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Storm cycles in the last millennium recorded in Yongshu Reef, southern South China Sea

Ke-Fu Yu[a,b,c,*], Jian-Xin Zhao[b,1], Kenneth D. Collerson[b,2], Qi Shi[a,3], Te-Gu Chen[a,4], Pin-Xian Wang[c,5], Tung-Sheng Liu[d,6]

[a] South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
[b] Advanced Centre for Queensland University Isotope Research Excellence (ACQUIRE), The University of Queensland, Queensland 4072, Australia
[c] Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
[d] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

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Abstract

Large storm-relocated *Porites* coral blocks are widespread on the reef flats of Nansha area, southern South China Sea. Detailed investigations of coral reef ecology, geomorphology and sedimentation on Yongshu Reef indicate that such storm-relocated blocks originated from large *Porites lutea* corals growing on the spurs within the reef-front living coral zone. Because the coral reef has experienced sustained subsidence and reef development during the Holocene, dead corals were continuously covered by newly growing coral colonies. For this reason, the coral blocks must have been relocated by storms from the living sites and therefore the ages of these storm-relocated corals should approximate the times when the storms occurred. Rapid emplacement of these blocks is also evidenced by the lack of coral overgrowth, encrustation or subtidal alteration.

U-series dating of the storm-relocated blocks as well as of in situ reef flat corals suggests that, during the last 1000 years, at least six strong storms occurred in 1064 ± 30, 1210 ± 5–1201 ± 4, 1336 ± 9, 1443 ± 9, 1685 ± 8–1680 ± 6, 1872 ± 15 AD, respectively, with an average 160-year cycle (110–240 years). The last storm, which occurred in 1872 ± 15 AD, also led to mortality of the reef flat corals dated at ~ 130 years ago. Thus, the storm had significant impacts on coral reef ecology and morphology.

Keywords: Storm; Coral reef; U-series dating; Late Holocene; South China Sea

* Corresponding author. Advanced Centre for Queensland University Isotope Research Excellence (ACQUIRE), The University of Queensland, Queensland 4072, Australia. Tel.: +61-7-33469753; fax: +61-7-33658530.

E-mail addresses: kyu@earth.uq.edu.au (K.-F. Yu), j.zhao@uq.edu.au (J.-X. Zhao), k.collerson@uq.edu.au (K.D. Collerson), shiqi@scsio.ac.cn (Q. Shi), kefuyu@scsio.ac.cn (T.-G. Chen), pxwang@online.sh.cn (P.-X. Wang), tsliu@public.bta.net.cn (T.-S. Liu).

[1] Fax: +61-7-33658530.
[2] Fax: +61-7-33658530.
[3] Fax: +86-20-84451672.
[4] Fax: +86-20-84451672.
[5] Fax: +86-21-65983207.
[6] Fax: +86-10-62558066.

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1. Introduction

Throughout tropical regions of the world, typhoons, cyclones or hurricanes play a significant role in periodic ecological perturbation of coral reef communities by influencing coral reef geomorphology and community compositions (Perry, 2001; Tilmant et al., 1994). This occurs primarily not only as a result of direct physical disturbance, but also associated with reduced seawater salinities, increased turbidity and sedimentation, and sediment rubble transportation and deposition, increased dissolved organic carbon, decreased dissolved oxygen, and altered water flow. These changes obviously affect the function of the whole reef ecosystem. Hurricanes are thus believed to play a role similar to that of bush fires in terrestrial systems (Hughes and Connell, 1999).

With regard to physical disturbance, most literature (Cheal et al., 2002; Guilcher, 1988; Morton, 2002; Nadaoka et al., 2001; Perry, 2001; Stoddart, 1971; Turpin and Bortone, 2002) focused on direct destruction of the reef corals, such as demolishment of branching corals, reduced living coral coverage, and dislodgment of reef frame blocks (up to 2 m^3) and massive corals. During the last century, most major hurricanes sweeping coral reef sites in the Caribbean resulted in massive disturbance to large areas of coral reefs (Tilmant et al., 1994). Observations from Belize indicate that after Hurricane Hattie in 1961, up to 80% of the reef corals disappeared on the barrier reef north of the storm track (Guilcher, 1988). During the 1982–1983 hurricane season, 50–100% of the living communities down to at least 40 m at Rangiroa Atoll were destroyed (Guilcher, 1988). It was also concluded that, after hurricanes, one dominant species might be replaced by another species, resulting in a discontinuity in reef genesis (Guilcher, 1988; Ostrander et al., 2000). In some cases, severe typhoons may also cause coral bleaching (Morton, 2002).

The frequency of hurricanes, cyclones or typhoons is probably important in the evolutionary history of regional ecosystems and their disturbances may play an important role in shaping the life-history strategy of the indigenous species (Turpin and Bortone, 2002). According to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones, and thus there is an increasing need to understand both the short- and long-term impact of

