Coastal plain evolution in southern Hainan Island, China

WANG Ying[1], MARTINI I. Peter[2], ZHU Dakui[1], ZHANG Yongzhan[1] & TANG Wenwu[1]

1. Key Laboratory of Coast & Island Development of Ministry of Education of China, Dept. of Geo & Ocean Sciences, Nanjing University, Nanjing 210093, China;
2. Department of Land Resource Science, University of Guelph, Guelph, ON. Canada (pmartini@uoguelph.ca)

Correspondence should be addressed to Wang Ying (wangying@nju.edu.cn)

Abstract **The coast of southern Hainan Island is characterized by wide sandy embayments, which consist of (i) drowned valleys bounded by steep bedrock hills and only locally receiving sediments, and embayments of various dimensions covered either by (ii) alluvial-deltaic deposits or by (iii) sands of coastal beach ridges/barriers and associated elongated lagoons. During the late Tertiary-Pleistocene the area has experienced isostatic and eustatic movements associated with neotectonics and climatic changes. Such history is recorded in terraces at various altitudes (80, 40, 20 m asl) and sequences of coastal sand ridges/baymouth bars. The Holocene variations in sea level and climate are recorded in the dated coastal ridges, coral reef and beachrock. Conditions suitable for reef development started about 8000 a BP. The GPR profiles also show that the internal structures of the sand ridges have composite nature being formed by several superimposed secondary ridges.**

Keywords: sand barrier system, coral reef, sea level change, southern Hainan Island.

The study area is located in Hainan Island, China between 18°10′4″—20°9′40″N and 108°36′43″—111°2′31″E. The island is separated from mainland China to the north by the 18 km wide Qiongzhou Strait. The island is about 33920 km^2 with a total coastline length of 1528.4 km. It has a central mountainous area with peaks reaching 1876 m asl, surrounded by hills, terraced highlands and coastal lowlands[1].

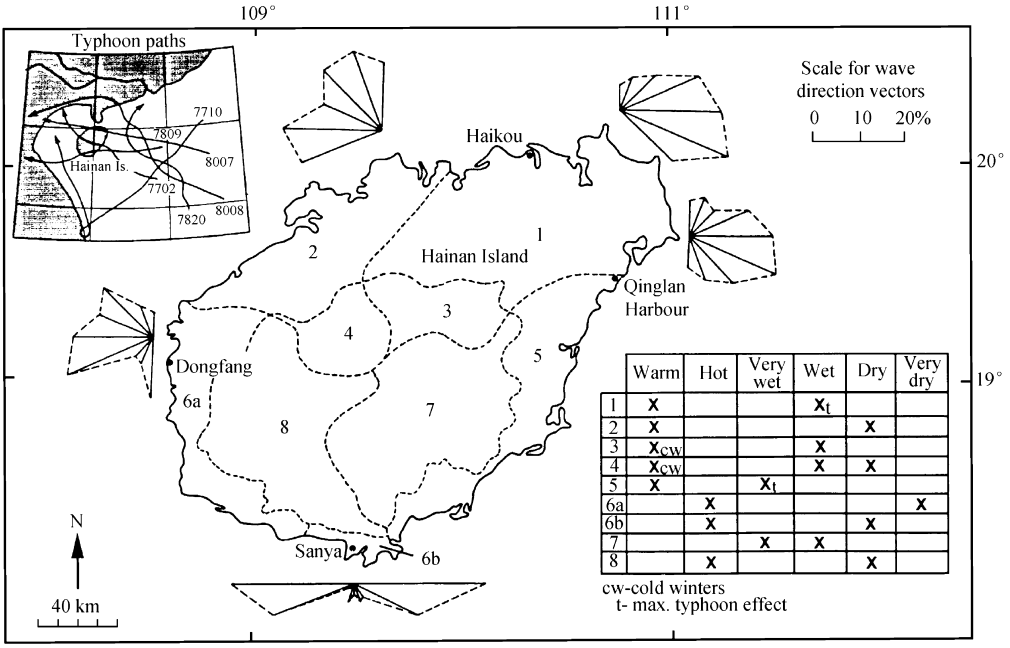
Hainan Island is located on a passive continental margin setting in the northern part of the South China Sea. The island has a complex geological history. It is composed of several terranes accreted during the Paleozoic as they migrated northward from the Australian zone to the Chinese zone. The accretion led to several orogenies, remnants of which constitute the predominantly metamorphic and granitic central mountains and hills. Since Mesozoic times the geological history of the island has developed in unison with mainland China. This has led to repeat Mesozoic emplacement of granite and some rhyolite volcanism, and to the development of the E-W oriented extensional/transtensional basin centered in the Qiongzhou Strait. The northern part of the island has experienced extensive Cenozoic to Holocene basaltic volcanism[2]. During more recent times, the coastal areas of the island have experienced major extensional and transtensional stresses indirectly related to the Himalayan orogeny (transcurrent movements associated with the Red River strike slip fault system) and the distant Philippine plate subduction[1]. Similar to other parts of the world, the island has been affected by major sea level variations due to Pleistocene glaciations[3,4]. The contacts of the various terrenes and other geological zones are recorded in morphotectonic alignments that follow major ancient faults, in part reactivated through the ages. The major ones are oriented NE-SW across the island, E-W oriented ones in the north and south and a NW-SE fault sets that dissect the other trends. The major faults determine, among other things, the overall parallelogram-shape of the island, the major valley direction and the drainage of some of the major rivers, and the localization of promontories and embayments.

