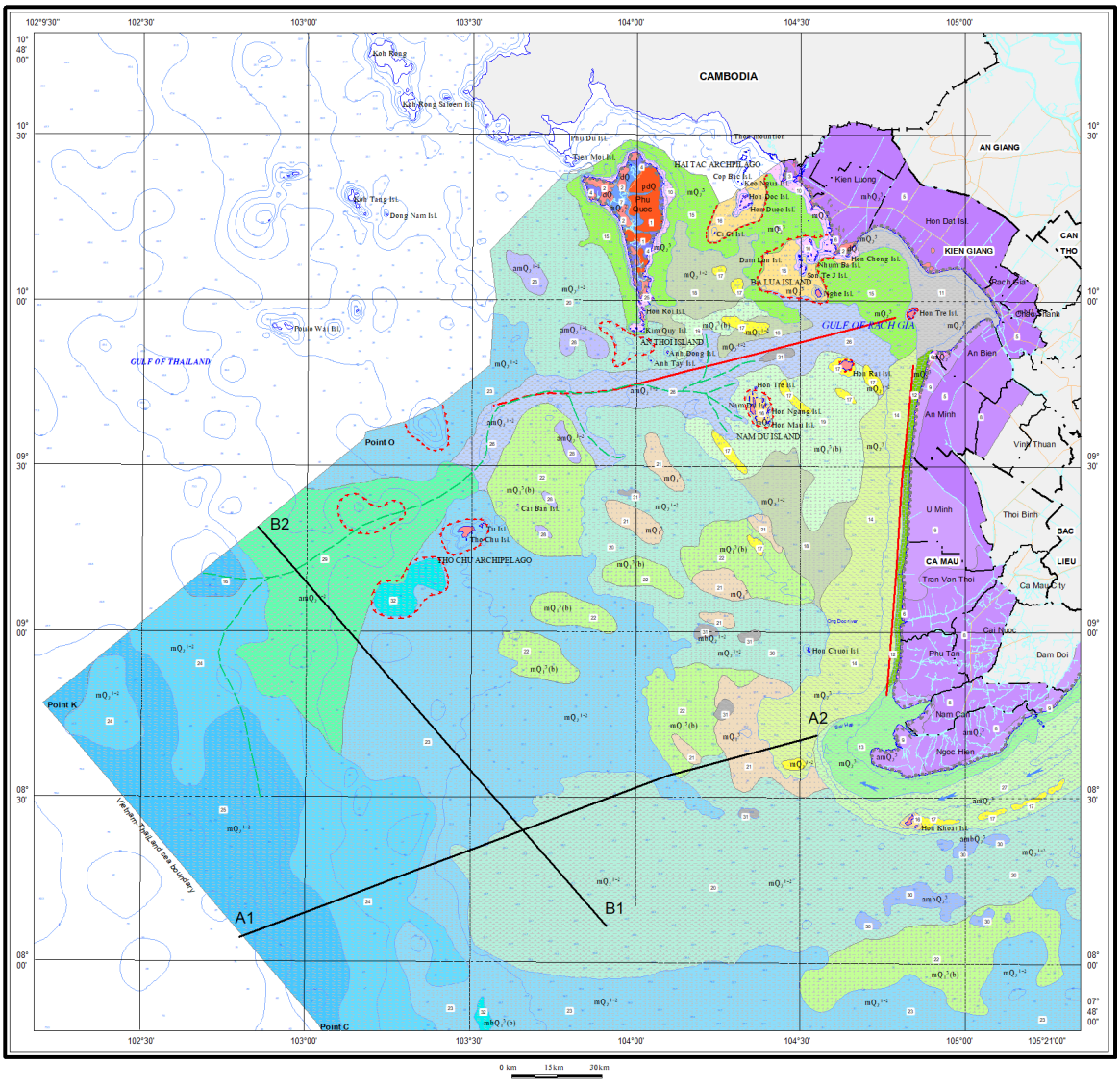
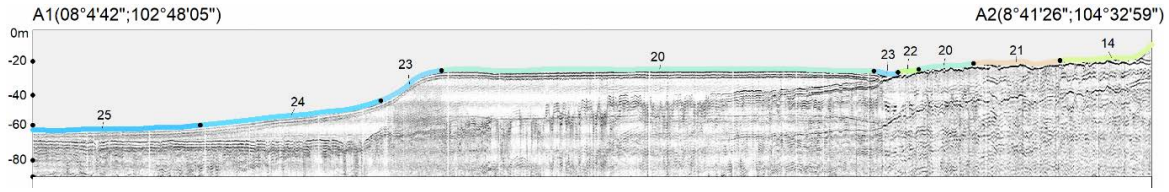
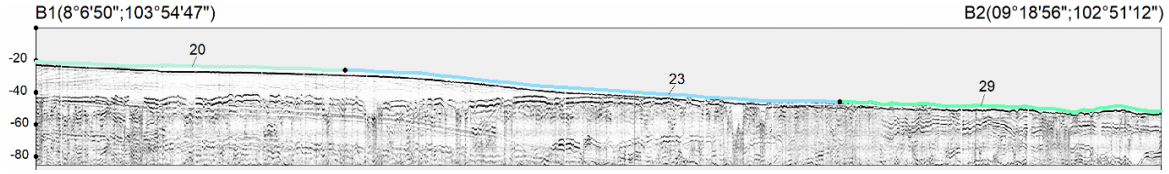


