On biogeomorphology of Luhuitou fringing reef of Sanya City, Hainan Island, China

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Abstract **Based on comprehensive survey of 6 transects on Luhuitou fringing reef in Sanya City of Hainan Island, China, some features of its biogeomorphologic processes were found, including (ⅰ) three basic biogeomorphologic units: inner reef flat, outer reef flat and reef slope; (ⅱ) two important biogeomorphologic boundary lines: up limit for live flat coral growing between inner and outer reef flats is Mean Lower Low Water of tropic tide ±15 cm; the break in slope between reef flat and reef slope is Theoretical Lowest Tide ±15 cm; (ⅲ) three types of reef flat profiles in response to distinctive Holocene sea level changes and dynamic condition: Luhuitou type responds to falling sea level and low wave energy; Xiaodonghai type to falling sea sevel and high wave energy; type for atolls of Nansha Islands to stable sea level and low wave energy; (ⅳ) hermatypic coral community is the most essential member in coral reef ecosystem and plays the most important role in biogeomorphologic process. Over the past 30 years Luhuitou fringing reef was severely destroyed by human activities, its biogeomorphologic function severely weakened, and it needs urgent management and protection.**

Keywords: fringing reefs, biogeomorphology, reef flat, sea level change, Hainan Island.

One of the main responses of the coral reef ecosystem to global changes is seen in its biogeomorphologic processes, and has been emphasized in Focus 2 of the "Land-Ocean Interaction in the Coastal Zone (LOICZ) of Global Changes"[1]. The biota of the coastal zone, such as coral reefs, mangroves, seagrass and various kinds of benthos, plays a fundamental role in the supplement (principally of carbonates), retention, stabilization and, to a less degree, erosion of sedimentary material in the nearshore zone[2]. The two-way interaction between such biologically driven and physical (hydrological, sedimentary and geomorphologic) processes is defined here as a biogeomorphologic process[1]. This research takes Luhuitou fringing reef in Sanya City of Hainan Island, China, as a case study for better understanding of biogeomorphologic processes of coral reefs and their response to environmental changes, like sea level change, and for generating some ideas about management and conservation of coral reefs.

1 Study area and research methods

Hainan Island is situated at the northern edge of the global coral reef zone. Luhuitou fringing reef (fig. 1) is one of the best-developed fringing reefs in Hainan Island and became part of the Sanya National Coral Reef Nature Reserve in 1990. The studied fringing reef area included the west 3.1 km coast (Luhuitou Bay) and the east 2.1 km coast (Xiaodonghai Bay) of Luhuitou peninsula, a tombolo based on a raised coral reef formation[3]. No fringing reefs occur along the 5.5 km rock coastline at the head of Luhuitou peninsula. Research on the biology[4—9], geomorphology[3,10,11], and geology[13—18] of this fringing reef is extensive. The high sea level in mid-Holocene, which formed the raised coral reefs and Luhuitou tombolo has been confirmed[14,15]. That is important context for recent reef flat development in this area. Wave climate depends on seasonal monsoons and individual typhoons. The NE wind and waves in winter are of longer duration and stronger than the S wind and waves in summer. Typhoons with frequent tracks from east to west, and storm waves occur in July—November. So the Luhuitou coast is leeward and a low wave energy coast, and the Xiaodonghai coast is windward and a high wave energy coast. The tide is an irregular diurnal type, the mean tidal ranging 0.9 m and largest one 2.14 m. Annual mean surface sea water temperature is 26.8℃ and January mean temperature is 22.6℃. Sea water salinity is 29.9‰—34.2‰. Transparency of seawater is about 10 m[13].

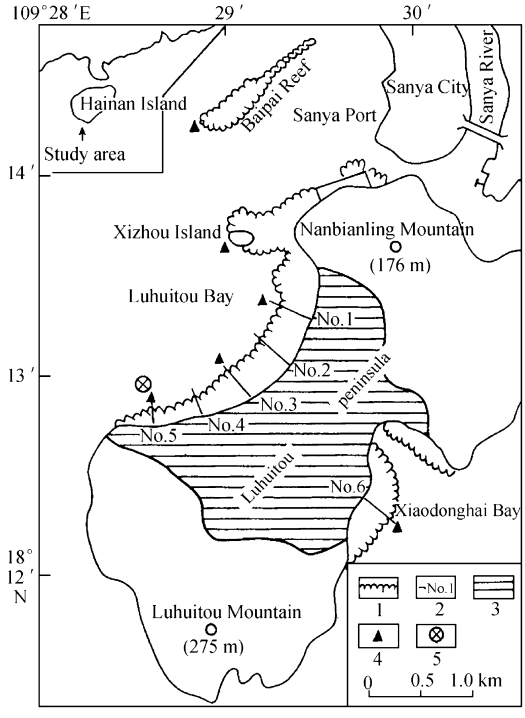

Fig. 1. Study area and layout of survey items in Luhuitou fringing reef of Sanya City, Hainan Island. 1, Coral reefs; 2, transects and Nos.; 3, coral reef tombolo; 4, diving survey sites; 5, temporary tide station.