Hainan Island has monsoon tropical to subtropical climate with an annual average temperature between 22°C and 26°C. The annual average rainfall is between 1500—2000 mm, but variously distributed with the dryer areas to the west due to orographic effect of the high central mountains (fig. 1)[1]. Oceanographic conditions are characterized by micro- to meso-tides (1—3 m tidal excursions), mostly of the diurnal type except along the southern and southeastern coasts where irregular diurnal tide balances over one month period[5,6]. NE wave prevail during winter, SE and SW waves prevail during summer (fig. 1). Storm waves are usually on the order of 2—3 m, but they can reach up to more than 5 m during typhoons. The strongest waves develop along the east coast and part of the SW coasts. The southern coast and sheltered bays receive the lowest waves. Typhoons are frequent, particularly during summer, and they derive both from the west Pacific Ocean and from the South China Sea. During the past 35 years the southern largest town of Sanya has experienced a total of about 180 typhoons, with wind velocities as high as 40 m/s (Beaufort equivalent 8)[7].

1 Study design

Nanjing University has studied the coastal zone of Hainan Islands for approximately half a century. Considerable amount of information has been obtained both offshore and inshore, through mapping of coastal morphology and sediments, surveying of seismic profiles, analyzing of cores and dating of reefs[8,9]. Recently Ground Penetrating Radar (GPR) has been used to establish the internal structures of the coastal deposits, particularly of coastal sand ridges.

The GPR utilized was a pulse EKKO IV radar system equipped with a 1000 V transmitter and 100 MHz antennas. The instrument transmits to the ground short pulses of high frequency electromagnetic (EM) energy that is refracted and reflected at material discontinuities underground. The receiver monitors the portion of the energy reflected back to the surface against delay time. The delay time of the pulse from transmission to reception is a function of the EM propagation velocity though the substrate material and the depth of the reflectors. By moving the transmitter and receiver along a transect, a profile of the substrate can be recorded showing horizontal distance in meters and vertical two-way time of the EM wave in nanoseconds. The latter can be transformed into depth-meters knowing the velocity of transmission of the EM though the sediments present at the site. Assuming a velocity of 0.1 m/ns, the resolution of the GPR with the 100 MHz antennas is of about 0.25—0.50 m. The depth of penetration of the EM wave depends on the lithological composition of the deposits and their interstitial fluids. It ranges from maximum penetration obtainable in dry sand to no penetration in clay layers or porous material with salty interstrial fluids. The data are recorded and stored digitally, and therefore they can be processed similarly to seismic data by sophisticated processing software. A GPR survey consists of two parts:



	Warm	Hot	Very wet	Wet	Dry	Very dry
1	X			X_t		
2	X				X	
3	X_{cw}			X		
4	X_{cw}			X	X	
5	X		X_t			
6a		X				X
6b		X			X	
7			X	X		
8		X			X	

Fig. 1. Climatic zone and rose diagrams showing frequencies of occurrence of maximum wave height during year. Inset indicates most common paths of typhoons affecting the island.