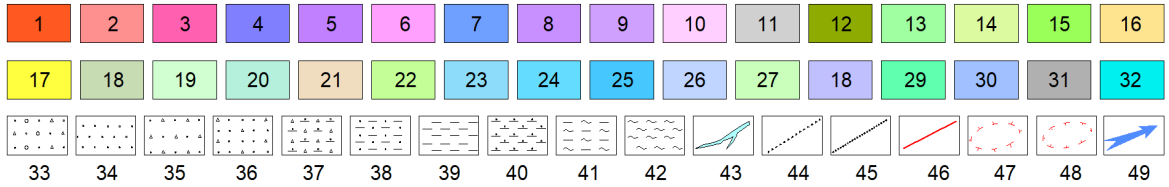
Figure 2. Geological map of the SW waters of Vietnam



Geomorphological - seismological cross-section A1A2



Geomorphological - seismological cross-section B1B2



EXPLANATION:

I. GEOMORPHOLOGY OF COASTAL CONTINENT AND ISLANDS

Synthetic abrasive source surface group

1- Synthetic erosion-accumulation surface (proluvial-deluvial), undivided Quaternary age, 150–500 m altitude, composed of continental sedimentary rocks and loose sediments; 2- Synthetic erosion-accumulation (deluvial) surface, undivided Quaternary period, 15–250 m altitude, consisting of terrigenous or eruptive rocks and loose sediments; 3- Erosion washed topography karst, late Holocene age, composed of limestone.

Surface group of marine origin

4- Sea accumulating surface, late Holocene age, 2–5 m high, composed mainly of powdery sand and seashells; 5- Swallow Sea accretion surface, late Holocene age, 1–1.5 m elevation. Ingredients from clay powder, less plant humus; 6- Slightly inclined marine accretion surface, late Holocene age, 0.5–1.0 m elevation.

Group of the mixed river and sea surface

7- Sea surface accumulation, late Holocene age, elevation 2.5–5 m, mainly composed of powder and clay; 8- Sea surface accumulation, late Holocene age, 1–3 m high, primarily consisting of mud, sand, and clay.

Surface group of biological origin - sea - river

9- Sea surface accumulating marine life, late Holocene age, 0.5–1.5 m altitude, mainly composed of clay powder and mud containing many plant relics.

II. BENEFITS OF THE SEA

Surface group of marine origin

10- Abrasive-accumulative surface caused by waves, late Holocene age, 0–5 m deep, composed mainly of sand and powder, containing many marine life; 11- Tide accumulating surface, late Holocene age, 0–5 m deep, composed mainly of mud; 12- Mixed surface of tidal and coastal currents, late Holocene age, depth of 0–5 m, mainly composed of mud and sand; 13- Mixed tidal wave accumulation surface, late Holocene age,

10–20 m depth, composition of sand, clay powder, containing laterite, little sand; 14- The surface of coastal sea accumulation, late Holocene age, depth of 5–20 m, mainly composed of clay mud; 15- The surface of coastal sea accumulation, late Holocene age, 5–10 m deep, mainly composed of sand, mud, gravel; 16- Abrasive accumulation surface of the sea, late Holocene age, surrounded by islands or reefs, 5–10 m deep, composed of coarse materials such as gravel, sand; 17- Accumulation of sea surface, early-middle Holocene age, 15–25 m depth, developed on ancient val system, mainly composed of sand, gravel, silt containing many marine relics; 18- The surface of shallow coastal sea accumulation, early-middle Holocene age, 10–20 m depth, composed of shallow marine facies mud; 19- The surface of coastal shallow sea accumulation, late Pleistocene age, late part, ancient tidal flat form, 10–20 m deep, composed of sand, gravel, mud; 20- Old sea accretion surface, early-middle Holocene age, depth 25–30, composed of sand and alluvial facies, tidal flats; 21- The ancient coastal sea accretion surface, late Pleistocene age, late part, 20–30 m deep, mainly composed of sand and mud; 22- Sea surface accumulation, late Pleistocene age, late part, 25–35 m deep, mainly composed of clay, mud, sand, gravel, gravel containing laterite, shallow marine facies; 23- Sea accumulating surface, early-middle Holocene age, 30–50 m depth, mainly composed of shallow marine facies; 24- Short marine accretion surface, early-middle Holocene age, 50–70 m depth, composed of shallow marine facies; 25- Short marine accretion concave surface, early-middle Holocene age, distributed at a depth of 80 m, composed of shallow marine facies.

Surface group of marine origin

26- The low-lying surface accumulates ancient river valleys, the early-middle Holocene, the depth is 10–40 m, and the main composition is alluvial mud and sand; 27- River-sea accumulation surface, late Holocene age, depth of 5–20 m, mainly composed of sand, clay, and brown mud; 28- The surface of river-sea accumulation, early - middle Holocene age, depth of 20–30 m, mainly composed of sand facies, sediments of ancient shoreline; 29- The surface of sea and river accumulation, early-middle Holocene age, depth of 40–60 m, mainly composed of sand and silt containing plant humus in the delta.

Group of accretionary surface swamp sea

30- River-sea-swamp accumulation surface, late Holocene age, 20–30 m deep, composed of muddy clay and fine sand; 31- The accumulated low-lying surface of marine marsh origin, early-middle Holocene age, depth of 20–30 m, composed mainly of marsh facies; 32- Swallow-accumulated low-lying surface, late Pleistocene age, 50–60 m deep, mainly composed of silty clay.

