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Research Paper

U-series dating of dead *Porites* corals in the South China sea: Evidence for episodic coral mortality over the past two centuries

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Abstract

High-precision (up to ±1–2 years) U-series dating of dead *in situ* massive *Porites* corals on the reef flats of Yongshu and Meiji Reefs, Nansha area, southern South China Sea reveals that mortality of these massive corals occurred many times over the past two centuries, many of which appear to correlate in time with historic El Niño events. Despite different habitats of corals, at least six mortality events occurred simultaneously on both reefs (e.g. in 1869–1873, 1917–1920, 1957–1961, 1971, 1982–1983 and 1999–2000 AD), reflecting the occurrence of large-scale regional events. We speculate that many of such mortality events, especially those dated at 1998–2000, 1991, 1982–1983, 1971, and 1957–1958 AD with an overall uncertainty of ±1–2 years, are probably due to high temperature bleaching during El Niño years (e.g. 1997–1998, 1991–1992, 1982–1983, 1972–1973 and 1957–1959 AD). This study demonstrates that individual colonies of massive corals have died at different times over the past two centuries and mass spectrometric U-series dating of very young corals with a precision of up to ±1–2 years is likely to become a powerful tool for reconstruction of past coral mortality history and investigation of global warming and coral bleaching.

Keywords: TIMS U-series dating; Coral mortality; Coral bleaching; El Niño; South China Sea

1. Introduction

Coral reefs are the biologically most diverse ecosystems in the marine environment, comparable in richness and economic, social and cultural values to tropical rainforests of terrestrial habitats (Connell, 1978; Dight and Scherl, 1997; Jackson, 1991; Stone et al., 1999). However, such valuable aquatic resources have been undergoing significant degradation and decline worldwide in recent years due to human and natural disturbances. Bleaching (Glynn, 1983; Roberts, 1987), induced by climate warming (Brown and Ogden, 1993; Glynn, 1991; Jimenez et al., 2001; Mumby et al., 2001) or associated with solar radiation (Dunne and Brown, 2001; Lesser, 1997), is thought to be the most important cause of mortality, and an increasing problem in most major coral reef regions of the world (Fagoonee et al., 1999). The well-known 1997–1998 bleaching event caused severe mortality of massive corals throughout the world (Fitt et al., 2001; Marshall and Baird, 2000; Wilkinson et al., 1999); many corals killed were several hundred years old, some as old as 700 years of age (Anonymous, 1998; Harvell et al., 2001). Although biologists have been aware of localized bleaching for over a century, mass bleaching

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episodes that result in large-scale coral mortality were first recorded in the early 1980s (Glynn, 1983; Glynn, 1993). Since then several similar bleaching events have occurred in reefs around the world, with strong evidence for a significant increase in the frequency and severity of bleaching in recent decades (Bruno et al., 2001; Glynn, 1993). Prior to the late 1960s, reports of coral bleaching were scattered or almost nonexistent in the literature (Stone et al., 1999). Many ecologists consider that large-scale mass bleaching is a new phenomenon (Buddemeier and Fautin, 1993; Glynn, 1991), but it is still difficult to completely rule out the possibilities that mass bleaching or mortality has been occurring undetected in the past centuries, or even during the mid-Holocene when SSTs were $\sim 1\,^{\circ}C$ warmer than present (Corrège et al., 2000; Gagan et al., 1998; Yu et al., 2004b, 2005). The issue of coral bleaching has received attention only recently and little is known of past coral mortality history.

To understand coral reef bleaching and mortality history as well as recovery mechanisms, we dated *in situ* dead massive *Porites* and microatolls on the reef flats of Yongshu and Meiji Reefs, Nansha area, southern South China Sea using high-precision thermal ionization mass spectrometric (TIMS) U-series dating techniques. Coral reefs in this area are directly influenced by the Western Pacific Warm Pool. They are far away from mainland around the South China Sea (closest to Philippine that is 300 and 450 km away from the two reefs, respectively), and therefore relatively undisturbed by human activity. In this regard, coral mortality history in this area will have regional climate significance. Unlike branching corals, massive corals are rarely transported after death and thus their surface ages should reliably record the times when they died. Moreover, all massive corals contain countable annual growth bands. In this regard, when a TIMS U-series date is obtained, the surface age of the coral can be readily determined by extracting the number of annual growth bands above the sampling locality from the U-series date.

The TIMS U-series dating method is capable of dating pristine corals in the age range of 0–1000 years with a 2σ uncertainty of only 1–5 years (Edwards et al., 1987, 1988; Weisler et al., 2006; Yu et al., 2004a). This method has been successfully applied to the dating of recent seismic activities (Edwards et al., 1988; Zachariasen et al., 1999) and the U-series ages agree well with independent band counting results. In this study, we show through high-precision TIMS U-series dating that several of coral mortality episodes in the South China Sea appear to fall within historic El Niño events.

2. Location and climate

2.1. Yongshu reef

Yongshu Reef (9°32′–9°42′N, 112°52′–113°04′E; see Fig. 1a,b) is a spindle-shaped reef, about 25 km long and 6 km wide, and with a total area 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). Based on systematic field investigations, six biogeological–biogeomorphological and sedimentary zones are recognized around the lagoon and reported in detail by Yu et al. (2004a). They are from outer to inner zones (1) reef-front living coral zone, (2) outer reef-flat coral zone, (3) reef-ridge branching-coral-cemented zone, (4) inner reef-flat branching-coral/sand zone, (5) lagoon slope branching-coral/fine-sand zone, and (6) lagoon basin silt zone. Detailed studies of drilled cores, including Nanyong-1 (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-4 (total depth of 15.4 m) (Yu et al., 2006) from the lagoon, show that the Holocene coral reef started to develop at a depth of 17–18 m at about 7350–8000 years BP (radiocarbon dates).

Instrumental data from the Yongshu Reef Observatory which was set up in 1988 show that the mean annual air temperature is 28.1 °C, mean annual sea surface temperature is 28.6 °C, annual rainfall is 2260.2 ($\pm$350) mm and annual sunshine is 2378.2 ($\pm$147). The surface salinity in this area ranges from 33.0‰ to 33.5‰, with monthly variability < 1‰. The area is affected by southwest summer monsoons between June and September and northeast winter monsoons between November and April. Table 1 outlines the monthly climate parameters.

2.2. Meiji reef

Meiji Reef (~9°55′ N, 115°32′ E; see Fig. 1a,d), about 8.6 km × 6.5 km in size, is an oval-shaped reef and located about 200 km east of Yongshu Reef. Only limited field survey was carried out on this reef during a brief trip in 2004. The reef is characterized by a large lagoon with a maximum water depth of 30 m, surrounded by a ring of reef flat. There are three small channels connecting the lagoon to the open ocean at the southern and western parts of the atoll. The ecological zones are very similar to that of Yongshu Reef, but the corals are more abundant.