(i) To calculate the near surface average velocities needed to estimate depth of reflectors, a Common Mid Point (CMP) technique was used at a few characteristic sites. This consists of relatively short (up to 30—50 m) transects where the antennas and transmitter and receiver are progressively moved away from each other in relation to central point in incremental short (5 cm) steps. In this way the central reflectors are the same and their distance from the instrument and the arrival delay time of the reflected wave increase.

(ii) Routinely, a reflection survey was used along pre-established, topographically surveyed transects, keeping the distance between antennas (thus transmitter and receiver) constant (1 m) and shifting their position in 25 cm steps. A standard setting was used with a time window of 512, sampling interval of 800, stacks of 64. The field data were corrected for topographic elevation and processes with automatic gain control (AGC) and various other settings to optimize resolution and lower noise.

2 South coastal zone of Hainan Island

The southern coastal zone of Hainan Island is characterized by terraced bedrock hills backed by high mountains, a relatively narrow sandy coastal plain, a highly indented promontory-and-embayment coastline, and a shallow offshore area.

The mountains and hills are mostly composed of Palaeozoic metamorphic and sedimentary rocks, intruded by Paleozoic and Mesozoic granites. They are dissected by major NE-SW faults, locally indented by E-W and NW-SE trending faults. The lower hills show several well-developed terraces. The highest and smallest terrace is just a notch found at several locations at about 80 m asl. The second terrace is a sloping one that grades from 60m to about 40m elevation. A well-defined terrace, locally with preserved marine deposits occurs at 20 m asl[8,9] (Plate Ⅰ).

The promontories are an extension of the central hills. Their position is dictated by the NE-SW trending fault system, but they are also indented by NW-SE and E-W trending faults. The interplay between these faults and the marine reworking of sediments along the coasts has led to local complex structures. The Luhuitou peninsula is an example of this (Plate Ⅰ). The peninsula consists of the present promontory of the Luhuitou Mt. composed of Mesozoic granite, steep sided, with the 20-m isobath hugging close to land (less than 10 m from the shoreline). This is joined to the main island (Nanbian Mt.) by a lowland formed by a series of sandy bars (tombolos), lagoons and reefal platforms. The bedrock of the Nanbian Mt. is bedded Paleozoic sandstone, conglomerates and carbonates. Characteristic erosional coastal alcoves are found at about 15—20 m elevation along the eastern side of the Luhuitou cape and other parts of the Nanbian Mt. and adjacent hills.

The quasi-regular spacing of the promontories, jetting out to sea for considerable distance all along the southern coast of Hainan Island has the effect of breaking longshore sediment transport into non-communicating cells. They also protect some embayments, such as Sanya Bay, from large swells associated with typhoons.

The embayments consist of (ⅰ) narrow drowned valleys bounded by steep bedrock hills, (ⅱ) embayments characterized by surficial alluvial-deltaic deposits, and (ⅲ) embayments of various dimensions filled by sands of coastal ridges/barriers and associated elongated lagoons.

Drowned valleys. Very narrow, relatively deep embayments are preferentially formed along NE-SW faults. They receive little sediment from inland and for the most part they remain submerged, constituting valley drowned during the postglacial transgression. Yulin Bay and harbor area is a typical example. The embayment is surrounded by hills composed of Paleozoic sedimentary and metamorphic rocks and Mesozoic granite. The embayment consists of a narrow, long inland northern branch, in part silted up and in part reaching depth of about 10 m, and an inverted funnel-shaped, relatively deep (10—20 m) southern bay 1—2 km wide at the mouth and 25 km long. Its overall trend and shores have been indented and segmented by relatively close-spaced NW-SE trending faults.

Alluvial-coastal plain. Extensive alluvial-coastal plains have developed to the southwest such as those of the Loloxi River (west to Baoping Bay) and of the Ningyuan River (Plate Ⅰ).