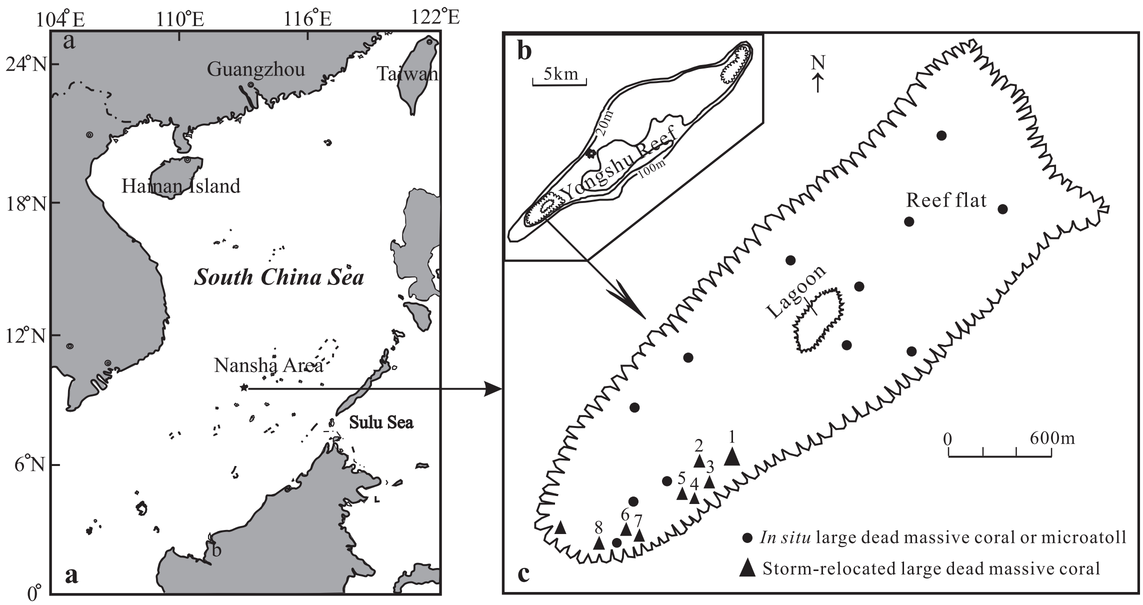

Fig. 1. Location map of Yongshu Reef, Nansha area, South China Sea. Note that storm-relocated coral blocks are distributed along the SW corner of the reef island. Numbers 1–8 with triangles correspond to localities of samples YSO-37, YSO-38, YSO-02-13, YSO-02-15, YSO-02-19, SWYS-1, SWYS-2, and SWYS-5, respectively (see Table 1).

storm events. Understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events. However, such studies are limited to only a few case studies (Macintyre et al., 2001; Perry, 2001; Woodroffe and Grime, 1999).

Nansha area (Fig. 1a), located in the southern South China Sea, is under the influence of the East-Asian monsoon. It is an example of a coral reef environment that might be directly affected by typhoon activity (Stoddart, 1971). In fact, typhoon- or strong storm-induced redistribution of massive reef blocks (most >2 m^3) is widespread on the reef flats. Unlike other reefs, however, most of the storm-relocated blocks on the reef flat in this area are massive *Porites lutea* corals, rather than cemented reef rocks. In this paper, we present U-series geochronological data from Yongshu Reef, an atoll in Nansha area, and explore the climatic implications of these results.

2. Location and climate

Yongshu Reef (9°32′–9°42′N, 112°52′–113°04′E; see Fig. 1b) in the South China Sea is an open spindle-shaped atoll (about 25 km long in NEE–SWW direction and 6 km wide in NW–SE direction) and covers an area of about 110 km^2. A closed lagoon (380 m long, 150 m wide and maximum 12 m deep) is situated in the center of the southwest reef flat (Fig. 1c). The area around the lagoon is referred to as the "small atoll". It is significant that Yongshu Reef stands over 2000 m above the seafloor and is located >500 km away from the nearest mainland, and is therefore relatively undisturbed by human activity.

Instrumental data from the Yongshu Reef Observatory show that the mean annual air temperature, sea surface temperature, rainfall and sunshine duration are 28.1, 28.6 °C, 1722.8 mm and 2436 h, respectively.

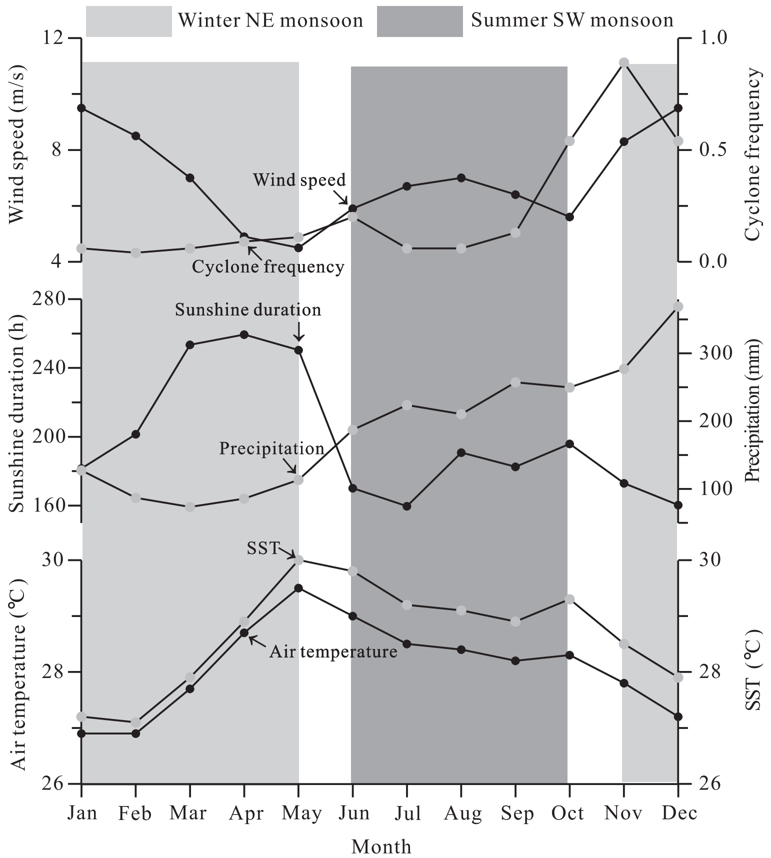

Fig. 2. Monthly climatic data for Yongshu Reef, Nansha area, South China Sea. SST—sea surface temperature.

The surface salinity in this area ranges from 33.0 to 33.5, with monthly variability < 1.0. Fig. 2 outlines the monthly climate parameters.

From June to September (Fig. 2), the area is under the influence of southwest monsoons with an average wind speed of 6.5 m/s. From November to April, the area is affected by northeast monsoons with an average wind speed of 8.0 m/s. A total of 129 tropical cyclones swept across the Nansha area during the period of 1949 to 1998, with an average recurrence rate of 2.8 per year, and a maximum of 9 occurred in 1971. Eighteen of these storms originated in the Nansha area and 71% of tropical cyclones occurred from October to December. The severest typhoon was Sarah in 1979, which resulted in wind speeds of 50 m/s. The 1988 Tess typhoon resulted in a wind speed of 38.4 m/s in Yongshu Reef. These severe tropical cyclones result in heavy rainfall, e.g. typhoon Tesesa in 1994 produced 228.1 mm precipitation within 4 days.

Surface water currents are also controlled by monsoons. In winter, the current speed is 0.51 to 0.77 m/s, with a maximum of 1 m/s. In summer, it is about 0.5 m/s. The wave directions in winter are northeast with an average height of 0.7–1.5 m, and southwest in summer with a height about 1.0–2.0 m. These directions are consistent with wind patterns.