3. Field observations of coral mortality

Dead, massive *Porites* corals and living microatolls (diameter 1–2.5 m) are widespread in the inner reef flats of both Yongshu and Meiji Reefs. About 20–30% of *Porites* corals in this zone were found dead. On Yongshu Reef, the heights of these dead coral colonies are usually less than 70 cm (< 50 years growth history), suggesting frequent growth disturbances; however, the dead corals on Meiji Reef are much larger and their heights are around 1–2.5 m (~80–220 years growth history). Some living corals with heights of 3–4 m were also found on Meiji Reef. The difference in coral sizes between the two reefs may be related to their different physical environments. For instance, the channels and the large and deep lagoon of Meiji Reef allow exchange of the reef water with the open

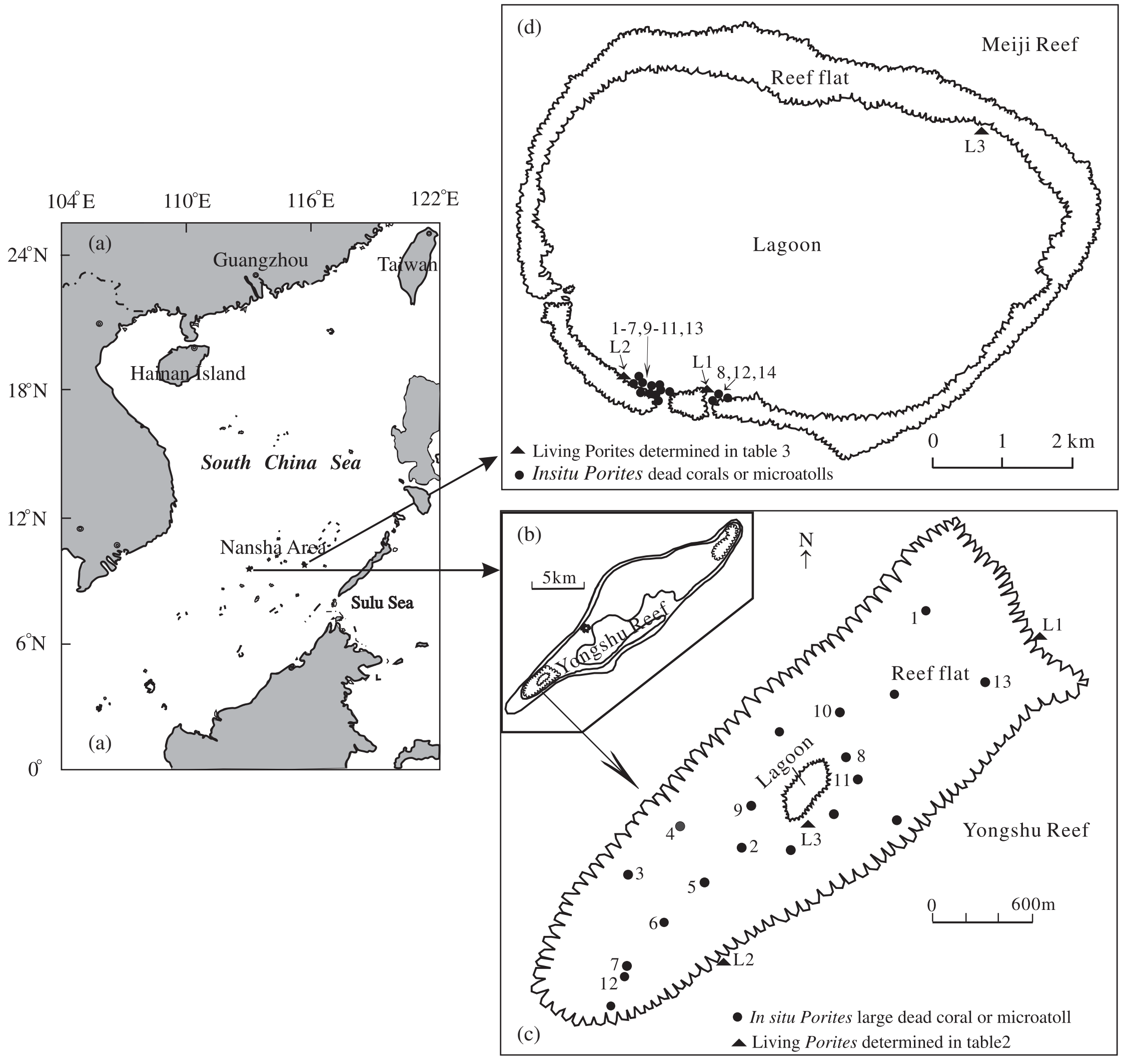

Fig. 1. Location map of Yongshu and Meiji Reefs, Nansha area, South China Sea. (a) Map of the whole South China Sea showing the locations of Yongshu and Meiji Reefs. (b) The whole Yongshu Reef including unexposed parts. (c) The exposed southwest Yongshu Reef with a small lagoon. (d) Map of the Meiji Reef. Note that the localities of samples listed in Tables 2–3 are also shown in Maps (c and d).

Table 1
Instrumental climatic records for the Yongshu Reef. Nansha area, southern South China Sea

Month	1	2	3	4	5	6	7	8	9	10	11	12	Average (total)
Air temperature/°C	26.9	26.9	27.7	28.7	29.5	29.0	28.5	28.4	28.2	28.3	27.8	27.2	28.1
SST/°C	27.2	27.1	27.9	28.9	30.0	29.8	29.2	29.1	28.9	29.3	28.5	27.9	28.6
Precipitation/mm	127.4	86.7	73.4	85.5	113.4	187.0	223.6	210.3	257.1	249.6	276.9	369.3	2260.2
Sunshine duration /h	181.5	201.5	253.4	259.4	250.3	170.1	159.6	190.8	182.5	195.9	172.9	160.3	2378.2
Tropical cyclones	0.06	0.04	0.06	0.09	0.11	0.20	0.06	0.06	0.13	0.54	0.89	0.54	2.80

Note: The frequency of cyclone occurrence is for the whole Nansha area.

marine water, providing good habitat for coral growth. Although these dead corals are often covered by living coral recruitment (*Porites*, *Acropora*) or inhabited by clams, their original dead surfaces are usually well preserved and readily identifiable. Considering the facts that (1) the inner-reef flats on both reefs are below the low spring tide, (2) many dead massive corals are covered by living coral recruitment (Fig. 2a,b), and (3) many larger corals on Meiji Reef (Fig. 2c) are still alive, we argue that their deaths are more likely due to natural disturbance, rather than senescence.

4. Samples, analytical methods and results

Cores were collected from dead massive *Porites* corals or microatolls on the reef flat of Yongshu Reef in April–May