III. OTHER LABELS

The petrographic composition

33- Gravels and pebbles; 34- Sand; 35- Sand grit deposits; 36- Sand; 37- Gravel, sand, and mud; 38- Sand and mud; 39- Mud; 40- Sandy mud; 41- Muddy clay deposits; 42- Clay;

Topographical elements

43- Rivers and streams; 44- Coastal erosion; 45- Coastal accretion; 46- Tectonic faults shown on topography; 47- Local uplifting; 48- Local subsidence; 49- Alluvial flow

Synthetic erosion-accumulation surface, elevation 15–250 m, undivided Quaternary age (dQ)

This surface is scattered on islands, archipelagos, and the coastal strip. The bedrock that makes up the surface has a relatively diverse composition. The hills in Phu Quoc island are composed of early Cretaceous sedimentary rocks, the Phu Quoc Formation (K_1pq) distributed in the West and South of the island. The hills along the coast from Rach Gia to Kien Luong consist of sedimentary or volcanic rocks belonging to the formations $D_{2-3}hh$, K_2dc, K_2nc, T_2anc^1, T_2anc^2, and T_2anc^3. This surface also occurs in Tho Chu, Hon Nghe, Hon Tre, Hon Rat, and Nam Du islands. In the coastal strip, this surface is scattered on the shoreline from

Rach Gia to Kien Luong, which are gentle hills with a height of a few dozen to over 150 m, such as Bao Sen hill - 73 m, Nhon hill - 181 m, Dong hill - 125 m, Soa hill - 78 m, Ong Cop (Tiger) hill 101 m, and Rach Dung hill 207 m. On the archipelagos are small-scale low hills such as the Ba Lua archipelago consisting of 34 islands (about 70 km^2); the Hai Tac archipelago consists of 24 islands, with an altitude is less than 100 m, the largest is Hon Tre (1,100 ha); the Nam Du archipelago consists of 21 islands, the largest is Nam Du island with an area of 4.4 km^2, a height of 309 m; An Thoi archipelago has more than 16 islands, covering an area of 5.7 km; Tho Chu archipelago consists of 8 islands, of which Hon Nhan island has an area of about 2 km, the highest point is 40 m (the A1 base point, coordinates $9^o15'$N-$103^o27'$E of the baseline of Vietnam).

Physical and chemical weathering, combined with surface erosion, slope, and cavitation processes of the flow, temporarily lowered the heights of hills and formed slopes and cones. detrital cone) is composed of sediments with low selectivity and poor roundness, mechanical differentiation is apparent: at the top is coarse debris, and at the bottom of the slope are finer components such as grit, sand, and clay.

The surface of karst eroding driftwood, late Holocene age

Figure 3. Topography of residual karst (upper, left), seawater marks at Cay Ot mountain (lower, left), Cave Tien (lower, right) photos taken in North Binh An commune[1]

[1]Vu Van Phai, Nguyen Hieu, Vu Tuan Anh, Duong Tuan Ngoc, 2008. Establishing a geomorphological map of the Southwest coast of Vietnam from 30–100 m. Component project: Investigate geological characteristics, geodynamics, mineral geology, environmental geology and forecast geological hazards in Vietnam's waters from 30–100 m of water at the rate of 1:500,000. *Marine Geology and Mineral Center, General Department of Geology and Minerals of Vietnam.*

The surface is composed of limestone, scattered along the coast of Ha Tien from Hon Da Dung to close to the Vietnam-Cambodia border, most concentrated in the area between Bai Chit and Hon Chong. This surface is the remnant karst topography of the Ha Tien Formation ($P_{1-2}ht$), which lies unconformably over the Hon Chong formation observed in Hang Chua. The karst process is typical of the dissolution mechanism by surface water, groundwater, and the mechanical destruction mechanism of gravity landslides on the slopes. At the foot of many limestone blocks, there are also traces of sea level in different periods with three noticeable lines: the modern waterline has an altitude of about 0.5–0.7 meters above the high tide level; the 2nd line is at the height of 1.5–3.0 meters, and the third is at the height of 4.0–4.5 meters (Figure 3). These blocks all have steep walls and are almost independent of each other. They are concentrated in the Kien Luong - Ba Hon town area, such as Com mountain, Ba Hon mountain, Cay Xoai mountain, Bai Voi mountain, Khoe La mountain, Hang Cay Ot mountain, Hang Tien mountain, etc. At Mount Com, Saurin (ref?) found marine shell fossils and dated C^{14} radioactivity to over 4,000 years ago.

Group of surfaces of marine origin

Sea accretion surface, 2–5 m high, late Holocene age

This surface is mainly composed of sand, powder, and shells, distributed in a narrow strip running along the current coastline and extending to the south of Phu Quoc island, occupying an area of about 108 km^2. The formation time of the surface can be related to the late Holocene early sea retreat (mQ_2^3). The composition of the surface is medium to fine-grained sand mixed with a small amount of silty clay and shells; the sediment is white or yellow gray. The surface is currently being used as a living area for residents. Human activities strongly influence topography.

Sea-marsh accumulation surface, 1–1.5 m high, late Holocene age

The sloping surface has an absolute height ranging from 1–1.5 m, composed of clay powder, little humus, and poorly decomposed tree trunks of brown, mahogany, and dark gray color (mbQ_2^3), with extended distribution along the coastal strip of Thoi Binh, An Ninh, An Bien, Chau Thanh districts, to Rach Gia, the whole Hon Dat, and Kien Luong Districts, Kien Giang province, with an area of about 3,000 km^2. A surface is a place for agricultural cultivation, which has been transformed to build residential areas. This surface formation is related to the late Holocene Depression.