The Loloxi River originates from the Changmao Reservoir, flows southwest, and finally enters into Wanglougang Bay. The Loloxi River alluvial-coastal plain is relatively wide (about 20 km at the shore), dominated by the irregular meandering river and its lobate delta. The Ningyuan alluvial-coastal plain is, instead, typical of a relatively narrow embayment (about 10 km wide at the shore). It is partially filled with fine-grained alluvial and estuarine deltaic-coastal sediments. The structure of the alluvial-coastal plain is characterized by remnant fluvial bars and channels due to switching and migration of the river channel, and by residual coastal bars exposed along the margins of the embayment.

Sandy ridge/lagoon coastal plain. Coastal plains dominated by well-developed coastal sand ridges are well developed in parts of southern Hainan Island. Some of the largest ones have developed in Yalong Bay (fig. 2), Sanya Bay, Xiaodonghai Bay (fig. 3), southeastern part of Lingshui Bay, and the southwestern of Yinggehai area. The sand ridges have formed on various substrata ranging from reef platforms and pre-Pleistocene bedrock.

A good succession of sand ridges occurs from inland to the shore in the narrow embayment north of the Phoenix village in the Sanya Bay area (Plate Ⅰ; fig. 4). The

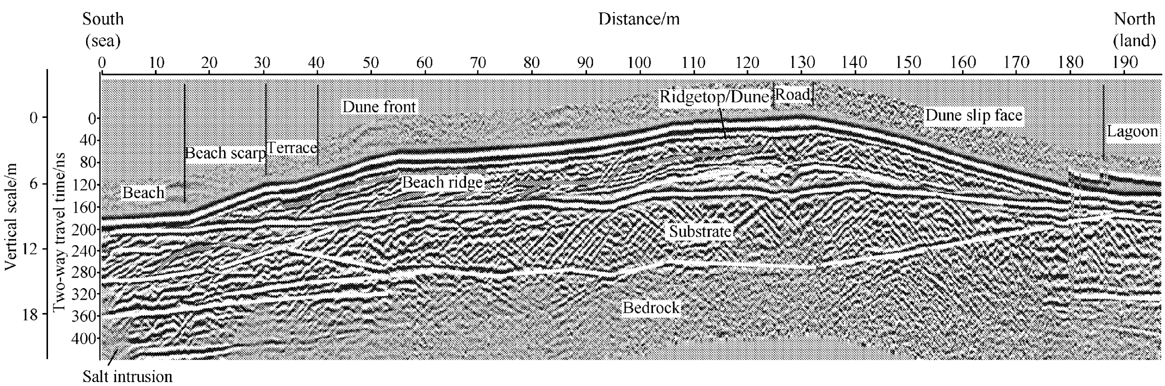


Fig. 2. GPR profile of Yalong Bay beach ridge (east to Yulin Bay).

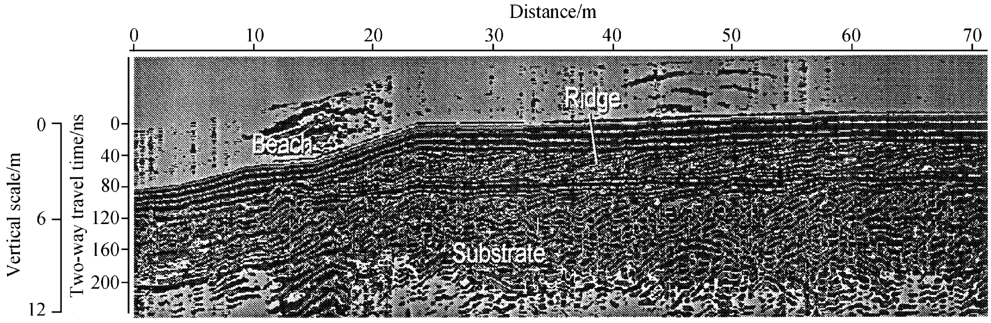


Fig. 3. GPR profile of Xiaodonghai beach ridge (in the east coast of Luhuitou Peninsula).