3. Field geology and ecology

Yongshu Reef was developed since Tertiary over a basement consisting of Proterozoic–Palaeozoic metamorphic and Mesozoic magmatic rocks, similar in rock assemblages to the continental slope in the northern South China Sea (Zhu et al., 1997). The basement was revealed at a depth of 1500–1900 m during deep drilling by petroleum exploration companies (see Zhu et al., 1997). Detailed studies of three cores (Fig. 3) from the reef, including Nanyong-1

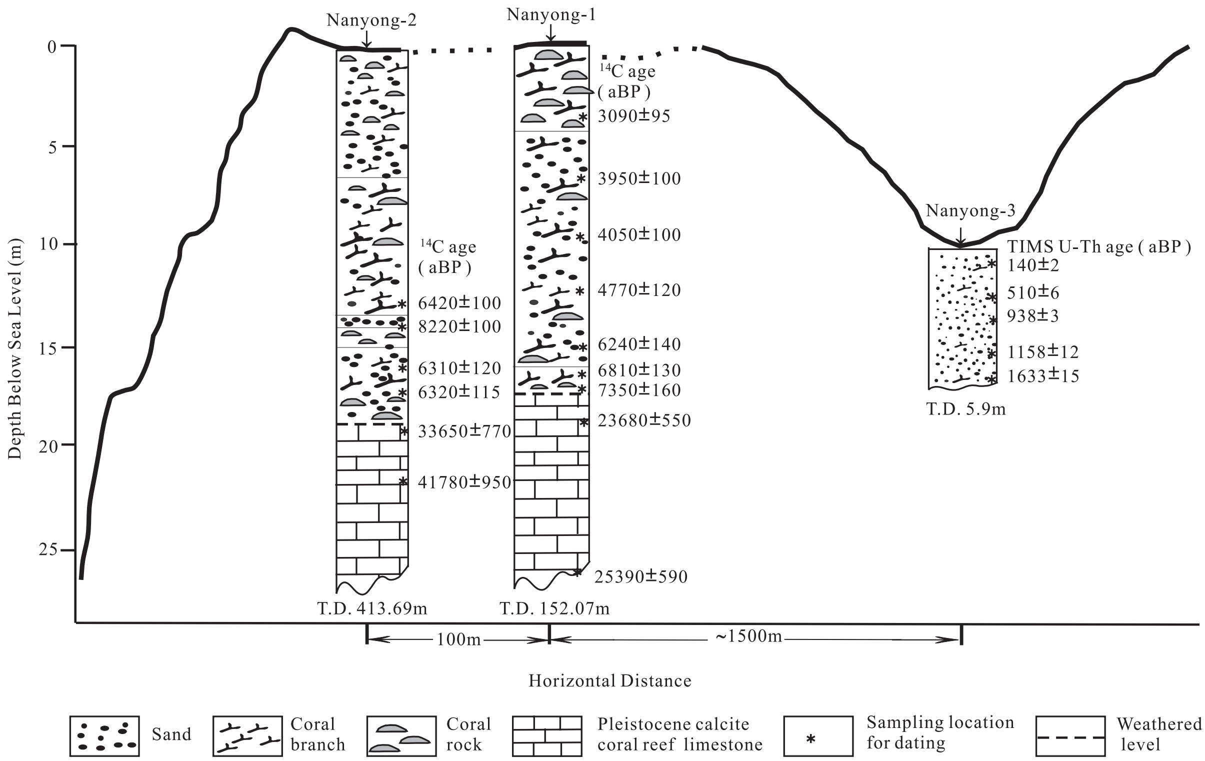

Fig. 3. Stratigraphical columns of three cores Nanyang-1 (9°32′24″N, 122°52′46″E), Nanyang-2 (9°33′N, 122°52′E) and Nanyang-3 (9°32′57″N, 122°53′23″E) showing Holocene coral reef structure of Yongshu Reef, Nansha area, South China Sea. Radiocarbon dates are at 1σ (after Zhao et al., 1992; Zhu et al., 1997; Wen et al., 2001). aBP—years before present (relative to 1950 AD).

(total depth of 152.07 m) (Zhao et al., 1992) and Nanyong-2 (total depth of 413.69 m) (Zhu et al., 1997) from the reef flat and Nanyong-3 (total depth of 5.9 m) (Wen et al., 2001) from the lagoon, show that the coral reef growth was initiated during the Holocene at about 7350 to 8000 years ago, and unconformably overlies weathered Pleistocene coral reef limestone at a depth of 17–18 m. Radiocarbon ages of these cores indicate that the reef was continuously developing throughout the Holocene, probably as a result of continued subsidence, combined with sea level rise initially. The total subsidence over the last 1000 years is about 2–3 m (Zhao et al., 1992; Zhu et al., 1997).

Two detailed field investigations, with a particular emphasis on the storm-relocated coral blocks on the reef flat, were carried out in April to May 1999, and May to June 2002. We first carried out a reconnaissance investigation of sedimentation, ecology, geomorphology and distribution of storm-relocated blocks on the small atoll using a motorboat and through underwater observation, to establish biogeomorphologic and sedimentary zones. This work was followed by six traverses parallel to the long and short axes of the small atoll that transected all recognized zones. During this work, detailed GPS position, water depth, sediment characteristics (sand, living coral, reef rock) and coral types (massive or branching) were measured for each of 166 observational localities (Yu et al., 2003).

Based on such systematic field investigations, six biogeological and sedimentary zones are recognized (Fig. 4). From outer to inner zones, these are (1) reef-front living coral zone, (2) outer reef-flat coral zone, (3) reef-ridge coral-branch-cemented zone, (4) inner reef-flat branch-coral/sand zone, (5) lagoon slope branch-coral/fine-sand zone, and (6) lagoon basin-floor silt zone.

3.1. Reef-front living coral zone

This zone, termed the "outer slope" in some studies (Guilcher, 1988), surrounds the whole reef. Slope angle varies between different sites, and is interrupted by a terrace at a depth of 17–18 m. Numerous spur-and-groove systems (4–5 m wide and 2–3 m deep) cross the slope and are covered with living corals dominated by branching *Pocillopora* sp. and *Acropora* sp. Large massive *Porites lutea* corals (>1.5 m in diameter) are also present, but not widespread, growing on the spurs 3–4 m underwater. Two cores about 1.4 m long were drilled in 1999. The upper 50-year section of one core was analyzed for C–O isotopes (Yu et al., 2001). Other massive corals such as *Favia* sp., *Goniastera* sp. and *Galaxea* sp. can also be found, but are not as large as *Porites* sp. corals. This zone shows great biodiversity, with almost all species in the Nansha area being found in this zone. Living coral coverage within this zone is up to 90%.