The surface of the sea accumulation is gently inclined, 0.5–1.0 m high, late Holocene age

These are tidal flats of the late Holocene age, distributed in narrow bands running along the shoreline from Ca Mau cape to Ha Tien; the most extensive beach width, up to 2.5 km, is usually located in the estuary or protruding nose, often affected by tides. The tidal regime here belongs to the rare diurnal type. The maximum tidal magnitude is from 1.1 m to 1.3 m. The composition of the landfill surface varies depending on the source. The shoreline structure of the area from Hon Dat to Hon Chong is clayish silt and dark gray sand. The composition of the beach surface varies depending on the source, in which the area from Hon Dat to Hon Chong is clay, silt, and dark gray sand.

Group of surfaces of the mixed sea and river origin

The surface of sea and river accumulation, 2.5–5 m high, late Holocene age

The surface of sea and river accumulation of late Holocene age (amQ_2^3), distributed in Phu Quoc island, is relatively flat; the elevation ranges from 2.5–5 m, and the area is about 140 km^2, mainly composed of powder and clay.

The surface of sea and river accumulation, 1–3 m high, late Holocene age

This topography is a late Holocene river and sea accumulation plain, at an altitude of 1–3 m, distributed over an area of about 2,500 km^2, mainly concentrated in the coastal district of Ca Mau province and a part of

about 500 km^2 in An Bien district, An Ninh, Vinh Thuan of Kien Giang province. The plain is divided by a dense network of rivers. The sediment composition is mainly mud, clay, yellowish gray silt, ash gray sandy clay contaminated with alum, and salt containing Foraminifera relics. Sediment thickness varies from 2–4 m and tends to increase to the South-Southwest.

Group of surfaces of biological origin - sea - river

Surface accretion marine - organisms, 0.5–1.5 m high, late Holocene age

The surface of marine-organism accumulation developed from the late Holocene period (mQ_2^3), distributed at an altitude of 0.5–1.5 m into a large area in the low-lying swampy terrain of U Minh Ha and a narrow strip in the coastal districts in Ca Mau province, having an area of over 1,000 km^2. Sediment composition is mainly silty clay and mud, containing many plant relics. In the area in U Minh Ha is mahogany brown peat containing plant humus and poorly decomposed tree trunks. Here there is an absolute age value of C^{14} taken from the trunk at a depth of 2.0 m for 902 ± 64 years. Sediment thickness is 2–4 m.

Surfaces of the equivalent origin on the seafloor

Surface group of marine origin

Surface wear-accumulation due to waves, depth 0–5 m, late Holocene age (mQ_2^3)

This surface is distributed within a water depth of 5 m around Phu Quoc island, islets of Ba Lua archipelago, and along the shoreline from Hon Dat to Ha Tien. The role of wave dynamics predominates for the abrasive activity of exposed solid rock formations on the coast and the accumulation of loose sediments of sand, silt, and powder, containing many marine carcasses at the junction between rocky islands and shore. The bedrock exposed on the coast and islands consists of sandstone, clayish shale, and siliceous schist of the Hon Chong Formation (in the Hon Chong port area, at the foot of Rach Dung mountain), and volcanic rocks interspersed with thin layers of siltstone, shale, and schist of the Hon Ngang Formation is scattered from Hon Chong cape to the Vietnam - Cambodia border and around the islands. Because the protrusions are low, the abrasive walls are not high, so the abrasive platforms are composed of boulders and pebbles of various sizes and with poor selective grinding.

Creating a valve system on the beaches is not typical because the wave activity here is less intense than on the Central and Northern coasts. The beach profile usually has a gentle wavy shape, and the upper part often has a steeper slope, corresponding to the distribution of coarser materials. The shape of the beach profile also changes depending on the wave mode: with a wave height of 0.5–1 m, it is enough to provide wave energy from 0.05–0.14 kg/cm^2 and can disturb sediments and beach terrain. Accordingly, this terrain can be classified as unstable.

Tidal accumulation surface, depth 0–5 m, late Holocene age (mQ_2^3)

This species is distributed in the area of Rach Gia bay and is a strip extending from Hon Chong to An Bien and surrounding Hon Tre island, limiting the outer limit to a depth of 5 m. In terms of dynamics, this surface is formed in a closed bay; the impact of East, Northeast, and Northwest waves is almost absent, while Southwest waves are islanded along the coast, such as Hon Nghe, Hon Tre, and Hon Rai shielded. Materials from within the bank and from Rach Gia river are retained, deposited, and distributed fairly evenly on the beach surface and redistributed due to the process of high tide and low tide. Areas such as An Bien - Rach Soi, North Rach Gia, and Northeastern Hon Chong develop mud flats with a thickness of 0.2–1.2 m, creating favorable conditions for the development of saltwater forests. At the edge are cork, black tiger, mangrove, and mam trees forming a barrier against the waves that affect the shore and collect alluvium from the continent to raise the surface of the beach gradually.

Thus, in surface formation, tides transport materials, and mangroves play a blocking role, creating a suitable environment for coastal sediment deposition. The typical landforms related to the directional tidal activity are not as common as in the Do Son - Quang Yen area, but we can encounter a ridge extending in front of the Rach Soi estuary with a length of up to 400–500 m wide by hundreds of meters. The bar has the form of an ellipse extending parallel to the axis of the tidal ellipse in the estuary, i.e., in the same direction as the direction of tidal flow.