Six transects were set up, No.1—No.5 were on Luhuitou coast from north to south and No.6 on Xiaodonghai coast (fig. 1). The survey time was October of 1998, January, April and August of 1999. The main survey items included: (ⅰ) Leveling survey, geomorphologic and sedimentary description, and quantitative description of hermatypic coral community structure along each transect; (ⅱ) diving survey for coral community on reef slope of transects Nos. 1, 3, 5, 6, and Xizhou Island and Baipai Reef; and (ⅲ) tidal level observations at Luhuitou temporary tide station off transect No.5 during each survey time. We paid special attention to the relationship between reef flat elevation and tidal levels using leveling survey data of transects and tide observation data from temporary tide station and nearby official Sanya oceanographic station. Twenty-one surveys of temporary sea level for comparison with transect surveys and Luhuitou tide data were completed with ±6.5 cm of standard deviation. Taking the same day or the same multi-day mean sea level from two tide stations as a common level, the data of TLT (Theoretical Lowest Tide, as Chart Datum in China and 90 cm below the mean sea level in Sanya waters) and the mean sea level were transferred from Sanya oceanographic station to Luhuitou station with the standard deviation <±10 cm. This method has been successfully applied to a similar mangrove research work[19]. All elevations and water depths in text have been transferred and take TLT as datum plane.

2 Results and discussion

(ⅰ) Geomorphologic structure and biogeomorphologic units of Luhuitou fringing reef. Most fringing reefs are structurally similar, with extensive intertidal reef flats enclosed by a short outer reef slope[20]. In Luhuitou fringing reef (fig. 2 and table 1) geomorphologic units include sand beaches (unit Ⅰ), reef flats (unit Ⅱ), reef slope (unit Ⅲ). Each unit is separated from others by a break in slope and has different topography, sediments,