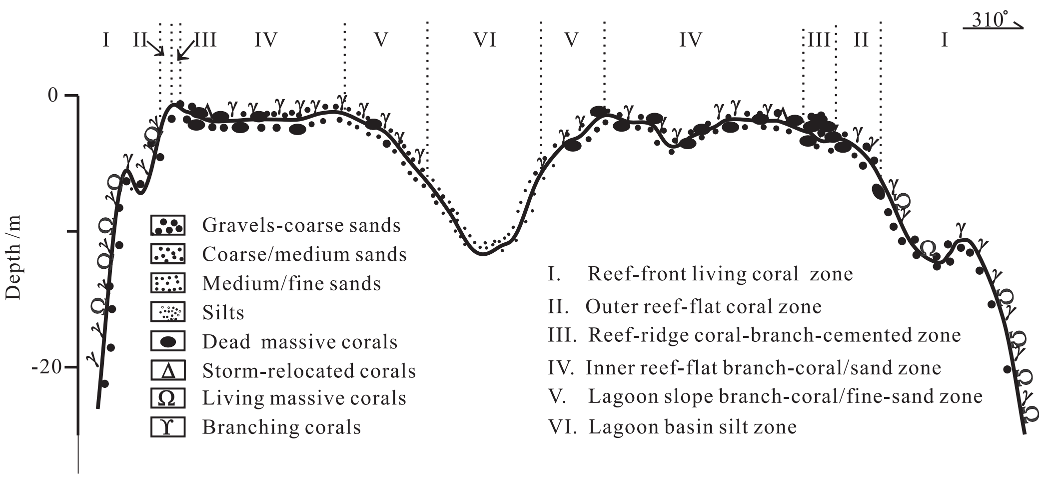

Fig. 4. Cross-section showing distribution of biogeological and sedimentary zones of the small atoll at Yongshu Reef.

3.2. Outer reef-flat coral zone

The surface of this zone, which is about 10 m wide, is cemented by algae and has a morphology that is saw-shaped toward the sea, resulting from the distribution of the spur and groove systems. This zone is kept wet by wave–reef interaction, allowing many massive and branching coral species to grow, although the size is usually very small. The massive corals, such as *Porites lutea*, are no more than 30 cm in diameter. Some branches and coral gravels can be found in the depressions.

3.3. Reef-ridge coral-branch-cemented zone

This zone is the highest part of the atoll. It is composed of semi-cemented broken coral branches together with rubble and gravel. It is about 8–10 m wide and 20 cm higher than the reef flat surface. No living coral exists in this zone, which is exposed (like a white ring) during the daily low-tide period.

3.4. Inner reef-flat branch-coral/sand zone

This zone is the widest part of the atoll with width varying from about 500 m along the short axis to about 1600 m along the long axis. The usual water depth is about 1–2 m, increasing toward the lagoon. During low spring tides, this zone is generally exposed to the atmosphere. However, numerous pools and long water-filled stripes of various sizes also exist, providing habitats for living branching corals and some small massive corals. Towards the lagoon, the coverage of living corals, dominated by *Acropora* sp., increases (up to 60%), but they may not have a long growth history due to bleaching or other causes. Mass mortality of these branched corals frequently occurs in this zone. Some small living massive *Porites* (< 35 cm in diameter) can be found within the *Acropora* colonies. The zone is covered with many in situ dead *Porites* corals and microatolls (diameter 1–2.5 m), some being surrounded by living *Porites* and forming new microatolls. All 59 cores from these in situ dead *Porites* corals indicate that they are less than 70 cm in depth, implying very short growth histories (< 50 years). In contrast, storm-relocated blocks, most composed of massive *Porites* corals, are 1–2.5 m in height and 1–3 m^3 in volume, which are significantly larger than the in situ corals (Fig. 5). These coral blocks are littered mainly on the southwest part of the zone. All such samples analyzed in this study were from this area. The size and population of storm-relocated blocks decrease towards the lagoon.

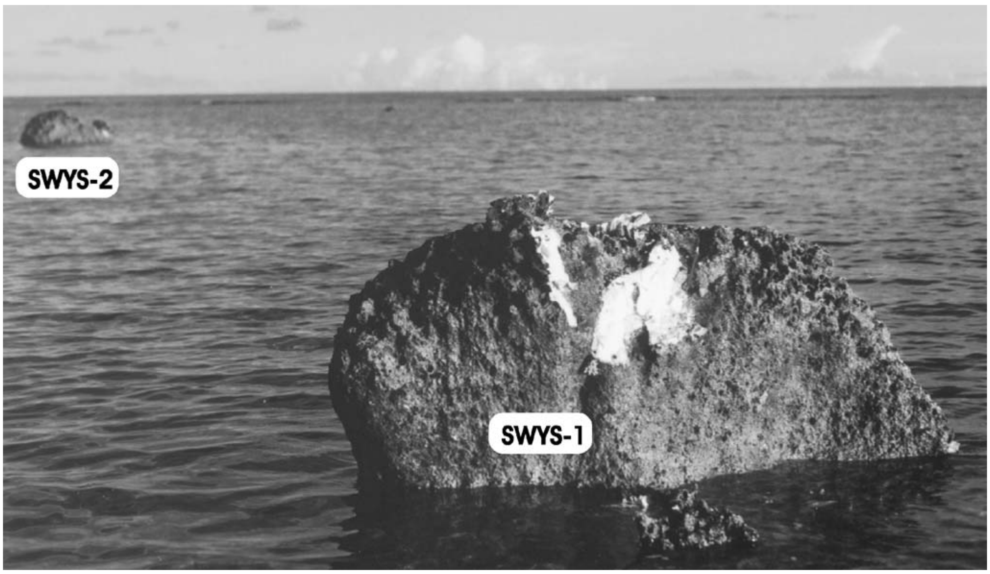

Fig. 5. Examples of storm-relocated large *Porites* coral blocks on the reef flat of Yongshu reef.