The surface of mixed tidal and inshore currents, depth 0–5 m, late Holocene age (mQ_2^3)

Distributed in a narrow strip running parallel to the shoreline, extending from Thuan Hoa, An Ninh, Kien Giang to Cai Doi town Vam Phu Tan, Ca Mau in the depth of 0–5 m. The average surface width is 1–2 km. The terrain is relatively flat; the slope ranges from 0.0080–0.020. The composition of the surface is mainly mud, and silt, sometimes mixed with plant humus. The system of coastal saltwater forests is well developed, creating favorable conditions for the growth of the height and width of the tidal marsh. The average displacement of the shoreline in this area is not large, only about 10–15 m/year. In recent years, the displacement speed has slowed down and even tended to shift from accretion to erosion. The material supply is mainly from the mainland through the canal system and partly brought down from the North by longshore wave currents. The impact of wave currents is only strong in the summer months, with wave heights of 0.9–1.0 m, sometimes up to 2.5–3 m. The East and Northeast waves hardly affect the area. The daily tide regime and small tidal magnitude (average 1.0 m) have created a favorable dynamic environment for the dominant accumulation process.

Sea accretion surface, depth 0–5 m, late Holocene age (mQ_2^3)

The surface is classified as modern/late Holocene (mQ_2^3). This surface is limited to a depth of 0–5 m, including the Eastern shoreline of the study area and Ca Mau cape, with an area of more than 900 km^2. The width of the surface is extended from 4 km on the Eastern shore and gradually increases to 16–18 km at Cape Ca Mau. The terrain has a very slight inclination and is almost horizontal. The surface is mainly composed of fine-grained sediments of gray-brown clayish mud. Inside, there are generations of thriving mangrove forests. The source of materials for the accumulation process here is mainly due to the longshore currents brought from the mouth of the Mekong river around the cape of Ca Mau and then to the North. Another part is taken by the tide from the East Vietnam Sea through the Bo De river to the mouth of the Cua Lon river (the Bo De - Cua Lon river is a saline river).

Sea accretion surface, depth 5–20 m, late Holocene age (mQ_2^3)

The surface of late Holocene accretion is distributed in a strip 150 km long, 15 km wide at a depth of 5–20 m, with an area of 2,600 km^2 in the coastal regions of An Minh, U Minh, Tran Van Thoi, and Phu Tan. The sediments that make up this topographical surface are mainly clayish mud. Under the primary influence of the aggregate flow, alluvium from the Mekong river has moved around Ca Mau cape, forming an accumulation surface.

The surface of coastal sea accumulation, late Holocene age (mQ_2^3), distributed from a depth of 5–10 m, is composed mainly of sand, mud, and gravel

This surface is distributed from 5–10 m in 2 areas. The first area extends continuously from around Phu Quoc island, extending to the outside of Hon Ci Ci, Hai Tac archipelago, Dam Lon island, and Ba Lua archipelago, with an area of about 1,500 km^2. The second area is from Hon Nghe, Hon Nhum Ba, and Hon Chuong to Rach Gia bay, with an area of approximately 700 km^2. The topographical surface is slightly inclined from the shore to the sea, mainly composed of mud and gravel. The driving force affecting the bottom topography is the dominant tidal current. The surface has been created from the late Holocene to the present day.

Surface of marine erosion-accumulation, depth 5–10 m, late Holocene age (mQ_2^3), surrounded by islands or shoals

The surface is composed of coarse materials such as grit and sand, with limited distribution around rock boulders and shoals of Hai Tac archipelago with an area of about 220 km^2; Ba Lua archipelago with an area of around 263 km^2 and Nam Du archipelago with an area of approximately 50 km^2. The surface has been developed since the late Holocene period.

Sea accretion surface, depth 15–25 m, early-middle Holocene age (mQ_2^{1-2}), developed on ancient valve system

Surface accumulation, with limited distribution as spots, began to appear on the seabed of the Hon Khoai area, Cape Ca Mau, and then moved to the Northwest through the Nam Du archipelago to the Ba Lua archipelago. This surface is dated from the early-middle Holocene (mQ_2^{1-2}), developed on ancient valves under the influence of waves or a combination of waves and combined currents (the surface is distributed on the sea floor in the Hon Khoai area) in the depth of 15–25 m. The structure of the surface is mainly sand, grit, and silt containing many marine remains.

Surface accumulating sea depth from 10–20 m, early-middle Holocene age (mQ_2^{1-2})

This accretion surface has an early-middle Holocene age (mQ_2^{1-2}) limited distribution in the area: in the central depression in the iso-depth 10 m to 13–15 m deep, the surface is relatively flat, limited to the West Phu Quoc island, An Thoi archipelago to the South, Ba Luan archipelago to the Northeast and Hai Tac archipelago to the North, with an area of about 670 km^2. In the South of the Nam Du archipelago, this surface is distributed at a depth of 15–20 m, with an area of about 830 km^2. The tidal currents dominate and carry sediments from the coastal zone, especially from the river, to re-accumulate, so the surface is mainly shallow marine facies.

The surface of shallow sea accumulation along the shore, depth of 10–20 m, late Pleistocene age of the late part (mQ_1^3(b)), ancient tidal flat form

The surface of this type is located adjacent to the surface of the early-middle Holocene age above mentioned; they are limited in distribution in the An Thoi archipelago at a depth of 10–15 m with an area of about 196 km^2; at the seabed area of Nam Du archipelago at a depth of 15–20 m, an area of approximately 1,600 km^2. The surface formed from the late Pleistocene of the late part (mQ_1^3(*b*)), the tidal current prevailed and transported the sediment to redistribution; the deposit was mainly sand and gravel.