succession consists of five sand ridges/baymouth bars, plus a higher (40m asl) marine terrace (Baodao) rimmed by marine sand[10]. The ridges are generally composed of coarse-grained sand, becoming increasingly finer grained in successive younger ones and they are highly weathered (brick red coloration). The internal structure of older ridges is difficult to detect because of deep weathering, some homogenization and slight cementation. The Liangqin bar is the most seaward of the baymouth bars fully enclosed in the narrow Phoenix embayment. It has an approximate elevation of 20 m. The Tongjin-Yanglan bar that has an elevation of 10—15 m follows it seaward. This is a very large (about 9 km long, 600 m wide and 13 m high), composite sand ridge that closes the Phoenix embayment and spills over onto the large Sanya Bay inlet. It is composed of very coarse-grained quartzose sand, highly weathered with some interstitial neogenic clay matrix. The surficial sediments have a reddish color and massive appearance with few ghosts of former bedding. The GPR penetrates the sediments of the ridge and detect few lensing layers alternating with quasi-chaotic reflectors and the water table at about 8 m depth.

Farther seaward from the Tongjin-Yanglan bar there are two large, composite ridges/barriers that differ greatly from the previous ones. They are the Haipo bar and the Sanya bar/barrier.

The Haipo bar is a large structure about 10 km long, 450 m wide and 10 m high. Where surveyed, the bar is composed of a 90 m wide frontal beach system and a main body. It is composed of coarse- to medium-grained, light gray-yellowish/brownish, slightly weathered, feldspathic quartz sand with occasional comminuted, abraded shell fragment. Good GPR profile shows that the internal structures of the sand ridge have a composite nature being formed by several superimposed secondary ridges. In most cases, the cross-beds of the component secondary ridges dip seaward indicating progradation in that direction. Occasional landward dipping cross-beds in the back part of the ridge record washover events. At the time the Haipo ridge was forming, most of the wide inland area of the present Sanya Bay was inundated, and an arm of this water formed the lagoon of the Haipo bar.

The Sanya bar/barrier is a large composite structure rimming and enclosing the semi-lunate apex of the large bay (Plate Ⅰ). It is mainly composed of medium to light gray fine quartzose feldspathic sand. Several cores taken in the bar indicate an upper succession of alternating strata (each 2—3 m thick) of gray sand and dark gray clayish sand, which overlays a prevalently fossiliferous, dark gray clay succession (fig. 5). In places some gravels are presented. The basal unit is probably an open marine bay deposits. The upper succession indicates that the sand of the ridge has repeatedly migrated landward onto and interfingers with lagoon silty deposits. Silty lagoon deposits are also exposed at the seaward margin of the barrier. No GPR profiles were taken on the Sanya bar because it is mostly built up (urbanized). Dates of shells from cores of the Sanya bar and associated fine lagoonal/tidal inlet sediments indicate a range from 8305 ± 80 a (a= yrs BP) for the deepest samples (1.46 m) to about 7420 ± 425 a at depth of 0.84 m to 3395 ± 235 a at depth of 0.37 m. It is during the formation of this ridge/barrier that elongated, narrow tidal inlets developed and are still active today carrying salt water several kilometers inland.

At Dadonghai Bay on the eastern side of the Luhuitou peninsula there is development of another large coastal sand ridge enclosing a small lagoon, which has been accurately dated (Plate Ⅰ). Shells at the base of this coastal sand ridge in contact with the underlying lagoon deposits have been dated at 4640 ± 165 a, and they are now found at 2 m asl. The top of the ridge has been dated at 3110 ± 725 a and it is now found at 5 m asl.

Reef development and Holocene relative sea level change. Whereas dating of the coastal ridges is generally difficult, coral reefs and shells cemented in beachrock can be readily dated and this allows reconstructing a rather precise history of the relative sea level change during the Holocene. Reefs have developed around promontories and offshore islands. In the Sanya Bay area, reefs have been studied in some details on the have been studied in some details on the