3.5. Lagoon slope branch-coral/fine-sand zone

This zone has a water depth of about 3–5 m, and is covered by white fine sand. *Acropora* communities with diameter about 1–1.5 m occur on the sandy floor. Very few massive corals, such as *Porites lutea*, occur in this zone.

3.6. Lagoon basin silt zone

This zone is about 5–12 m deep, and is entirely covered with white silts, except for a few living *Acropora*. Coral skeletons, *Halimeda* and foraminifera are the main sources of the lagoon sediments. No living massive corals (including *Porites*) occur within this zone.

4. Sample selection and analytical methods

A total of 59 dead massive *Porites* corals or microatolls from the reef flat were drilled using a hydraulic drill with a 6-cm inner diameter core barrel. Some living *Porites lutea* cores were also drilled in the reef front zone to determine their actual sizes and growth rates. About 20 surface samples were collected with a slash hammer from storm-generated reef blocks (all being *Porites* corals).

Ten in situ cores from the reef flat and two storm-relocated blocks were chosen for radiocarbon dating using standard techniques at the Radiocarbon Laboratory of Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Fifteen samples, including seven in situ corals and eight storm-relocated *Porites* were chosen for TIMS U-series dating in the University of Queensland. Detailed analytical procedure for TIMS U-series dating are described in Zhao et al. (2001).

5. Results

The age results are listed in Table 1. U-series ages for in situ corals range from 47 ± 2 to 212 ± 15 years ago (relative to 2003 AD), which appear to fall into three age groups: 47–81, 133–135 and 212 years ago. The radiocarbon ages are not as precise as they exceed the detection limit for the conventional radiocarbon dating method. However, samples dated by both radiocarbon and U-series methods yield broadly consistent ages. Based on this understanding, we infer that all other in situ samples dated by radiocarbon only are all of modern ages, as their radiocarbon ages are all less than 260 years. These results suggest that in situ large dead *Porites* and microatolls in the reef flat were all formed in recent time.

All eight samples of the storm-relocated *Porites* blocks yielded precise U-series ages of <1000 years. They fall into six time periods: 939 ± 30, 793 ± 5–802 ± 4 (average 798 ± 5), 667 ± 9, 560 ± 9, 318 ± 8–323 ± 6 (average 321 ± 7), 131 ± 15, with about 110–240 years gaps, suggesting cyclic storm activities. These ages can be converted to 1064 ± 30, 1210 ± 5–1201 ± 4, 1336 ± 9, 1443 ± 9, 1685 ± 8–1680 ± 6 (average 1682 ± 7), 1872 ± 15 AD, respectively.

6. Discussion

6.1. Source of storm-relocated Porites coral blocks

We argue that the *Porites lutea* corals growing on the spurs of the reef-front living coral zone, the optimum habitat for coral growth, are the only source of the storm-relocated large massive *Porites* blocks on the reef flat, simply because no other zones contain in situ corals of a size comparable to the storm-relocated blocks. In fact, among coral reefs worldwide, the most extensive damage to corals always occurs within this geomorphological zone, mainly because of the dynamic effect of direct wave impact.

According to Guilcher (1988), the blocks, which were thrown onto the reef flat in Rangiroa Atoll during the 1982–1983 hurricanes, were up to 20 m long, and their size decreased from the outer edge toward the lagoon. Even within the lagoon, blocks measuring 2 m were still found. At Funafuti, Hurricane Bebe built a rubble rampart ~19 km long and up to 4 m high on the southeastern side of the atoll, with a calculated volume of 1.4×10^6 m^3 and a mass of 2.8×10^6 tonnes. The largest storm blocks recorded are those at the northeast part of Rangiroa Atoll, Tuamotu Archipelago, where highly cemented blocks of reef rock up to ~6 m in height were pushed onto the reef flat. These storm blocks were derived from a

Table 1
Radiocarbon and TIMS U-series ages of the in situ *Porites* corals of the reef flat and storm-relocated *Porites* blocks on the reef flat

Sample name		U (ppm)	^{232}Th (ppb)	(^{230}Th/^{232}Th)	(^{230}Th/^{238}U)	(^{234}U/^{238}U)	Uncorr. ^{230}Th age (year)	Corr. ^{230}Th age (year)	Corr. initial (^{234}U/^{238}U)	δ^{234}U (T)	Uncalibrated ^{14}C age (aBP $\pm$ 2σ)	Year in AD
YSO-14-2	in situ										260 ± 200	1690
YSO-15-3	in situ										< 103	>1847
YSO-16-3	in situ										< 104	>1846
YSO-17-1	in situ										< 120	>1830
YSO-18-2	in situ										< 105	>1845
YSO-19-3	in situ										100 ± 120	~1850
YSO-20-2	in situ										< 119	>1831
YSO-21-3	in situ										80 ± 120	~1870
YSO-22-2	in situ										120 ± 200	~1830
YSO-23-3	in situ	2.4202	0.364	14.02	0.00069 ± 04	1.1524 ± 41	66 ± 4	62 ± 5	1.1525 ± 42	152.5 ± 4.2		1941 ± 5
YSO-26-3	in situ	2.3022	0.393	16.2	0.00091 ± 06	1.1526 ± 22	86 ± 5	81 ± 6	1.1526 ± 22	152.6 ± 2.2		1923 ± 6
YSO-35-2	in situ	2.6279	0.481	10.16	0.00061 ± 01	1.1490 ± 20	58 ± 1	53 ± 3	1.1490 ± 20	149.0 ± 2.0	260 ± 200	1950 ± 3
YSO-40-5	in situ	2.4429	0.484	35.0	0.00229 ± 15	1.1475 ± 23	217 ± 15	212 ± 15	1.1476 ± 23	147.6 ± 2.3		1791 ± 15
YSO-49-4	in situ	2.5295	0.553	20.4	0.00147 ± 09	1.1510 ± 25	139 ± 9	133 ± 9	1.1511 ± 25	151.1 ± 2.5		1870 ± 9
SWYS-3	in situ	2.3793	0.231	16.3	0.00052 ± 02	1.1493 ± 22	49 ± 2	47 ± 2	1.1494 ± 22	149.4 ± 2.2		1956 ± 2
SWYS-4	in situ	2.3403	0.206	50.2	0.00146 ± 03	1.1533 ± 21	137 ± 3	135 ± 3	1.1533 ± 21	153.3 ± 2.1		1868 ± 3
YSO-02-13	Relocated	2.0958	0.227	234.6	0.00838 ± 05	1.1483 ± 09	796 ± 5	793 ± 5	1.1487 ± 09	148.7 ± 0.9		1210 ± 5
YSO-02-15	Relocated	2.2603	0.587	40.7	0.00348 ± 06	1.1493 ± 15	330 ± 6	323 ± 6	1.1494 ± 15	149.4 ± 1.5		1680 ± 6
YSO-02-19	Relocated	2.4155	0.292	213.0	0.00848 ± 03	1.1495 ± 12	805 ± 3	802 ± 4	1.1499 ± 12	149.9 ± 1.2		1201 ± 4
SWYS-1	Relocated	2.4232	1.109	39.9	0.00602 ± 07	1.1485 ± 20	572 ± 7	560 ± 9	1.1488 ± 20	148.8 ± 2.0		1443 ± 9
SWYS-2	Relocated	2.5535	1.386	19.6	0.00351 ± 05	1.1513 ± 25	332 ± 5	318 ± 8	1.1514 ± 25	151.4 ± 2.5		1685 ± 8
SWYS-5	Relocated	2.7709	1.487	8.6	0.00152 ± 14	1.1463 ± 24	144 ± 13	131 ± 15	1.1464 ± 24	146.4 ± 2.4		1872 ± 15
YSO-37	Relocated	2.2684	4.232	16.86	0.01040 ± 20	1.1472 ± 19	987 ± 19	939 ± 30	1.1477 ± 20	147.7 ± 2.0	1160 ± 220	1064 ± 30
YSO-38	Relocated	2.2831	0.171	285.2	0.00704 ± 09	1.1480 ± 15	669 ± 9	667 ± 9	1.1483 ± 15	148.3 ± 1.5	750 ± 220	1336 ± 9