Surface of ancient tidal flats, depth of 20–30 m, early-middle Holocene age (mQ_2^{1-2})

The surface of ancient tidal flats is distributed in the southwest of Phu Quoc island from a depth of 20 m to 30 m with an area of about 2,000 km^2. This surface is also distributed in the seabed Southwest of Nam Du archipelago, extending down to Hon Chuoi, in an area of about 3,200 km^2 at a depth of 25–30 m. The accretion surface has an early-middle Holocene age (mQ_2^{1-2}), which is weakly affected by tidal dynamics and is composed of sandy mud and intertidal facies.

The surface of ancient coastal sea accumulation, depth of 20–30 m, middle-late Pleistocene age (mQ_1^{2-3})

The surface of ancient coastal sea accumulation is limited and distributed in the seabed west of Bay Hap estuary and exposed on the surface of ancient intertidal sea accumulation (adjacent topographic unit above), distributed from depth 20–30 m. The surface is mainly affected by tidal currents, primarily composed of sand and mud.

The surface of sea accumulation, depth of 25–35 m, late Pleistocene age (mQ_1^3(b))

The surface of sea accumulation is distributed in 2 terrain levels with depths of 25–30 m and 30–35 m. The upper step appears in the South of Nam Du archipelago at a depth of about 20–30 m, including three areas stretching about 130 km, an area of about 1,600 km^2. The lower step appears at a depth of

30–35 m, with two regions. The first area is about 5,50 km^2, located more than 30 km from the Tho Chu archipelago to the Southeast. The second area is about 32 km from Hon Tre island. South, the area is about 1,500 km^2. The surface is of marine origin, evolving from the late Pleistocene of the Late Part ($mQ_1^3(b)$). In the current period, the surface is mainly affected by the dynamics of the aggregate flow, with the tendency of accumulation predominating. The surface structure is mainly clay, mud, sand, grit, gravel containing laterite, and shallow marine facies.

The surface of marine accumulation, depth of 30–50 m, early-middle Holocene age (mQ_2^{1-2}), composed mainly of shallow marine facies clay

The accumulation surface is distributed at a depth of 30–50 m over a sea area of about 12,660 km^2, extending for about 400 km, starting from Tho Chu island and extending down to Ca Mau Cape. The surface formed in the early-mid Holocene marine environment (mQ_2^{1-2}). Currently, the terrain belongs to the propagating wave zone; the relatively quiet dynamic environment mainly comprises synthetic currents. The surface is primarily composed of shallow sea facies and clayish mud.

Shallow sea accretion surface, depth 50–70 m, early-middle Holocene age (mQ_2^{1-2})

Surface development in shallow coastal marine environments from the early-middle Holocene (mQ_2^{1-2}). The surface is in the southwest of the study area, over 80 km from Tho Chu island to the southwest in an area of about 5,500 km^2 wide, about 170 km long, about 12–40 km wide, distributed from a depth of 50–70 m. In the current period, the surface is located in the impact zone of the aggregate flow. The sediment tends to deposit to form the accumulating surface, mainly composed of shallow sea facies clay mud.

The low-lying surface of shallow sea accumulation, 80 m depth, early-middle Holocene age (mQ_2^{1-2}) is composed of shallow marine facies clay

The low-lying surface of the shallow sea is distributed in the depth of 70–80 m, in the sea about 150 km long, 15–40 km wide, and over 4,000 km^2. Surface accretion evolved from the early-middle Holocene (mQ_2^{1-2}) to the present. The surface is mainly affected by currents close to the bottom with the tendency to accumulate. The sediments are primarily shallow marine facies.

Surface group of the river and sea origin

The surface of ancient river valley accumulation, depth 10–40 m, early-middle Holocene age (am Q_2^{1-2})

The surface has a low-lying form, the remains of ancient river valleys of the early-middle Holocene age (amQ_2^{1-2}) appearing at a depth of 10–40 m, an area of about 2,500 km^2. The surface is mainly composed of sandy alluvial sediments. They form a strip about 150 km long, with an average width of 15 km, extending from the North of Tho Chu archipelago in the Northeast direction up to An Thoi archipelago, Nam Du archipelago, and Rai island and ending at 10 m deep water in Rach Gia bay.

The surface of river-sea accumulation, depth of 5–20 m, late Holocene age (amQ_2^3)

The surface of river-sea accumulation of late Holocene age (amQ_2^3), distributed in the south of Ca Mau cape, at a depth of 5–20 m, extending for about 100 km over an area of roughly 1,400 km^2. To the West, the surface tends to narrow in the Southern region of Bo De estuary, about 30 km wide and ending at the bottom 5 m deep in front of Bay Hap river mouth. This surface reflects the process of sediment dispersion and accumulation from the Mekong river system with the dominant tidal flow regime when reaching the pre-delta zone. The surface structure is mainly sand, clay, and brown mud.

The surface of river-sea accumulation, depth of 20–30 m, early-middle Holocene age (amQ_2^{1-2})

This surface is formed on an early Holocene - middle shoreline (amQ_2^{1-2}). The

surface is mainly composed of gravel and sand from the ancient shoreline. In the studied sea area, the surface is distributed at a depth of 20–30 m, with two areas in the southwest of Phu Quoc island: the first area is about 30 km from Phu Quoc island to the Southwest, with an area of approximately 110 km^2; The second area is about 15 km southwest of Phu Quoc island with an area of nearly 120 km^2.