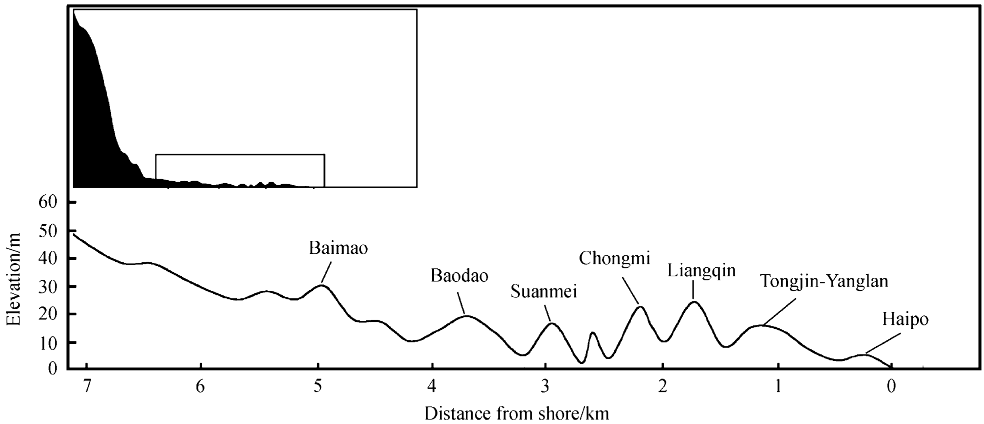


Fig. 4. Topographic profile of sand ridges developed along the Phoenix narrow embayment to the present coast (location shown in Plate Ⅰ).

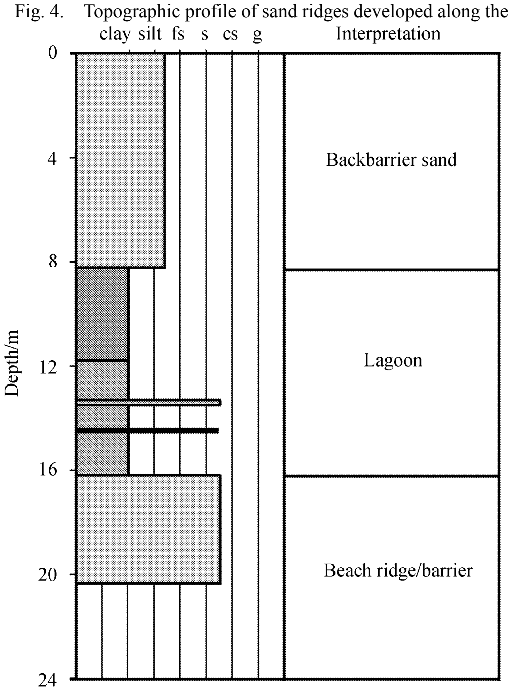


Fig. 5. Core from the Sanya bar/barrier showing ridge sand over lagoon material.

Luhuitou peninsula and Ximao Island (Plate Ⅰ). The oldest recorded date ((7680 ± 145) a) is of a reef head in living position from the base of the carbonate platform on the western side of the Luhuitou peninsula. It now lays at about 1m asl. At the top of the same platform about 4m higher, another coral has been dated at (5160 ± 139) a, now at about 5m asl. On the eastern side of the peninsula, near the southeastern edge of the promontory at Maanling cape, a coral head-stack has been dated at (6820 ± 154) a and is now found at about 2m asl. Beachrock has been dated from (4890 ± 120) a to (4750 ± 115) a and it is now found at about high-tidal level. The coralline sandy tombolos that join the southernmost cape of the peninsula to the main island rise to about 3 to 5 m asl.

Similar reef conditions occur on the western side of the Ximao Island in the middle of Sanya Bay. Coral heads have been dated at (4290 ±160) a, which are now found at about 2 m asl. They are topographically higher than the erosion surface of the reef platform dated at (5425 ± 130) a, which is at approximately present sea level.

Other reef material has been dated along the south shore of Hainan Island ranging down to 300 a, and corals are still living in the area. Beachrock associated with coralline areas usually show a slight development time lag in respect to the reef.

3 Discussion

(ⅰ) Terraces and coastal sand ridges. No numerical dates are available for the terraces found on the hills and promontories. However, their position in the landscape (80, 40—60 and 20 m asl) and deep brick red weathering suggest their relative antiquity. It is believed that they developed since late Tertiary—Early Pleistocene for the highest ones, to the Middle Pleistocene for the 20 m high terrace[1)] [9,11].

Similarly, no numerical dates are available from the older sand ridges systems, all calcareous shells having been dissolved and no organic matter having been found. In any case, the older ridges would be beyond the datable age with simple methods. For the most recent ridges, dates from shells indicate a mid-Holocene age younger than 8—7000 a.