Ratios in parentheses are activity ratios calculated from the atomic ratios. Errors are at 2σ level for the least significant digits. The ages are calculated using half-lives from ^{230}Th and ^{234}U of 75,380 and 244,600 years, respectively. Corr. and uncorr. denote corrected and uncorrected. The corrected ^{230}Th ages and initial (^{234}U/^{238}U) ratios include a negligible to small correction for initial/detrital U and Th using average crustal ^{232}Th/^{238}U atomic ratio of 3.8 ± 1.9 (^{230}Th, ^{234}U and ^{238}U are assumed to be in secular equilibrium). All the TIMS U-series ages (aBP) are relative to 2003 AD. ^{14}C ages (aBP) are relative to 1950 AD.

storm in 1900, when conditions must have greatly exceeded those of any recent hurricanes (Stoddart, 1971).

In Yongshu reef, large storm-relocated blocks are distributed mainly in the southwest parts of the inner reef flat zone, suggesting that they were thrown up to the reef flat surface by strong storms in the southwest monsoon season.

6.2. When were the large Porites blocks brought to the reef flat?

As described in the field geology section, the Yongshu Reef has experienced continued subsidence and development since the early Holocene, with total subsidence over the last 1000 years reaching about 2–3 m (Zhao et al., 1992; Zhu et al., 1997). Such a high subsidence rate explains why all surface samples of the in situ corals from the reef flat are less than 212 years old and why old dead corals were all covered by living coral colonies in the reef-front living coral zone. Because of this, the storm-relocated *Porites* blocks on the reef flat are most likely to have been relocated by strong storms from growing sites in the spurs of the reef front zone. Small blocks accompanying these large *Porites* blocks were probably washed away during later events. Thus, we argue that the dates of the storm-relocated coral blocks should approximate the ages of the strong storms, and the age distribution of these coral blocks should reflect the frequency of past strong storm events.

The above argument is also supported by the fact that none of the relocated blocks we studied show any signs of younger coral overgrowth, encrustation or subtidal alteration. If some of the older blocks had been dead for a period of time before they were relocated by a storm event, the above-mentioned post-death secondary processes would have occurred. In fact, the lack of visible subtidal alteration is also reflected by the highly uniform δ^{234}U(T) values of the relocated blocks, which are analytically indistinguishable from the values (149 ± 4) of the modern corals (Table 1; Stirling et al., 1998). δ^{234}U(T) has been considered by various workers as the best quantitative