The surface of river-sea accumulation, depth 40–60 m, early-middle Holocene age (amQ_2^{1-2})

Accumulation surface is of marine and river origin, early-middle Holocene age (amQ_2^{1-2}), distributed at a depth of 40–60 m, covering a large area west of Tho Chu Island army, a size of about 3,400 km^2, extending about 100 km in the North-South direction with a width of about 40 km. The surface structure is primarily sand and silt containing plant humus of deltaic facies. At present, the surface is mainly affected by the synthetic flow.

Surface group of marine-swamp accretion origin

The surface of river-sea-swamp accumulation, depth of 20–30 m, late Holocene age ($ambQ_2^3$)

The deposition surface is of river-sea-marsh origin, late Holocene age ($ambQ_2^3$), distributed at a depth of 20–30 m with a limited area, located 6 km to 20 km south of Hon Khoai island. The surface is composed of clayish mud and fine sand.

The low-lying surface accumulation of marine-marsh origin, early-middle Holocene age (mbQ_2^{1-2}), distributed at a depth of 20-30m and composed mainly of marsh facies

Surface distribution is limited and scattered in the west of Hon Chuoi island; the area is about 60 km^2, sea-marsh origin, early - middle Holocene age (mbQ_2^{1-2}), distributed at a depth of 20–30 m, structure mainly by swamp facies.

Low lying surface of the sea - marsh, depth 50–60 m, late Pleistocene age (mbQ_1^3(b))

This surface has a minimal distribution with an area of about 40 km^2 at the bottom 50–60 m deep, composed mainly of clayish mud.

The history of terrain development in the late Pleistocene-Holocene period

The Southwestern waters of Vietnam, the Gulf of Thailand to the straits between the islands of Sumatra, Borneo, and Java belong to the Sunda continental shelf (Sunda Shelf). The activities of glacial and interglacial, along with the lowering and rising of sea levels during the Quaternary period, greatly influenced the topography of the Sunda continental shelf area, including the SW coastal regions of Vietnam [3]. The most significant for the topographic formation of the SWCRVN is the last post-glacial advance (also known as the Flandrian advance) which occurred during the late Pleistocene-Holocene period.

The sea receded globally during the late Pleistocene due to the impact of the last glaciation. Up to about 20 thousand years ago, the water level in the Sunda continental shelf was 100 m to 130 m lower than it is today [11–14]. Most of the area and large islands, such as Sumatra, Java, Borneo, and Bali, are also associated with the Asian continent. The coast at that time was located near the edge of the continental shelf today, about 400 km southeast of Ca Mau cape. Most of the study area is a flat plain; the origin is mainly of river deposition-cavitation and sea accumulation, slightly inclined to the southwest towards the center of the current Gulf of Thailand and the southeast towards the coast at that time. Only in the Northwest, adjacent to Ha Tien, Phu Quoc, and Nam Du areas, some residual hills and mountains rise high on the plain surface. A large tributary of the Mekong river system flows in the Northeast-Southwest direction through the plains between the hills and mountains of Phu Quoc and Nam Du, confluence with the ancient Mekong river at the center of the Gulf of Thailand today. Now, it flows in a northwest-southeast direction to the sea at the northern position near Natuna island.

Around 18-17 thousand years ago, due to the melting of the sea ice, the sea advanced

globally; this advance was called the Last Glacial Advance or the Flandrian Sea. At first, the sea moved very quickly, reaching a speed of 1 m/100 years. Seawater following the ancient river valleys overflowed into the Sunda continental shelf and the SW coastal regions of Vietnam. There were periods on the Sunda continental shelf where the sea advanced suddenly at a speed of 16 m/300 years between 14,400 and 14,100 years ago, the shoreline from a position of 96 m depth to a depth of 80 m compared to today [15]. The sea advanced at varying speeds, sometimes advancing quickly, sometimes slowly, and occasionally stopping entirely for some time, the main reason being related to global and regional climate change during the late Pleistocene-Holocene, thus preserving the ancient river topography as well as leaving many traces of different ancient shorelines on the surface of the sea floor today.

At the beginning of the Holocene, on the Sunda continental shelf, the shoreline was located at a depth of 56 m, here recorded sand and clay deposits containing Foraminifera coastal facies with an absolute age of 11.69 and 11.07 thousand years ago [16]. During the middle Holocene, about 6,000 to 4,500 years ago, the sea advance after the last glacial peak reached its maximum. The coastline at an altitude of 4–5 m penetrated the continent, forming accumulating and abrasive sea shelves along the southwestern plain.

About 4,000-3,000 years ago, the sea level receded from 1.5–3 m, exposing the current coastal plain in the 0–5 m wave zone into a continental regime. In the middle of the late Holocene (2,300-2,000 years), the sea rose again and reached a height of 1.5–2 m, causing the present modern coastal zone to be submerged in the ocean. At this time, high dunes were formed 1.5–5 m along the current coastal line. Then the sea level dropped to the present stage, exposing the plain and developing towards the sea. The process of the delta reaching the sea stopped 500–600 years ago today.