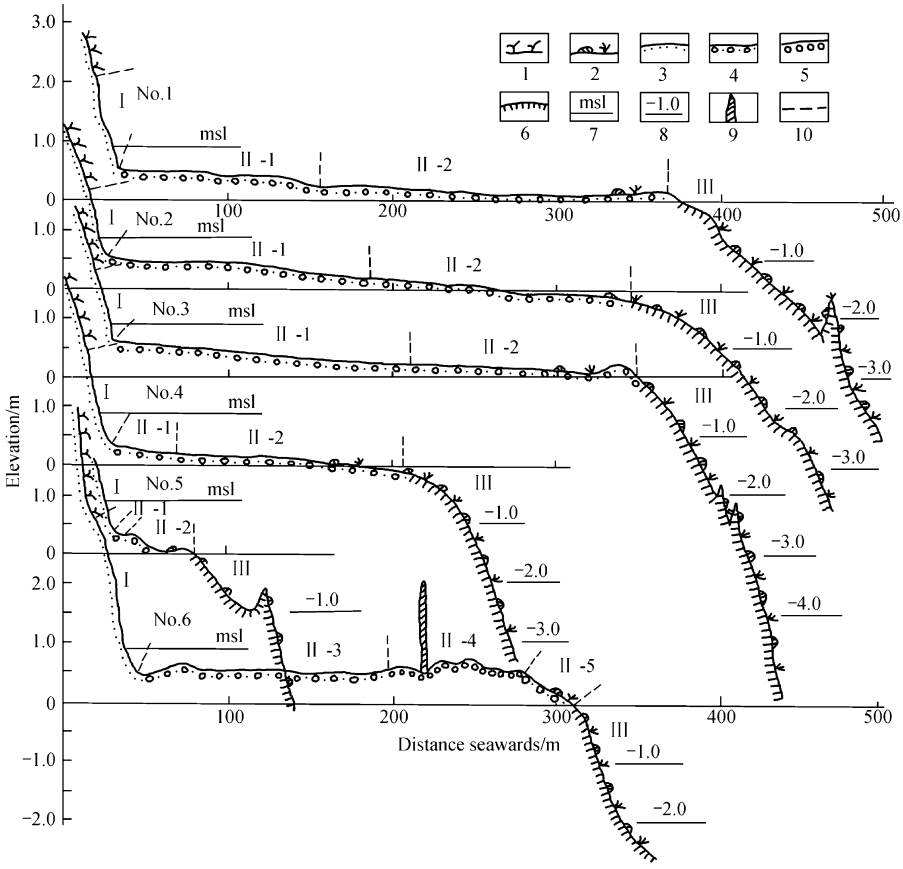

Fig. 2. Leveling surveyed profiles and geomorphologic zones of the Luhuitou fringing reefs of Sanya City, Hainan Island of China. 1, Vegetation; 2, live corals; 3, biogenic sand; 4, coral sand and gravel; 5, coral boulders; 6, original coral blocks; 7, mean sea level; 8, water depth; 9, big coral boulder; 10, boundary between geomorphologic units. Geomorphologic units: Ⅰ, Sand beach; Ⅱ, reef flat; Ⅱ-1, inner reef flat; Ⅱ-2, outer reef flat; Ⅱ-3, shallow depression; Ⅱ-4, boulder rampart; Ⅱ-5, encrusting algae pavement; Ⅲ, reef slope. See fig. 1 for locations of 6 transects.

Table 1 Morphological data by leveling survey for each geomorphologic unit of 6 transects on the Luhuitou fringing reef of Sanya City, Hainan Province

Transect No.	Morphological data of each geomorphologic units[a)]				
	Ⅰ	Ⅱ	Ⅱ-1	Ⅱ-2	Ⅲ
1	E=200-54 W=12 G=12.2	E=54-10 W=322 G=0.14	E=54-20 W=124 G=0.27	E=20-10 W=198 G=0.05	E=10-(-414) W=124 G=3.42
2	E=172-54 W=10 G=11.8	E=54-(-14) W=320 G=0.23	E=54-15 W=161 G=0.24	E=15-(-14) W=159 G=0.18	E=(-14)-(-377) W=131 G=2.77
3	E=188-55 W=12 G=11.1	E=55-0 W=318 G=0.17	E=55-18 W=180 G=0.21	E=18-0 W=138 G=0.13	E=0-(-444) W=80 G=5.55
4	E=215-31 W=18 G=10.2	E=31-(-9) W=174 G=0.30	E=31-17 W=38 G=0.37	E=17-(-9) W=136 G=0.19	E=(-9)-(-343) W=70 G=4.77
5	E=162-33 W=11 G=11.7	E=33-0 W=50 G=0.66	E=33-23 W=5 G=2.0	E=23-0 W=45 G=0.51	E=0-(-276) W=59 G=4.69
6	E=319-47 W=25 G=10.9	E=46-2 W=265 G=0.17	Ⅱ-3 E=46-61 W=151 G=near horizontal	Ⅱ-4 E=44-70 W=87 G=convex	Ⅱ-5 E=48-2 W=27 G=1.70	E=2-(-272) W=54 G=5.07

a) E, Elevations in cm at landward and seaward edges for each unit or of maximum and minimum only for units Ⅱ-3 and Ⅱ-4; W, width in m; G, gradient in %; unit Ⅲ only for leveling surveying part of the upper reef slope.

hydrodynamic condition and biological activities.

The sand beach units have widths of 10—25 m, gradients of 10.2%—12.2% and elevations of upper limit from 1.62—2.15 m (mean higher high water of tropic tide is 1.66 m) in Luhuitou and 3.19 m in Xiaodonghai. They consist of biogenic sand from fringing reefs in medium sand in Luhuitou or in coarse sand in Xiaodonghai. These landforms were formed by wave action at high tide, so they are dynamic geomorphologic units.

Reef flats (except transect No.5 near rock headland), have widths of 174—322 m and gradient of 0.14% —0.30%, and elevations of up and down limits of 31—55 cm, or 35—59 cm below mean sea level, and 10— (–14) cm, or about TLT. They are underlain by original coral blocks and infilled with broken coral gravel and sand.

In Luhuitou the smooth and gentle reef flats can be divided to inner reef flat (unit Ⅱ-1) without any live corals and outer reef flat (unit Ⅱ-2) with small and scattered live corals. The former has width of 38—128 m, gradient of 0.21%—0.37%. On it the coral biogeomorphologic process has stopped and the scattered weathered original head corals or dead microatolls belong to the ancient biogeomorphologic products during mid-Holocene high sea level period. The latter has width of 136—198 m, gradient of 0.05%—0.19%. It is formed by modern weak biogeomorphologic processes at present sea level. A small sand and gravel ridge with height of 20 cm and width of 20 m on outer edges of reef flat of transect No.3 is the only important product of dynamic geomorphologic process.