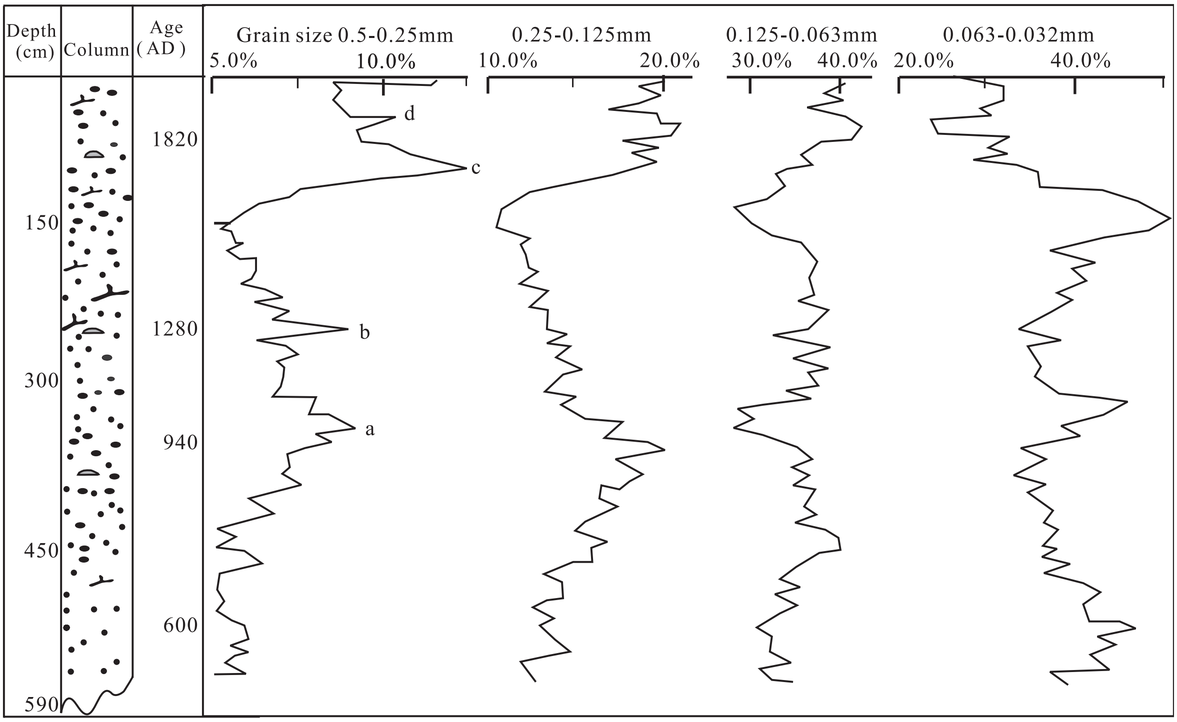

Fig. 6. Grain size distribution of the sediment profiles in core Nanyang-3 from the lagoon of the small atoll (after Wen et al., 2001). Note that four coarse-grain peaks occurred at 1060, 1280, 1680 and 1870 AD, respectively.

test for alteration of coral skeleton (see Stirling et al., 1998), with altered corals having $\delta^{234}U(T)$ deviated from the modern value due to U mobility.

6.3. Strong storm record over past 1000 years and its ecological implications

As described above, TIMS U-series ages of the storm-relocated blocks fall into six time periods: 1064 ± 30, 1210 ± 5–1201 ± 4 (average 1218 ± 5), 1336 ± 9, 1443 ± 9, 1685 ± 8–1680 ± 6 (average 1682 ± 7), 1872 ± 15 AD, respectively, reflecting a strong-storm recurrence rate of 110–240 years, or an average 160-year cycle. However, it must be emphasized that these relocated coral blocks only provide a minimum estimate of the storm frequency, as not necessarily all storms are capable of stripping corals from the reef front. Some storms, like Hurricane Lili in 1996, appear to have little immediate effect on the coral structure at San Salvador but its after-effects may have facilitated a rapid transition to a community dominated by macroalgae (Ostrander et al., 2000).

Grain size analysis (Wen et al., 2001) of an undisturbed core (Nanyong-3) from the lagoon shows that during the past 1000 years, sediment grain size increased four times, at 1060, 1280, 1680 and 1870 AD (a, b, c, and d in Fig. 6), respectively, which are comparable to four age groups of the storm-relocated blocks. In addition, most ^{14}C ages of 26 storm-relocated large *Porites* blocks (Zhu et al., 1991) from the 18 reefs (including Yongshu Reef) in Nansha area (Fig. 7) are within the last 1000 years, despite large age errors. Thus, both grain size distribution of the lagoon sediments and the storm-relocated blocks from neighboring reefs support our interpretation of the cyclicity of strong storm history during the past 1000 years. Strong storms violent enough to throw the large *Porites* blocks onto the reef flat are likely to

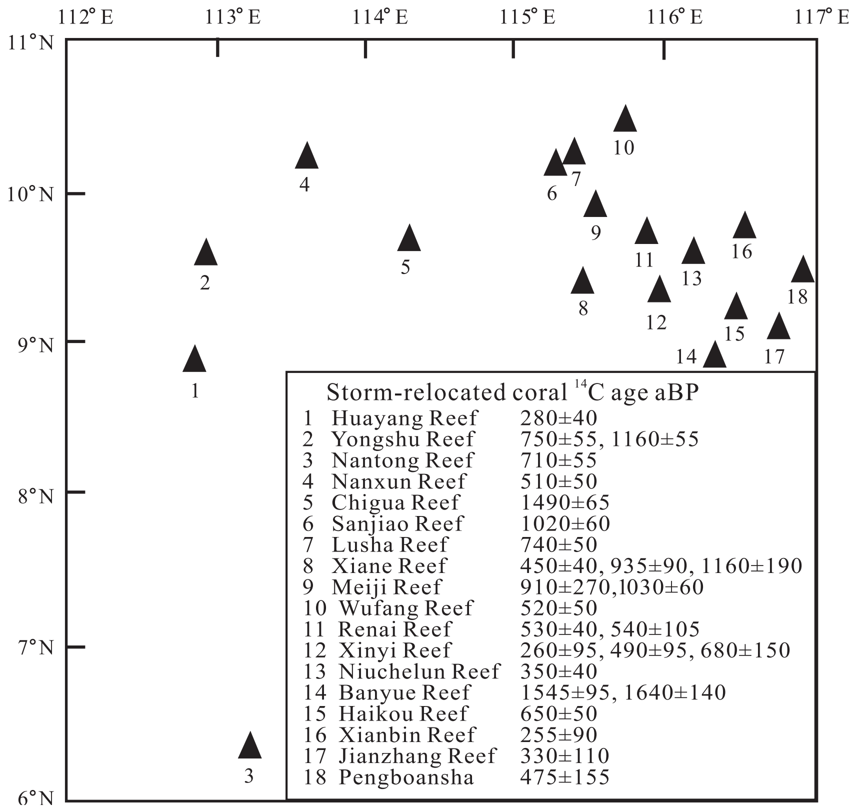

Fig. 7. Radiocarbon ages of the storm-relocated blocks from eighteen coral reefs in the Nansha area, South China Sea (after Zhu et al., 1991). aBP—years before present (relative to 1950 AD).

be related to typhoons. If correct, this suggests that in the southwest monsoon seasons in Nansha area, strong typhoons may have occurred at least every 110 to 240 years.

Samples YSO-49-4 and SWYS-4 from in situ large dead *Porites* in the reef flat yield almost identical ages of 1870 ± 9 and 1868 ± 3 AD, respectively. These are indistinguishable from the age of the last strong storm represented by sample SWYS-5 (1872 ± 15 AD). This suggests that deaths of the in situ *Porites* corals were probably caused by the strong storm or the typhoon. Many studies elsewhere show that severe storms such as cyclones, typhoons or hurricanes could cause significant disturbances to the coral reef ecology by (1) increasing turbidity, nutrient loading and dissolved organic carbon, and decreasing the dissolved oxygen levels (Tilmant et al., 1994); (2) reducing seawater salinity due to prolonged and intense rainfall (Lugo et al., 2000); (3) leading to low tides and exposing intertidal corals to air for longer periods (Hughes and Connell, 1999); (4) killing corals as larger coral blocks produced by storms roll over them (Stoddart, 1971); (5) decreasing and subsequently increasing water temperature abruptly (Nadaoka et al., 2001); and (6) disturbing the adaptation balance of reef communities, resulting in rapid change in dominant species (Ostrander et al., 2000). In Nansha area, these disturbances seem quite possible during a strong storm, although evidence for all such disturbances may not be readily available. It is likely that a combination of several such disturbances may have been responsible for the mortality of reef-flat corals.