Rising sea levels and human activities have resulted in many coastal erosions. Up to the present stage, climate change and sea level rise, according to monitoring data at Phu Quoc station (1986–2018), is 3.2 mm/year; at Tho Chu station (1995–2018) was 3.1 mm/year [2], increasing coastal erosion. From 2010–2018, the process of erosion and accretion took place alternately on the whole southwest coast. However, compared to the last time, the trend of erosion has increased. Notably, the sea section of An Minh district has a total erosion length of 27.91 km and an area of 222.3 ha, respectively. On the coastline of Tran Van Thoi district, erosion mainly affects a total size of 33.55 km and an area of 241 ha. The coast of Phu Quoc has moderate erosion in two sections of the beach in the Cua Can and Bai Thom areas and weak erosion scattered in some other places.

CONCLUSION

The topography of the southwest coastal regions of Vietnam consists of 32 geomorphological units. The seabed consists of 23 geomorphological units belonging to 3 groups of surfaces of similar origin: (i) sea, (ii) river-sea, and (iii) accumulation of marsh-sea. The coastal mainland and islands have four groups of surfaces of similar origin, including (i) general erosion, (ii) terrain of marine origin, (iii) terrain of the mixed river and sea origin, and (iv) terrain of biological origin-sea-river.

The most significant for forming the surface topography of the SW coastal regions of Vietnam today is the last post-glacial transition that occurred during the late Pleistocene-Holocene period. In the current period, the area's topography is strongly affected by climate change, sea level rise, and human activities, and the coastal regions and islands are accelerating erosion and narrowing the area.

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REFERENCES

[1] Micallef, A., Krastel, S., and Savini, A. (Eds.), 2017. Submarine geomorphology.

Springer. https://doi.org/10.1007/978-3-319-57852-1

[2] Ministry of Natural Resources and Environment, 2020. Climate change scenario. Viet Nam Publishing House of Natural Resources, Environment and Cartography. (in Vietnamese).

[3] Voris, H. K., 2000. Maps of Pleistocene sea levels in Southeast Asia: shorelines, river systems and time durations. *Journal of biogeography*, *27*(5), 1153–1167. https://doi.org/10.1046/j.1365-2699.2000.00489.x

[4] Son, V. T., 2004. Environmental geochemistry of neashore sea from Rach Gia-Vung Tau. *Doctor disertation on Geology*. *VNU University of Science*. (in Vietnamese).

[5] Thuc, H. V., 2002. Characteristics of the material composition and development history of Quaternary sedimentary formations in the coastal waters of southwestern Vietnam. *Doctor disertation on Geology*. *VNU University of Science*. (in Vietnamese).

[6] Ionin, A. S., Kaplin, P. A., and Medvedev, V. S., 1961. Classification of the world coasts (applied for Physiographical atlas of the world). *Tr. okeano-grafich. komissii*., *12*, 94–108. (in Russian).

[7] Leonchev, O. K., 1956. On the issue of classification and mapping of marine geomorphology. *Scientific announcement of the University of Moscow*. (in Russian).

[8] Son, N. T., Huy, D. V., Thanh, T. D., and Cu, N. H., 2010. Morpho-genetic classification of Vietnam coast. *Anthology of Marine Environment and Resources*, *15*, 31–49. (in Vietnamese).

[9] Epstein, X. V., 1965. Design of unified annotations to create geomorphological maps of scale. In *Geomorphological Mapping Methods. Moscow Science Publishing House*. pp. 9–18. (in Russian).

[10] Thorsnes, T., Bjarnadóttir, L. R., Jarna, A., Baeten, N., Scott, G., Guinan, J., Monteys, X., Dove, D., Green, S., Gafeira, J., and Stevenson, A., 2018. National programmes: geomorphological mapping at multiple scales for multiple purposes. In *Submarine geomorphology* (pp. 535–552). *Springer, Cham*. doi: 10.1007/978-3-319-57852-1_28

[11] Son, N. T., and Phung, T., 1979. On the types of sea-coasts of Vietnam. *Collection of Marine Research Works*, *1*(2), 103–113. (in Vietnamese).

[12] Ty, L., Quynh, N., and Canh, T., 1986. Geomorphology of the continental shelf of Indochina and adjacent areas. In *Geology of Cambodia-Laos-Vietnam*. *Science and Technics Publishing House, Hanoi*. pp. 135–145. (in Vietnamese).

[13] Hanebuth, T. J., Stattegger, K., and Bojanowski, A., 2009. Termination of the Last Glacial Maximum sea-level lowstand: The Sunda-Shelf data revisited. *Global and Planetary Change*, *66*(1–2), 76–84. doi: 10.1016/j.gloplacha.2008.03.011

[14] Korotky, A. M., Razjigaeva, N. G., Ganzey, L. A., Volkov, V. G., Grebennikova, T. A., Bazarova, V. B., and Kovalukh, N. N., 1995. Late Pleistocene-Holocene coastal development of islands off Vietnam. *Journal of Southeast Asian Earth Sciences*, *11*(4), 301–308. https://doi.org/10.1016/0743-9547(94)E0016-7

[15] Hanebuth, T., Stattegger, K., and Grootes, P. M., 2000. Rapid flooding of the Sunda Shelf: a late-glacial sea-level record. *Science*, *288*(5468), 1033–1035. doi: 10.1126/science.288.5468.10

[16] Schimanski, A., and Stattegger, K., 2005. Deglacial and Holocene evolution of the Vietnam shelf: stratigraphy, sediments and sea-level change. *Marine Geology*, *214*(4), 365–387. https://doi.org/10.1016/j.margeo.2004.11.001