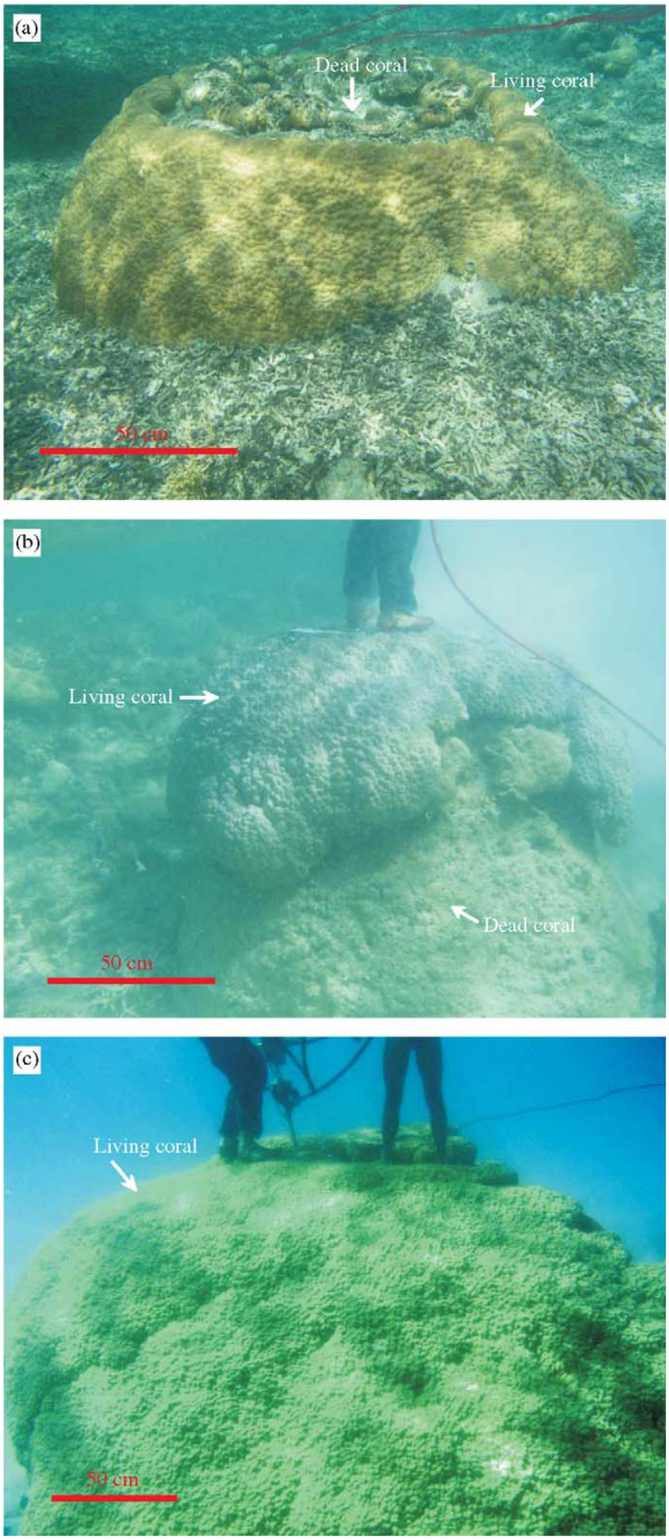

Fig. 2. Images of coral colonies in the inner reef flat zone of Meiji Reef. (a) MJO11-1, surrounded by living *Porites* coral (~20–25 cm thick) and forming a microatoll. (b) MJO13-1, is covered by living *Porites* coral. (c) Living *Porites* coral with diameter 3–4 m lives in the same zone.

1999 using a hydraulic drill machine with a 6 cm inner diameter core barrel. Two more samples (SWYS-3 and 4) were collected in May–June 2002. Thirteen samples of *in situ Porites* corals were chosen for TIMS U-series dating at University of Queensland (UQ) in 2003.

Cores were also collected from dead massive *Porites* from the inner reef flat zone and the lagoon slope in the vicinity of the southern channels (Fig. 1d) of Meiji Reef in May 2004 using a new hydraulic drill machine with an 8 cm inner diameter core barrel. Fourteen of them were chosen for TIMS U-series dating at UQ in July 2004.

Three living corals collected from Yongshu reef in May 1999, and another three collected from Meiji reef in May 2004 were also analyzed to determine the initial/detrital Th isotopic compositions in the local seawater.

Detailed analytical procedures are similar to those described in Zhao et al. (2001), except the known $^{236}U/^{233}U$ ratio in the ^{229}Th-^{233}U-^{236}U mixed spike was used for mass fractionation correction for the unknown samples. All isotope signals were measured in peak jumping mode on a Daly detector, with Th being measured manually in the daytime, and U automatically at night. The isotopic composition of the mixed spike was determined to be: $^{233}U/^{236}U = 0.96341 \pm 0.00033$, $^{233}U/^{238}U = 80.2 \pm 1.2$, $^{233}U/^{234}U = 206.90 \pm 0.62$, $^{233}U/^{235}U = 4405 \pm 26$, $^{229}Th/^{232}Th = 8180 \pm 260$ and $^{229}Th/^{230}Th = 20910 \pm 210$ (all errors quoted at 2σ). For determination of U isotopic ratios in the spike, we first measured the fractionation-uncorrected raw ratios by repeated analyses of the spike only. Then we mixed the spike with the HU-1 standard and unknown samples, measured the mixed ratios, and performed spike un-mixing and mass fractionation correction on $^{233}U/^{236}U$ in the spike iteratively by normalizing to $^{238}U/^{235}U = 137.88$ in the natural samples. Then we used the fractionation-corrected $^{233}U/^{236}U$ (0.96341 ± 0.00033) to correct for $^{233}U/^{238}U$, $^{233}U/^{234}U$ and $^{233}U/^{235}U$ ratios in the spike. For measurement of Th isotopic ratios in the spike, we first determined the raw ratios through repeated measurements of the spike, and then applied fractionation correction using a nominal fractionation factor of -0.14% per mass unit calculated from a mean raw $^{238}U/^{235}U$ ratio obtained on the machine over a period of time as a reference. We used U and Th metal standards to calibrate the spike concentrations and then used the secular equilibrium standard HU-1 (a fraction taken from USGS in Denvor) to calibrate the $^{233}U/^{229}Th$ ratio of the mixed spike following the procedures described in Ludwig et al. (1992) and Stirling et al. (1995). Mass spectrometric analyses of 15 separate spiked HU-1 solutions yielded a mean $^{233}U/^{229}Th$ ratio of 9.754 ± 0.0012 ($2\sigma_m$).

The analytical results are listed in Table 2 for Yongshu Reef and Table 3 for Meiji Reef. All samples contain 2–3 ppm U and their $\delta^{234}U$ values are in the range of 149 ± 4‰, typical of modern seawater and modern or recent pristine corals reported in other studies (Cobb et al., 2003; Delanghe et al., 2002; Stirling et al., 1995; Weisler et al., 2006; Yu et al., 2004a). ^{232}Th contents in these samples vary between 0.14 and 0.65 ppb. The U-series data indicate that all the corals grew over the past two centuries.

Table 2
TIMS U-series ages for *in situ Porites* corals on the reef flat of Yongshu Reef, Nansha area, southern South China Sea

Sample name	Years from sampling location to the surface	U (ppm)	^{232}Th (ppb)	($^{230}Th/^{232}Th$)	($^{230}Th/^{238}U$)	($^{234}U/^{238}U$)	Uncorr. ^{230}Th Age (yr)	Corr. ^{230}Th Age (yr)	$\delta^{234}U(T)$	Mortality (surface) age (Year in AD)	Year dated	Location code in Fig. 1
YSL2-01	1	2.5291	0.194	3.990	0.000101±02	1.1491±09	9.5±0.2	6.5±0.6	149.1±0.9	2000.0±0.6	2005.5	L1
YSL24-1	1	2.4826	0.273	3.428	0.000124±04	1.1473±11	11.8±0.7	7.5±1.0	147.3±1.1	1999.0±1.0	2005.5	L2
YSL8-1	1	2.7223	0.267	3.621	0.000117±09	1.1492±13	11.1±0.9	7.2±1.1	149.2±1.3	1999.3±1.1	2005.5	L3
YSO-51-4	35	2.3840	0.194	16.64	0.000447±06	1.1516±19	42.2±0.6	39.0±0.9	151.6±1.9	1999.0±0.9	2003	1
YSO-01-2	35	2.3036	0.478	8.550	0.000584±11	1.1496±19	55.3±1.1	47.1±1.9	149.6±1.9	1990.9±1.9	2003	2
YSO-35-2	30	2.6279	0.481	10.16	0.000613±01	1.1490±20	58.0±1.0	50.8±1.7	149.0±2.0	1982.2±1.7	2003	3
YSO-29-3	35	2.3874	0.469	10.45	0.000676±12	1.1464±20	64.2±1.1	56.4±1.9	146.4±2.0	1981.6±1.9	2003	4
YSO-23-3	28	2.4202	0.364	14.02	0.000694±38	1.1524±41	65.5±3.6	59.6±3.7	152.4±4.1	1971.4±3.7	2003	5
YSO-26-3	34	2.3022	0.393	16.15	0.000908±57	1.1526±22	85.7±5.4	79.1±5.6	152.6±2.2	1957.9±5.6	2003	6
SWYS-3	0	2.3793	0.231	16.34	0.000523±02	1.1493±22	49.5±1.9	45.7±2.0	149.3±2.2	1957.3±2.0	2003	7
YSO-03-3	29	2.4642	0.42	16.97	0.000954±21	1.1542±41	89.9±2.0	83.3±2.4	1542±4.1	1948.7±2.4	2003	8
YSO-19-3	28	2.8714	0.649	13.24	0.000986±12	1.1520±13	93.1±1.2	84.3±2.1	152.0±1.3	1946.7±2.1	2003	9
YSO-57-4	32	2.3749	0.289	32.35	0.001299±49	1.1490±20	123.0±4.7	118.2±4.8	149.0±2.0	1916.8±4.8	2003	10
YSO-49-4	0	2.5295	0.553	20.40	0.001469±94	1.1510±25	138.9±8.9	130.3±9.0	151.0±2.5	1872.7±9.0	2003	11
SWYS-4	0	2.3403	0.206	50.23	0.001455±03	1.1533±21	137.3±2.8	133.9±2.9	153.3±2.1	1869.2±2.9	2003	12
YSO-40-5	36	2.4429	0.484	35.05	0.002287±154	1.1475±23	217±15	209±15	147.5±2.3	1830±15	2003	13