7. Conclusions

(1) Storm-relocated large *Porites* coral blocks littered on the reef flat of Yongshu Reef, southern South China Sea, are considered to be derived from the reef-front living coral zone. Since the area experienced continued subsidence and coral reef development since Holocene time, any dead corals would have been continuously covered by growing corals. Because of this, the storm-relocated coral blocks should be derived from living corals when the storm occurred and the ages of storm-relocated coral blocks should date such storms.

(2) TIMS U-series dates of the storm-relocated coral blocks suggest that during the past 1000 years, at least six exceptionally strong storms occurred at 1064 ± 30, 1210 ± 5–1201 ± 4 (average 1218 ± 5), 1336 ± 9, 1443 ± 9, 1685 ± 8–1680 ± 6 (average 1682 ± 7), 1872 ± 15 AD, respectively. The average recurrence frequency is 160 years (110–240 years).

(3) The preferential distribution of the storm-relocated blocks in the southwest part of the reef flat suggests that these strong storms occurred in the southwest monsoon seasons (from June to September).

(4) The last strong storm, occurring ~ 130 years ago, caused mortality of the reef flat corals. This suggests that such severe storms have significant impacts on coral reef ecology.

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References

Cheal, A.J., et al., 2002. Responses of coral and fish assemblages to a severe but short-lived tropical cyclone on the Great Barrier Reef, Australia. Coral Reefs 21, 131–142.

Guilcher, A., 1988. Coral Reef Geomorphology Wiley, Chichester. 228 pp.

Hughes, T.P., Connell, J.H., 1999. Multiple stressors on coral reefs: A long-term perspective. Limnol. Oceanogr. 44, 932–940.

Lugo, A.E., Rogers, C., Nixon, S., 2000. Hurricanes, coral reefs and rainforests: resistance, ruin and recovery in the Caribbean. Ambio 29, 106–114.

Macintyre, I.G., Glynn, P.W., Steneck, R.S., 2001. A classic Caribbean algal ridge, Holandes Cays, Panama: an algal coated storm deposit. Coral Reefs 20, 95–105.

Morton, B., 2002. Effects of extreme rainfall, typhoons and declaration of marine reserve status on corals beached at Cape d'Aguilar (1998 and 1999). J. Mar. Biol. Assoc. UK 82, 729–743.

Nadaoka, K., et al., 2001. A field observation on hydrodynamic and thermal environments of a fringing reef at Ishigaki Island under typhoon and normal atmospheric conditions. Coral Reefs 20, 387–398.

Ostrander, G.K., Armstrong, K.M., Knobbe, E.T., Gerace, D., Scully, E.P., 2000. Rapid transition in the structure of a coral reef community: The effects of coral bleaching and physical disturbance. Proc. Natl. Acad. Sci. U. S. A. 97, 5297–5302.

Perry, C.T., 2001. Storm-induced coral rubble deposition: Pleistocene records of natural reef disturbance and community response. Coral Reefs 20, 171–183.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. Earth Planet. Sci. Lett. 160 (3–4), 745–762.

Stoddart, D.R., 1971. Coral reefs and islands and catastrophic storms. In: Steers, J.A. (Ed.), Applied Coastal Geomorphology. Macmillan, London, pp. 155–197.

Tilmant, J.T., et al., 1994. Hurricane-Andrew effects on marine resources. Bioscience 44, 230–237.

Turpin, R.K., Bortone, S.A., 2002. Pre- and post-hurricane assessment of artificial reefs: evidence for potential use as refugia in a fishery management strategy. ICES J. Mar. Sci. 59, S74–S82.

Walsh, K.J.E., Ryan, B.F., 2000. Tropical cyclone intensity increase near Australia as a result of climate change. J. Climate 13, 3029–3036.

Wen, X.S., Luo, Y.L., Zhao, H.T., Wu, L.J., 2001. Granulometric characteristics and its environmental significance of core in small lagoon of Yongshu Atoll. Chin. J. Trop. Oceanogr. 20, 15–20 (in Chinese).

Woodroffe, C.D., Grime, D., 1999. Storm impact and evolution of a mangrove-fringed chenier plain, Shoal Bay, Darwin, Australia. Mar. Geol. 159, 303–321.

Yu, K.F., Chen, T.G., Huang, D.C., Zhao, H.T., Zhong, J.L., Liu, D.S., 2001. The high-resolution climate recorded in the delta O-18 of *Porites lutea* from the Nansha Islands of China. Chin. Sci. Bull. 46, 2097–2102.

Yu, K.F., Zhao, J.X., Shi, Q., Zhong, J.L., Chen, T.G., 2003. New insight into biological–geomorphological–sedimentary zones and environment records at the southwest reef bracelet of Yongshu Reef, Nansha Islands. Chin. Mar. Geol. Quat. Geol. 23, 1–7 (in Chinese with English abstract).

Zhao, H.T., Sha, Q.A., Zhu, Y.Z., 1992. Quaternary Coral Reef Geology of Yongshu Reef, Nansha Islands. Ocean Press, Beijing, 264 pp. In Chinese with English abstract.

Zhao, J.X., Xia, Q.K., Collerson, K.D., 2001. Timing and duration of the Last Interglacial inferred from high resolution U-series chronology of stalagmite growth in Southern Hemisphere. Earth Planet. Sci. Lett. 184, 635–644.

Zhu, Y.Z., Nie, B.F., Wang, Y.Q., 1991. Coral reef sediments respectively in the southern and northern parts of Nansha Islands. In: Zhao, H.T. (Ed.), Symposium (1) on Geology, Geophysics and Reef Islands of Nansha Islands and Adjacent Areas, Ocean Press, Beijing, pp. 224–232. In Chinese.

Zhu, Y.Z., Sha, Q.A., Guo, L.F., Yu, K.F., Zhao, H.T., 1997. Cenozoic coral reef geology of Yongshu Reef, Nansha Islands. Chinese Science Press, Beijing, pp. 1–134. In Chinese with English abstract.