1) Study group of marine geomorphology and sedimentology of Nanjing University, Research Report on Coastal Environment along Baopin Bay

to Sanya Bay, Hainan Island and Development of Sanya Harbor, 1986.

The relative time sequence and the approximate antiquity of the various sand ridges are suggested by their position in the landscape, by their component materials, and by the degree of weathering. It is believed that the older sand ridges probably developed since Early Pleistocene[9,11]. During the Middle Pleistocene embayments like the Phoenix one got filled with sediments and were fully enclosed by large, composite ridges such as the Tongjin-Yanglan bar. The fact that the sand ridges/baymouth bars in the narrow Phoenix embayment are well preserved indicate that the sand ridges were for the most part formed during an overall regression, perhaps punctuated by temporary transgressions. At that time, the short mountain streams carried relatively coarse material to these sites, mostly sand from the granite hills, which was reworked onto the coastal structures.

From the Tongjin-Yanglan bar to the Haipo bar a drastic change occurs, from a highly weathered, partially homogenized system of the former to a slightly weathered to fresh system with internal structures well preserved in the latter. The Haipo bar was probably formed during the penultimate interglacial highstand, showing seaward progradation associated with abundant sedimentation of material in part derived from rivers and, for the most part, from reworking of the shallow shoreface.

During the subsequent glacial-maximum regression much material was distributed onto the shallow shelf. These sediments were later partly reworked onshore to form the Sanya bar and similar other coastal ridges along the south shore of Hainan Island, probably during the Holocene optimum. Differently from other ridges of the area, the Sanya bar shows marked landward migration.

At the present, under tropical climatic conditions and luxuriant vegetation cover, the coast receives little sediment from inland rivers (less than about 10%)[12], and the constituting material mostly derives from offshore relict deposits. The present rise in sea level measured by tidal gauges is small (0.64 mm/a, measurement from 1954 to 1992) and a dynamic coastal equilibrium has developed[9]. Some erosion occurs on the more exposed parts of the Haipo bar and the material is transported along shore and deposited together with what is derived from the shoreface on the Sanya bar/barrier in the inner part of the bay.

(ii) Reefs and related features. During the Holocene transgression, water conditions became propitious for the development of reefs at approximately 8000 a. The reef grew vigorously until approximately 5—4000 a during the transgression and high sea level stand at the Holocene temperature optimum. At its highest, the sea level is thought to have been about 2 m higher than the present[4]. At that time and just subsequent to the high sea level, conditions were right for the formation of extensive beachrock development in tropical settings. During the transgression, the Luhuitou cape became for a time an island separated from the Nanbian Mt. to the north by a narrow isthmus. As reef developed and material eroded from them was redistributed along the isthmus tombolos formed separated by a middle lagoon. These tied the Luhuitou cape with the main island forming the Luhuitou peninsula.

Subsequent to the 8000—4500 a initial reef growth, reef development continued probably at varying rates through time. Periods of apparently more intense reef development have occurred between 8000 a and 4500 a, at around 3400 a and 2500 a. Almost invariably, rapid reef growth seems to have been accompanied and/or followed with a slight time gap by the formation of beachrock.

There are clear indications that Holocene shoreline deposits are now found about 1 to 2 m above sea level. This may be partly due to eustatic changes associated with the variable Holocene climate, partly to slight isostatic movements that have been reported but not yet satisfactorily documented from various parts of the island.

4 Conclusions

Although Hainan Island is located on a cratonic area, its coastal architecture is dictated by the bedrock lithology and the fault trends (NE-SW, E-W, and NW-SE), the latter governs the major geomorphologic features there including the overall shape of the island, the orientation of the central high mountains, the river drainage patterns, and the localization of the coastal promontories and embayments.

The island contains also a good record of interaction between eustatic and isostatic movements during the Quaternary and their effect on sedimentation and geomorphic features. Utilizing relative dating, the late Tertiary-Pleistocene evolution of the coastline is based primarily on succession of highstand coastal features. This is indicated by the formation of terraces and coastal sand bars/baymouth bars that are progressively uplifted. More accurate date control allows reconstruction of the onset of reef development during the early Holocene transgression, and suggests periodic rate fluctuations in reef and beachrock development.

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