Note: Ratios in parentheses are activity ratios calculated from the atomic ratios, but normalized to measured values of secular-equilibrium HU-1 standard following the method of Ludwig et al. (1992). Errors are at 2σ level for the least significant digits. $\delta^{234}U = [(^{234}U/^{238}U)-1] \times 1000$ and $\delta^{234}U(T) = \delta^{234}U(O)e^{\lambda 234T}$, where the age ($T$) is calculated using Isoplot EX 2.3 (Ludwig, 1999) with decay constants $\lambda_{238} = 1.551 \times 10^{-10}\,yr^{-1}$ (for ^{238}U),$\lambda_{234} = 2.835 \times 10^{-6}\,yr^{-1}$(for ^{234}U) and $\lambda_{230} = 9.195 \times 10^{-6}\,yr^{-1}$ (for ^{230}Th), respectively. 2σ errors in the uncorrected (uncorr.) ages were propagated directly from the uncertainties in the ($^{230}Th/^{238}U$) and ($^{234}U/^{238}U$). The corrected (corr.) ^{230}Th ages were calculated using non-radiogenic ($^{230}Th/^{232}Th$) = 1.26±0.25 back-calculated based on measurements of three living corals (YSL2-01, YSL24-1, YSL8-1) collected in May 1999. The TIMS U-series ages are relative to the year dated. The mortality (surface) age (in years AD) refers to the time when the coral head died, which was estimated based on the corrected TIMS ^{230}Th age and the number of annual layers above the sampling location. See text for discussion.

Table 3
TIMS U-series ages for *in situ Porites* corals on the reef flat of Meiji Reef, Nansha area, southern South China Sea

Sample name	Annual bands from sampling location to the surface	U (ppm)	^{232}Th (ppb)	(^{230}Th/^{232}Th)	(^{230}Th/^{238}U)	(^{234}U/ ^{238}U)	uncorr. ^{230}Th Age (yr)	corr. ^{230}Th Age (yr)	$\delta^{234}U$ (T)	Mortality (surface) age (Year in AD)	Year dated	Location code in Fig. 1
MJL4-1	1	2.2502	0.144	2.25	0.000048 ± 00	1.1447 ± 10	4.5 ± 0.1	1.9 ± 0.5	144.7 ± 1.0	2004.5 ± 0.5	2005.5	L1
MJL7-1	1	2.6497	0.211	2.13	0.000056 ± 00	1.1505 ± 10	5.3 ± 0.2	2.0 ± 0.7	150.5 ± 1.0	2004.6 ± 0.7	2005.5	L2
MJL9-1	1	2.6243	0.204	2.20	0.000056 ± 00	1.1474 ± 11	5.3 ± 0.3	2.1 ± 0.7	147.4 ± 1.1	2004.3 ± 0.7	2005.5	L3
MJO14-2	59	2.4130	0.386	13.96	0.000736 ± 20	1.1487 ± 11	69.7 ± 1.9	63.1 ± 2.3	148.7 ± 1.1	1999.9 ± 2.3	2004	1
MJO15-2	10	2.8744	0.247	7.03	0.000199 ± 05	1.1512 ± 12	18.8 ± 0.6	15.3 ± 0.9	151.2 ± 1.2	1998.7 ± 0.9	2004	2
MJO13-1	8	2.4212	0.235	11.44	0.000365 ± 06	1.1490 ± 14	34.6 ± 0.6	30.6 ± 1.0	149.0 ± 1.3	1982.9 ± 1.0	2005.5	3
MJO10-2	23	2.3261	0.308	14.76	0.000644 ± 12	1.1471 ± 10	61.1 ± 1.2	55.6 ± 1.6	147.1 ± 1.0	1971.4 ± 1.6	2004	4
MJO19-1	15	2.4392	0.326	14.75	0.000651 ± 12	1.1478 ± 17	61.7 ± 1.2	56.1 ± 1.6	147.8 ± 1.7	1964.4 ± 1.6	2005.5	5
MJO11-1	68	2.6120	0.265	36.38	0.001219 ± 11	1.1478 ± 10	115.5 ± 1.1	111.3 ± 1.4	147.8 ± 1.0	1960.7 ± 1.4	2004	6
MJO12-1	13	2.5074	0.161	40.57	0.000857 ± 14	1.1457 ± 11	81.4 ± 1.4	78.7 ± 1.5	145.7 ± 1.1	1937.3 ± 1.5	2004	7
MJO6-1	8	2.2876	0.291	24.47	0.001025 ± 12	1.1484 ± 11	97.1 ± 1.2	91.8 ± 1.6	148.4 ± 1.1	1920.1 ± 1.6	2004	8
MJO10-1	13	2.5594	0.620	14.60	0.001165 ± 15	1.1496 ± 15	110.3 ± 1.5	100.3 ± 2.5	149.6 ± 1.5	1916.7 ± 2.5	2004	9
MJO17-1	22	2.3679	0.291	34.87	0.001413 ± 12	1.1490 ± 13	133.8 ± 1.2	128.8 ± 1.6	149.0 ± 1.2	1897.2 ± 1.6	2004	10
MJO13-2	6	2.3622	0.368	28.11	0.001445 ± 20	1.1514 ± 14	136.5 ± 1.9	130.1 ± 2.3	151.4 ± 1.4	1879.9 ± 2.3	2004	11
MJO2-5	95	2.6455	0.476	42.23	0.002507 ± 21	1.1530 ± 12	236.7 ± 2.1	229.3 ± 2.6	153.0 ± 1.2	1869.7 ± 2.6	2004	12
MJO8-2	76	2.4133	0.558	30.54	0.002325 ± 33	1.1481 ± 09	220.5 ± 3.2	210.9 ± 3.7	148.1 ± 0.9	1869.0 ± 3.7	2004	13
MJO5-1	2	2.3333	0.212	51.41	0.001539 ± 11	1.1460 ± 16	146.2 ± 1.1	142.4 ± 1.3	146.0 ± 1.6	1865.1 ± 1.3	2005.5	14

Notes are the same as in Table 2, except the corrected ^{230}Th ages were calculated using non-radiogenic (^{230}Th/^{232}Th) = 1.32 ± 0.26 back-calculated based on measurements of three living corals (MJL4-1, MJL7-1 and MJL9-1) collected in May 2004.