In Xiaodonghai the storm wave makes more modification in all geomorphologic units than in Luhuitou, e.g. higher upper vegetation line and coarser sand in sand beach, remarkable boulder rampart in reef flat, well developed spur-and-groove structure in reef slope. The reef flat may be divided into three parts: near horizontal shallow depression (unit Ⅱ-3) with width of 151 m, elevation range of 46—61 cm, sediments of coral sand and gravel and some growing seagrass, ragged and convex boulder rampart (Ⅱ-4) with width of 87 m, elevation range of 44—70 cm and sediments of boulders of which the largest is 1.5m×1.8m×1.4m; smooth and steep encrusting algae pavement (Ⅱ-5) with width of 27 m, gradient of 1.70%, sediments of coral gravel and sand cohered by encrusting algae, and strong wave action at low tide. The upper limit of live growing coral which is directly controlled by tide level, is at upper part of encrusting algae pavement with elevation of 37 cm, but live coral can get higher elevation in permanent pools on boulder rampart and outer part of shallow depression. Unit Ⅱ-5 may be homologue of outer reef flat. A few smooth dead microatolls in reef flat represent outcrops of biogeomorphologic formation.

Reef slopes (unit Ⅲ) have quite steep gradient of 2.77%—5.07% from leveling survey data (fig. 1 and table 1). Water depths at its lower limits are from 3.2 m in transect No. 1 to 6.0 m in transect Nos. 3 and 5 by diving survey data (table 2). It consists of ragged original reef block and coral sand and gravel on which are growing luxuriant and various live corals with cover 10%—100% and mainly in the range of 0— 4 m below TLT (table 2). The dominant coral genera are *Acropora* and *Porites*. Active coral biogeomorphologic processes are the main mechanism for outer reef expansion. The special spur-and- groove structure on the upper part of reef slope is better developed in Xiaodonghai than in Luhuitou. It is a typical growing coral landform but responds to local dynamical condition of strong waves and currents.

Table 2 Growing status of living corals and reef slope landform of the Luhuitou fringing reef of Sanya City, Hainan Island

Transect No.	Live coral cover of outer reef flat (%)	Reef slope zone[a)]		Luxuriant coral zone in reef slope zone[a)]		
		width/m	water depth/m	width/m	water depth/m	live coral cover (%)
1	1—3	50	0—3.2	20	1.0—1.7	15—30
2	1—3					10—40
3	1—2	70	0—6.0	50	0—3.5	30—60
4	1—3					50
5	1—3	60	0—6.0	25	1.4— 4.0	30—100
6	1—10	>60	0—3.5 below	>60	0—3.5 below	30—60

a) Data mainly from diving survey and mainly in transect Nos. 1, 3, 5, and 6.

The gentle sandy or muddy sea bed off steep reef slope consists of sediments with high $CaCO_3$ content (20%—80%[21]) coming from fringing reefs. It is not a typical biogeomorphologic unit but a dynamic geomorphologic unit shaped by current and wave.

So inner reef flat, outer reef flat and reef slopes are three basic biogeomorphologic units with features of growing coral, limited by tide levels, and modified by storm wave action especially those in Xiaodonghai. In Xiaodonghai the high wave energy makes more luxuriant live corals and more modification in all geomorphologic units than in Luhuitou, e.g. higher upper vegetation line and coarser sand in sand beach, remarkable boulder rampart in reef flat and well developed spur-and-groove structure in reef slope.

(ii) Two important biogeomorphologic boundary lines. Hermatypic coral, as main biogeomorphologic builder, cannot withstand long time (e.g. 3 h[22]) exposure to air, and tide elevations become controlling factor of upward growth for reef flats. That is the theoretical basis for use of the reef flat as an indicator of sea level change[22]. Many researchers mention this limit elevation, such as high tide[11], low tide neap[23], lowest low tide[3], low tide[10,24], lowest astronomical tide[25], or mean low tide spring $\pm$25 cm in the Great Barrier Reef[22]. According to analysis of Luhuitou tide data, the Mean Lower Low Tide (MLLT) of tropic tide here is 30 cm above TLT. By this research the upper limit of flat growing coral is 15—20 cm and 37 cm on low and high wave energy coasts respectively, or 10—15 cm below MLLT of tropic tide in Luhuitou Bay, and 7 cm above MLLT of tropic tide in Xiaodonghai Bay, or MLLT of tropic tide $\pm$15 cm with tidal inundation accumulation frequency of 88%—98%. This result is similar to ref. [22]. Here the MLLT of tropic tide in irregular diurnal tide waters corresponds to mean low spring tide in regular semi-diurnal tide waters.