5. Discussions

5.1. Interpretation of U-series data and establishment of coral mortality ages

As all these corals are extremely young, non-radiogenic Th correction becomes significant in the age calculation (as reflected by their low ^{230}Th/^{232}Th activity ratios), resulting in large uncertainties (Cobb et al., 2003). Procedural and spike blanks may also be an important factor for consideration.

We have measured our procedural ^{230}Th blank (including loading and filament blanks), which is around $3.3 \pm 3.3 \times 10^{-17}$ g, contributing less than 0.07 ± 0.07 year (~4 weeks) to the calculated coral ages. The procedural blanks for ^{238}U and ^{232}Th are both less than 5×10^{-12} g (based on repeated measurements over a long period of time). Such levels of blanks are negligible, because the overall age uncertainty is about $\pm$1–5 years, 13–65 times higher than the blank contribution. In addition, the ^{229}Th/^{230}Th and ^{229}Th/^{232}Th ratios in the spikes we used have been precisely determined (see above) and incorporated in the age calculation spreadsheet (and thus the spike blank is already extracted in the age calculation).

The major age uncertainty lies in non-radiogenic Th correction. According to Roy-Barman et al. (1996) and Cobb et al. (2003), the following potential non-radiogenic Th sources may affect non-radiogenic ^{230}Th/^{232}Th values of the corals: (1) Aeolian dusts with ^{230}Th/^{232}Th $\sim 4.4 \times 10^{-6}$ (activity ratio ~0.825); (2) Surface seawater containing dissolved and particulate Th (derived from Aeolian dusts) with ^{230}Th/^{232}Th ~5 to 10×10^{-6} (activity ratio ~1–2); (3) Th in deep seawater with ^{230}Th/^{232}Th $\sim 2 \times 10^{-4}$ (activity ratio ~50); and (4) Th in carbonate sands from ongoing erosion of coral reef (Robinson et al., 2004). We consider the former two types of sources, are predominant, due to the fact that South China Sea is a semi-enclosed marginal sea in the proximity of continental crust, that receives significant terrestrial dust input carried by East Asian winter monsoon air mass (Wang et al., 2005), differing from the site in the central Pacific (Cobb et al., 2003). The Nansha area is also different from reef sites in the eastern Pacific, where deep ocean water upwelling is significant during El Niño events.

To better constrain the non-radiogenic Th isotopic compositions, we measured growth bands of three living corals from each of the reefs. As the ages of the growth bands used for measurement are independently known, we use the known ages to back-calculate the non-radiogenic Th isotopic compositions. The three living corals widely distributed across Yongshu reef (see Fig. 1) were collected in May 1999 and we dated the growth bands one year below their surfaces in June 2005 (i.e. the materials were about 7.0-years old at the time of measurement). Based on the measured ^{230}Th/^{238}U and ^{234}U/^{238}U activity ratios and their known age, we back-calculated the expected non-radiogenic ^{230}Th/^{232}Th activity ratios. Such back-calculation was performed iteratively by adjusting the value of the non-radiogenic ^{230}Th/^{232}Th activity ratio for correction until the corrected ^{230}Th age of the living coral is equal to its known age. The expected non-radiogenic ^{230}Th/^{232}Th activity ratios for the three living corals are 1.060, 1.330 and 1.393, respectively, with a mean value of 1.26 ± 0.18, which is expected for a mixture of Aeolian dusts and surface seawater particulates. Similarly, three living corals widely distributed across Meiji reef (see Fig. 1) were collected in May 2004 and we dated the growth bands one year below their surfaces in June 2005 (i.e. the materials were about 2.0 years old at the time of measurement). Using the same back-calculation method, we obtained the following non-radiogenic ^{230}Th/^{232}Th activity ratios for Meiji reef: 1.255, 1.325 and 1.370, with a mean value of 1.32 ± 0.06, which is again expected for a mixture of Aeolian dusts and surface seawater particulates. The mean non-radiogenic ^{230}Th/^{232}Th activity ratios from both sites, despite ~200 km distance between each other, are very similar to each other, which could be due to the predominant control of Aeolian dusts carried by East Asian winter monsoon air mass (Wang et al., 2005). Considering possible variation with time and the analytical errors in the measurement of the living corals, we arbitrarily assigned a constant 20% uncertainty to the above-measured non-radiogenic ^{230}Th/^{232}Th activity ratios (i.e. 1.26 ± 0.25 and 1.32 ± 0.26) and used such values to calculate non-radiogenic Th-corrected ^{230}Th ages for samples from Yongshu and Meiji reefs, respectively (Tables 2 and 3). The non-radiogenic Th corrections result in the corrected ^{230}Th ages being 2–10 years younger than the uncorrected ^{230}Th ages, with an error magnification by ca. 7–300% derived mainly from the 20% uncertainty in the measured non-radiogenic ^{230}Th/^{232}Th activity ratio. The magnitude of age corrections and error magnification are mainly related to the sample age and ^{230}Th/^{232}Th activity ratio in the sample.

It is worthwhile to note that the consistent results from the six modern corals of known ages clearly indicate the dominant control of a single non-radiogenic Th source (the Aeolian dusts and their derivatives in seawater) in the Nansha area, with contribution from bank-top water with elevated ^{230}Th/^{232}Th activity ratios (7–18) being unlikely, although it might be a case in Bahamas (Robinson et al., 2004). For instance, if ^{230}Th/^{232}Th>2 is used for detrital corrections, the living corals and some youngest dead corals will yield non-radiogenic Th corrected ages that are younger than the times of sample collections.

We work out the mortality age for each dead coral on Yongshu and Meiji Reefs by extracting the number of annual growth bands above the sampling location from the corrected ^{230}Th age. The results for Yongshu are listed in Table 2 and illustrated in Fig. 2, and those for Meiji, in Table 3 and Fig. 3. Overall, the results show that at least nine episodes of coral mortality occurred on Yongshu Reef over the past two centuries, and eight episodes of mortality occurred on Meiji reef between 1865 and 2000 AD.

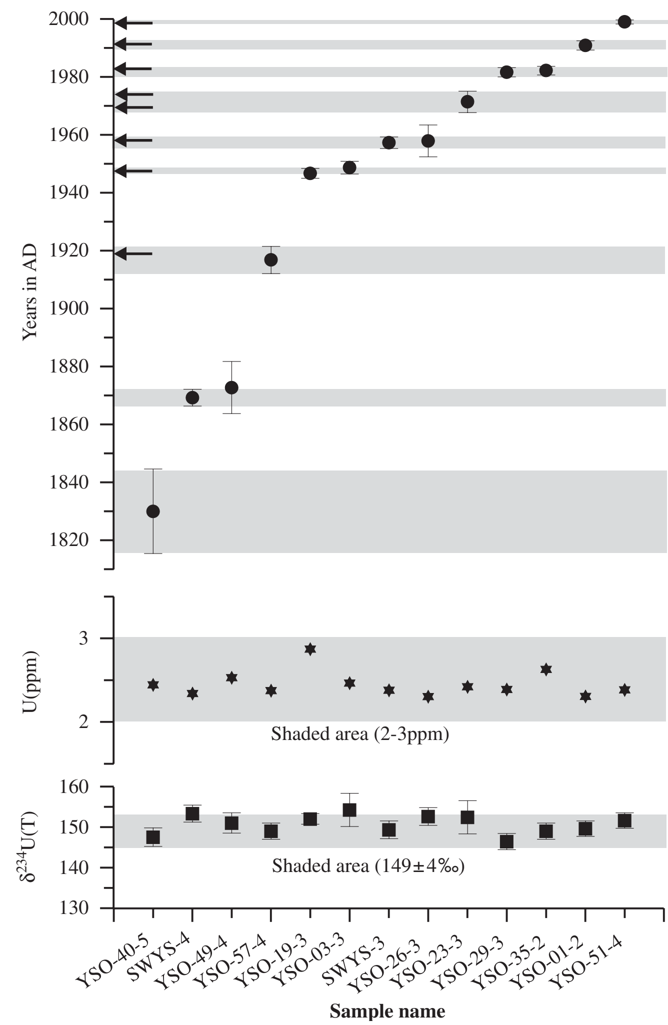

Fig. 3. Massive coral mortality age distribution of Yongshu Reef, showing an increased frequency (to 9-year cycle) since 1940s. Note that all the mortality events over the last century are correlated with historic El Niño events (shown as arrows). Also plotted are U abundances and δ^{234}U(T) values for the dated samples, all of which fall into the ranges for modern corals.

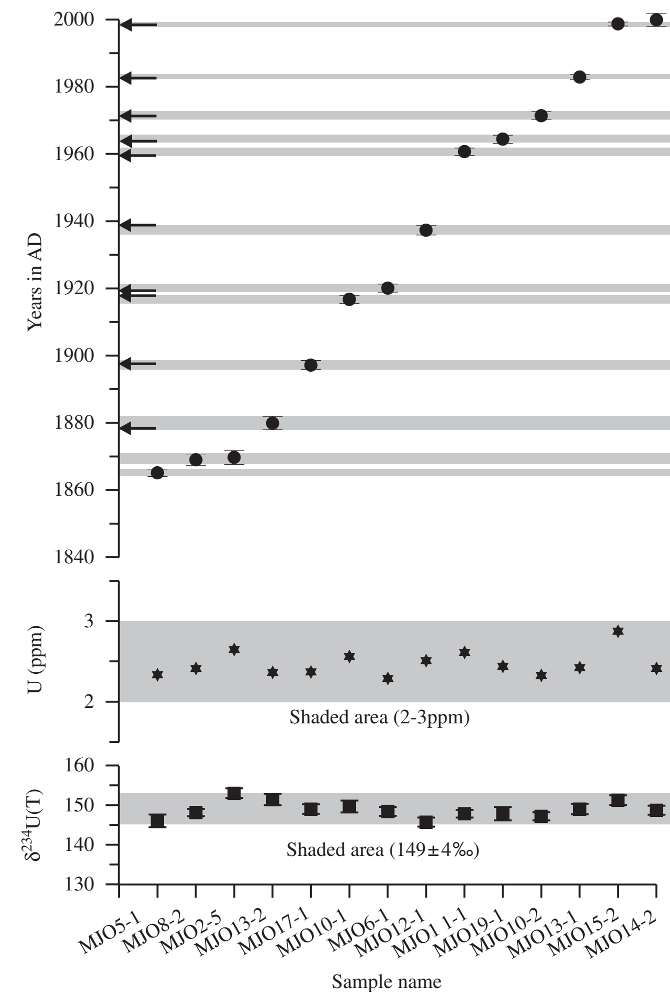

Fig. 4. Massive coral mortality age distribution of Meiji Reef. Note that most mortality events are correlated with historic El Niño events (shown as arrows). Also plotted are U abundances and δ^{234}U(T) values for the dated samples, all of which fall into the ranges for modern corals.

5.2. Coral mortality age distribution

The results (Tables 2 and 3) show that episodic mortality of massive coral colonies occurred over the past two centuries both on Yongshu and Meiji Reefs. The age distribution indicates that the frequency of coral mortality in Yongshu reef (Fig. 3) appears to have significantly increased in the 20th century, with nearly 70% of the mortality events occurring after 1940s, which is consistent with observed frequency increase in mass coral bleaching events since late 1970s (Glynn, 1996; Lough, 2000). However, the coral mortality frequency in Meiji Reef (Fig. 4) seems quite uniform over the past two centuries. It is likely the difference in the mortality frequencies could be due to sampling bias as a result of insufficient samples (only 13–14 samples from each reef) or different erosion, preservation and recruitment status. Alternatively, it could be due to different local environments. For instance, samples from Yongshu Reef are widely distributed in the inner-reef flat zone, but samples from Meiji reef are concentrated in two localities near the channels linking to open ocean (Fig. 1). It is likely that seawater temperature on the Yongshu Reef flat is warmer due to much shallower water depth, which may pose a stronger effect on coral health as a result of recent global warming since the middle of last century. In contrast, seawater near the channels of the Meiji reef might be cooler due to continuous convection and water mass exchange through the channels. Nevertheless, it is worthwhile to collect and date more samples from each reef to examine if the different mortality frequencies are real.

5.3. Possible causes of coral mortality

Due to the lack of systematic coral reef investigation in Nansha area, South China Sea, such numerous coral mortality events have never been reported; less is known about the causes of mortality. Coral mortality can be attributed to a number of reasons: (1) destruction from natural calamities, including high temperature and associated radiation leading to coral reef bleaching (Brown and Ogden, 1993; Dunne and Brown, 2001; Glynn, 1991; Jimenez et al., 2001; Lesser, 1997; Mumby et al., 2001), freshwater input leading to a lower salinity (Coles and Jokiel, 1992; Jokiel et al., 1993), rapid high-magnitude cooling which kills the reef corals (i.e. "cold bleaching") (Coles and Fadlallah, 1991; Gates et al., 1992; Hoegh-Guldberg, 2004; Yu et al., 2004b), extremely low tide leading to emergence of the coral reef (Fadlallah et al., 1995), severe storms (Guilcher, 1988; Morton, 2002), and volcanic eruptions (Maniwavie et al., 2001); (2) the feeding of the natural predators, such as *Acanthaster planci* (Colgan, 1987) and *Diadema antillarum* (Spalding et al., 2001); (3) destruction by human activities (Dight and Scherl, 1997; Grigg, 1995), such as digging, collecting, diving, ship grounding, over-fishing, oil drilling, and pollution; and (4) Outbreak of diseases (Harvell et al., 2001). As Yongshu Reef stands over 2000 m above the sea floor and is relatively far away from mainland, the deaths of such massive corals cannot be caused by human activity or freshwater input. Severe cooling events can be ruled out because the reef is close to the equator with winter SST minimum never dropping below 25 °C. All the sampled coral heads are below present low spring tide, some are from channel slopes with strong current flow. Thus it is also difficult to explain the mortality in terms of low tide emergence. In addition, the mortality cannot be caused by volcanic eruption, either, due to the lack of eruption record in the vicinity over the past two centuries.