Another biogeomorphologic boundary line is the break in slope between reef flat and reef slope and boundary line between scattered and luxuriant corals. Few researchers have determined exactly this boundary line by tide level. By this research it is 10—(−14) cm or TLT$\pm$15 cm. The difference between these two boundary lines is only about 30 cm, but it gives extensive room on outer reef flats for growing surface hermatypic coral[26] with tolerance of exposure and other adverse circumstances.

(iii) Three types of reef flat profiles in response to distinctive Holocene sea level changes and dynamic condition. Luhuitou type, as transect Nos. 1, 2, 3, and 4, is with gentle slope of gradient about 2‰ and with spreading weathered original head corals on flat surface. In the rear and highest part of its inner flat, weathered original head corals may have elevation up to 0.6 m above TLT, or 0.4 m above the upper limit of flat growing coral. That means that its inner reef flat is a relict growing form of corals from high sea level period. Only its outer flat is a real modern reef flat. This kind of profile is responding to sea level falling from mid-Holocene high sea level[14,15] to present, and low wave energy, which could protect elevated original reef flat from essential modification driven by dynamic conditions.

Xiaodonghai type, as transect No. 6, has a higher and near horizontal profile and with a remarkable boulder rampart. There are two reasons for its difference from that on Luhuitou. Both reef blocks transported by storm waves and a higher upper limit of live flat corals make the outer part of reef flat higher than that on Luhuitou. Higher and near horizontal profiles result. This type of reef flat profile is responding to falling sea level too, but essential modification of high wave energy.

For ease of comparison, we give other examples from precise echo sounding profiles of several atolls of Nansha Islands[27]. Thus reef flats have a lower (about 20 cm above TLT which is 100 cm below the mean sea level in Nansha waters), more extensive (with width of 560—1370 m) and near horizontal profiles with scattered live corals. It is clear that this type of reef flat profile belongs to typical growing form responding to stable sea level and low wave energy.

(iv) Hermatypic coral community is the most essential member in coral reef ecosystem and plays the most important role in biogeomorphologic process. During the past 6000 years, mainly in mid-Holocene warmer climate and higher sea level period, Luhuitou coral reef ecosystem has built a geological formation with mean thickness of about 10 m and area of 4.7 km^2 (3.2 km^2 tombolo and 1.5 km^2 reef flat and reef slope). Current hermatypic coral is stunted in growth under influence of low temperature in winter and land runoff, but luxuriant and healthy coral occurred in full reef slope and outer reef flat in the 1960s[3—5]. Along with population growing from 2 thousand in a fishing village in the 1950s to more than 100 thousand in Sanya City proper in the 1990s and more and more coastal development activities, this fringing reef was destroyed. The main stresses to coral reefs came from unreasonable human activities, like dredging reef block for building materiel and making lime, collecting coral for

tourism goods, over-fishing and destructive fishing methods, pollution and excessive sedimentation from land. Now live coral covers are only 1%—3% in most outer reef flat, and only 10%—60% in most luxuriant coral zones of reef slope (table 2). In Luhuitou fringing reef very often you can find broken corals, dead coral heads, corals covered by rubbish, smothering epibionts and sediments. You can find abundant sea weed and sea urchins, and disappearance of many high-value reef organisms, like groupers, lobsters, sea cucumbers, sea horses, giant clams, pearl shells, and trochus shells, etc. Hermatypic coral of Luhuitou coast consists of 12 family, 24 genus, 83 species by 70% of all species in Hainan Island in the 1960s[28] and 10 family, 21 genus, 58 species in the 1990s, and about one third of hermatypic coral species have become regionally extinct and more than 70% of coral colonies have ages less than 30 years[7,8]. Its dominant species are *Porites lutea, Goniastrea aspera, Platygyra crosslandi, Goniastrea pectinata,* and *Acropora prostrata* in order of importance[7,8]. In the area of north Luhuitou coast and near Sanya port and outlet of Sanya River, e.g. Xizhou Island and Baipai reef (fig. 1), the hermatypic coral almost fully disappeared and cannot be restored. From diving survey data in reef slope (table 2), it seems that the health status of coral reef ecosystem becomes better from North to South or with distance from the population center of Sanya City in Luhuitou Bay, and from Luhuitou Bay to Xiaodonghai Bay. The restoration process of corals may recommence after building of the Sanya National Coral Reefs Nature reserve in 1990, but some of the human impacts have still not stopped. The Luhuitou fringing reef needs urgent action for management, protection, restoration and reconstruction of coral reef ecosystem, reversing its general worsening trend and maintaining its biogeomorphologic function, biodiversity and resource productivity.

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