We consider that the episodic coral mortality of Yongshu and Meiji Reefs was probably caused by high temperature and radiation-induced bleaching, especially for the mortality events (e.g. in 1869–1873, 1917–1920, 1957–1961, 1971, 1982–1983 and 1999–2000 AD) occurring simultaneously on both reefs (Fig. 5), although some events, e.g. that during 1865–1880 AD, may also likely be due to severe storm events (Yu et al., 2004a). Numerous cases of bleaching-induced mortality have been reported worldwide over the last two decades. For instance, strong El Niño events during 1997–1998 (Glynn et al., 2001), 1991–1992 (Hoegh-Guldberg and Salvat, 1995; Jimenez and Cortes, 2003; Podesta and Glynn, 1997), 1987–1988 (Cook et al., 1990; Goreau and Macfarlane, 1990) and 1982–1983 (Glynn et al., 2001) have caused severe bleaching and mortality worldwide. Statistical comparison among 47 globally distributed coral reef bleaching sites (Lough, 2000) show that, during the 1997–98 bleaching event, warmest monthly SSTs at these sites range from 28.4 to 34.9 °C, with an average of ~30.3 °C. Nansha area is part of the Western Pacific Warm Pool, and its SST correlates with that of the eastern Pacific at a half-year lag (Wang et al., 2002). Monthly SST maxima, summer-season SST and annual SST variations over past 45 years (Fig. 6) for the Nansha area show that almost all the positive anomalies of these three SST parameters are correlated in

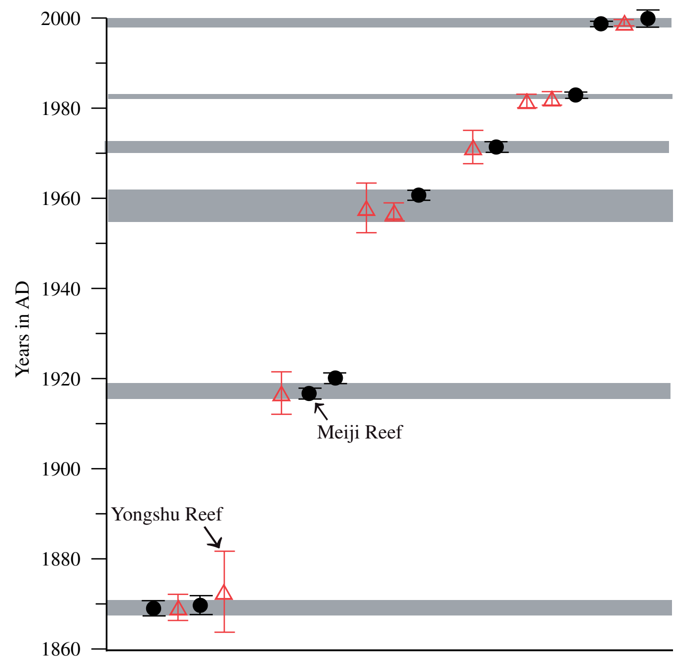

Fig. 5. Six mortality events that were identified on both Yongshu and Meiji Reefs, southern South China Sea.

time with historical El Niño events, e.g. during 1957–1959, 1965–1966, 1972–1973, 1982–1983, 1986–1988, 1991–1992, and 1997–1998 AD (See http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html). It is also interesting to note that most of the monthly SST maxima during El Niño years are close to or even above 30.3 °C, which is the average monthly SST maximum during 1997–1998 for 47 bleaching sites worldwide (Lough, 2000). In addition, monthly SSTs in Nansha area were 30.3 °C or higher for five consecutive months (May–September) in 1998 (Fig. 7), with an average of 30.7 °C, which was sufficiently high and lasted sufficiently long to cause coral bleaching. In fact, severe mass coral bleaching and death of large massive *Porites* corals were reported to have occurred on Kalayaan Island (11°–11°45′ N, 114°–116°20′ E) of the Nansha area in 1998 (Arceo et al., 2001). After this event, reefs around Philippine were significantly affected, with living coral coverage being reduced to 41% of the total reef area and dead coral coverage increasing to 49%. As Yongshu and Meiji Reefs are about 2° south (towards equator) of the Kalayaan Island, the SSTs in these reefs are expected to be even higher than those of Kalayaan Island and therefore coral bleaching is expected to be even more severe in 1998. In this regard, we suggest that it is the anomalously warm SST in the Nansha area that was responsible for the mortality of *Porites* corals in 1998 AD (Three samples dated at this age).

Apart from the 1998 mortality event, our results also show that the other most recent mortality events were dated at 1957.3 ± 2.0, 1957.9 ± 5.6, 1971.4 ± 3.7, 1981.6 ± 1.9, 1982.2 ± 1.7 and 1990.9 ± 1.9 AD on Yongshu Reef, within error of the 1957–1959, 1972–1973, 1982–1983 and 1991–1992 El Niño events. Similarly, mortality events

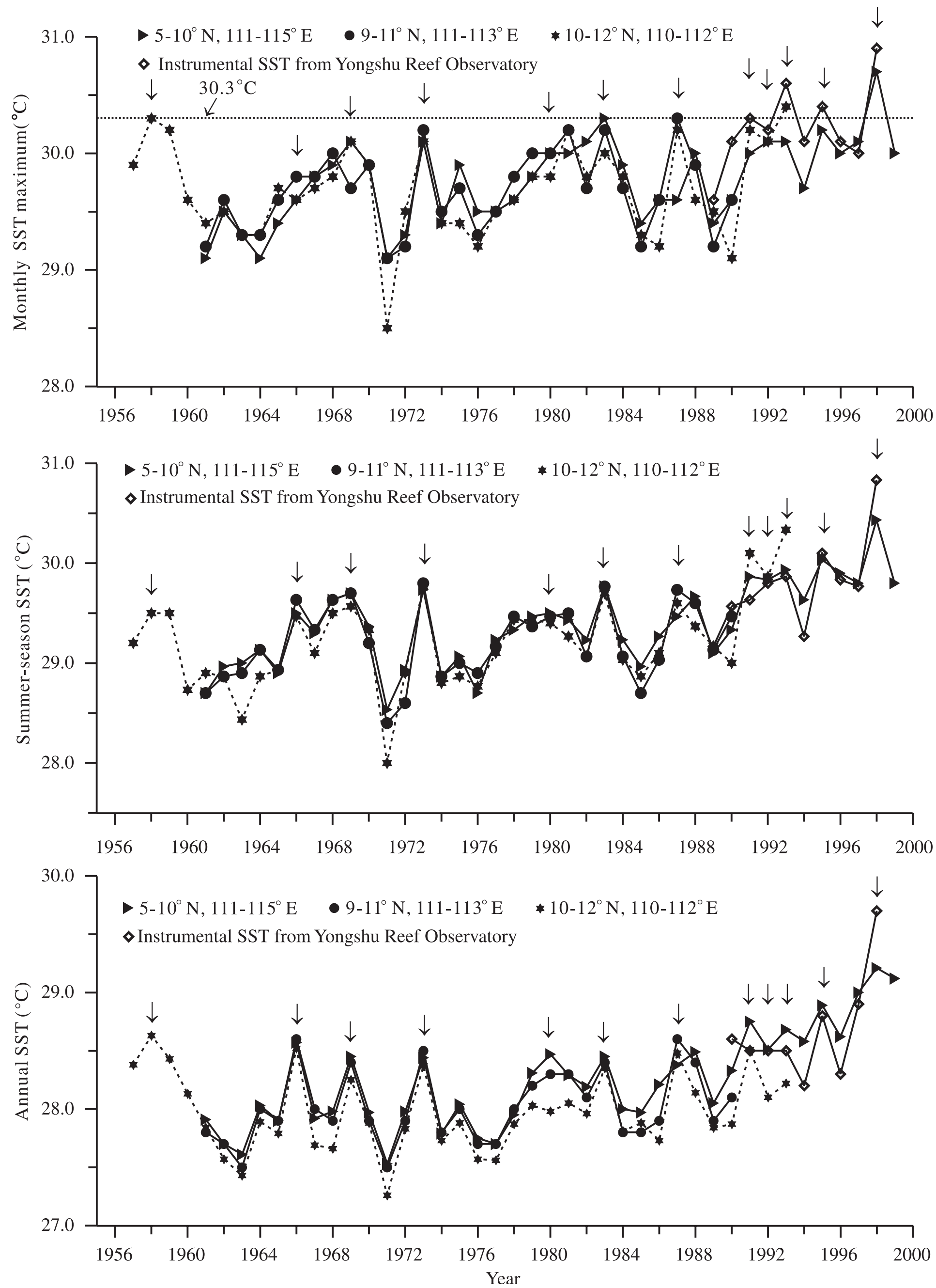

Fig. 6. Shipboard (for areas of 5–10°N/111–115°E, 9–11°N/111–113°E, 10–12°N/110–112°E, respectively), and instrumental SSTs in Nansha area for the past 45 years. Arrows indicate the El Niño years. Note that positive SST anomalies are well correlated with El Niño years. The 30.3 °C dashed straight line marks the average SST in the warmest month in 1998 recorded in 47 coral reef bleaching sites worldwide (Lough, 2000).

were also dated at 1960.7 ± 1.4, 1964.4 ± 1.6, 1971.4 ± 1.6, and 1982.9 ± 1.0 AD on Meiji Reef, which are all analytically within errors of the 1957–1959, 1965–1966, 1972–1973 and 1982–1983 El Niño events. The dates of some other earlier mortality events (e.g. 1948.7 ± 2.4, 1946.7 ± 2.1 on Yongshu and 1920.1 ± 1.6, 1916.7 ± 2.5, 1897.2 ± 1.6 AD on Meiji) are also comparable to historic records of El Niño events during 1946–1947, 1918–1919, and 1896–1897 AD (See http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears_1877-present.html). It is worthwhile to note that the frequency of El Niño recurrence is only about 3–7 years. The U-series age precisions for some samples (e.g. YSO-23-3, YSO-26-3) are too large to define an unequivocal correlation. However, precisions for most other samples, such as those dated at 1999.0 ± 1.0, 1990.9 ± 1.9, 1982.2 ± 1.7, 1981.6 ± 1.9, 1957.3 ± 2.0, 1946.7 ± 2.1 AD on Yongshu Reef, and 1998.7 ± 0.9, 1982.9 ± 1.0, 1971.4 ± 1.6, 1964.4 ± 1.6, 1960.7 ± 1.4, 1920.1 ± 1.6, 1897.2 ± 1.6 AD on Meiji Reef, are obviously consistent in timing with historic El Niño events. Although some dates are also analytically consistent with La Niña years (due to larger

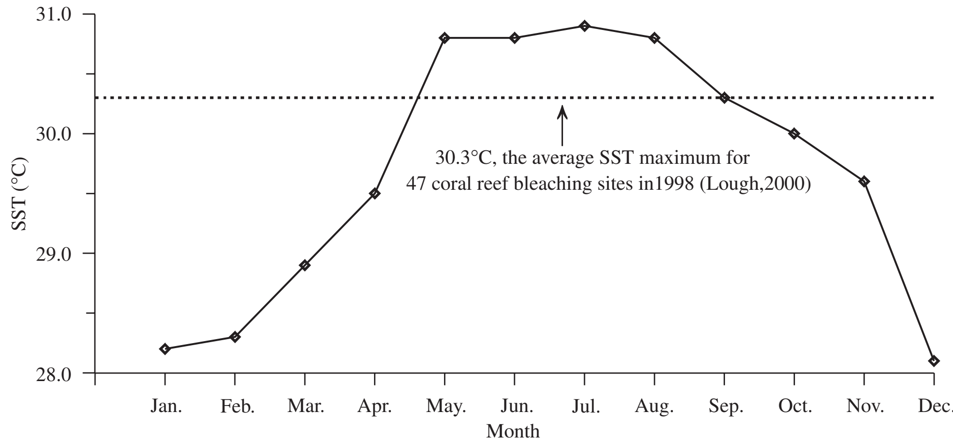

Fig. 7. Monthly instrumental SST record on Yongshu Reef during 1998 AD. Note that monthly SSTs from April to September are equal to or higher than 30.3 °C, the average SST maximum in 1998 for 47 coral reef bleaching sites worldwide (Lough, 2000).

age errors), the mortality of these corals cannot be linked to the La Niña event by "cold bleaching" (Hoegh-Guldberg, 2004; Yu et al., 2004b), simply because the coolest SSTs (>24 °C) in the region are still much too warm to kill the corals by cooling. Thus it is reasonable to argue that at least the ages of coral mortality in Nansha area of the South China Sea over the last century are consistent with the timing of El Niño-induced SST warming events in the region. The environmental conditions and past instrumental SST records in the region (Fig. 6) do suggest that El Niño-related positive summer SST anomalies appear to be the most likely cause for the coral mortality. Independent constraints on the link between coral mortality and El Niño-related summer SST anomaly can be obtained using high-resolution Sr/Ca or δ^{18}O-based SST records and trace element data in the dated dead corals, which will be determined in the near future.

5.4. Implications for the study of climate change and coral reef ecology

According to previous studies and quantitative assessments of mortality (Fujioka, 1999; Mumby et al., 2001; Stimson et al., 2002), there are significant differences among species in their response to bleaching, with fast-growing corals (e.g. *Acropora* and *Pocillopora*) being more severely affected by bleaching than slow-growing species (e.g. *Porites* and *Favia*). In this regard, massive *Porites* is considered to be most resistant to bleaching and thus least likely to be killed by bleaching. Because of this, the mortality of massive corals like *Porites* in Nansha area is an indication of severe climate events. For instance, the famous 1997–1998 bleaching event caused severe mortality of massive corals in many areas worldwide, such as the bulk of the Indian Ocean, causing severe global environmental problems. Although satellite remote sensing is being developed to monitor the ecology of coral reefs over a wide area (Isoun et al., 2003; Yamano et al., 2002), it cannot be used to detect past mortality history. Our study convincingly demonstrates that coral mortality history for many coral reef areas can be reconstructed through precise and accurate dating of killed massive corals. Our records also indicate that coral bleaching and mortality may have occurred over the past two centuries in the southern South China Sea, and the trend shows that it appears to become more severe in recent time. Knowledge of past bleaching, mortality and recovery history will help assessment of current ecological status of the world coral reefs and prediction of future trend.

It is also worthwhile to note that although there have been many times at which corals may have died of El Niño-induced warm-temperature bleaching, many of the other coral colonies next to the dead ones lived through these times and those died during the later events (e.g. in 1998) survived previous events. This observation does raise an interesting question that is worth further study, that is, whether an event that caused mortality in one coral can be seen as a stress band within the growth banding of nearby corals.

6. Conclusions

Our pilot study based on 33 samples from two reefs of Nansha area, southern South China Sea demonstrates that TIMS U-series dating of killed massive corals such as *Porites* is a promising new method for understanding coral mortality history as well as the mechanisms responsible for mortality. The results show that during past two centuries massive coral mortality recurred many times on Yongshu and Meiji reefs. It shows effectively that the TIMS U-series technique can be used to reconstruct the time of death of massive coral colonies, which might be assumed to have all died in the same event in the absence of this powerful technique. In addition, we demonstrate that many of these mortality events appear to correlate in time with historic El Niño events, and were probably related to El Niño-induced high SST bleaching.

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