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Variation of initial $^{230}Th/^{232}Th$ and limits of high precision U–Th dating of shallow-water corals

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Abstract

One hundred eighty U–Th data, including 23 isochrons on 24 pristine modern and Holocene corals and 33 seawater samples, were analyzed using sector-field mass spectrometry to understand the variability of initial $^{230}Th/^{232}Th$ ($^{230}Th/^{232}Th_0$). This dataset allows us to further assess the accuracy and precision of coral ^{230}Th dating method. By applying quality control, including careful sampling and subsampling protocols and the use of contamination-free storage and workbench spaces, the resulting low procedural blanks give an equivalent uncertainty in age of only ±0.2–0.3 yr for 1–2 g of coral sample. Using site-specific $^{230}Th/^{232}Th_0$ values or isochron techniques, our study demonstrates that corals with an age less than 100 yrs can be ^{230}Th-dated with precisions of ±1 yr. Six living subtidal coral samples were collected from two continental shelf sites, Nanwan off southern Taiwan in the western Pacific and Son Tra off central Vietnam in the South China Sea; one coral core was drilled from an open-ocean site, Santo Island, Vanuatu, in the western tropical Pacific; and modern and fossil intertidal coral slabs, 17 in total, were cut from six sites around the islands of Simeulue, Lago, North Pagai and South Pagai of Sumatra in the eastern Indian Ocean. The results indicate that the main source of thorium is the dissolved phase of seawater, with variation of $^{230}Th/^{232}Th_0$ depending on local hydrology. With intense input of terrestrial material, low $^{230}Th/^{232}Th_0$ atomic ratios of 4.9×10^{-6} and 3.2×10^{-6} with a 10% variation are observed in Nanwan and Son Tra, respectively. At the Santo site, we find a value of 5.6×10^{-6} at 4 horizons and one high value of 24×10^{-6} in a sample from AD 1974.6 ± 0.5, likely due to the upwelling of cold water during a La Niña event between AD 1973 and 1976. The natural dynamics of $^{230}Th/^{232}Th_0$ recorded in the intertidal corals at sites in the Sumatran islands are complicated so that this value varies significantly from 3.0 to 9.4×10^{-6}. Three of the 141 modern coral ^{230}Th ages differ from their true ages by −23 to +4, indicating the presence of detrital material with anomalous $^{230}Th/^{232}Th$ values. Duplicate measurement of coeval subsamples is therefore recommended to verify the age accuracy. This improved high precision coral ^{230}Th dating method raises the prospects of refining the age models for band-counted and tracer-tuned chronologies and of advancing coral paleoclimate research.

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1. INTRODUCTION

Geochemical and isotopic compositions in shallow-water coralline aragonite have been widely used as proxies to reconstruct paleoclimatic conditions (e.g., Wellington and Dunbar, 1995; Shen et al., 1996; Beck et al., 1997; Gagan et al., 1998; McCulloch et al., 1999, 2003; Hendy et al., 2002; Cutler et al., 2003; Shen et al., 2005a; Thompson and Goldstein, 2005). Since the 1990s, weekly to monthly resolution coral climate records over decadal, centennial, or millennial time scales have been published (e.g., Gagan and Chivas, 1995; Crowley et al., 1997; Evans et al., 1998; Linsley et al., 2000; Urban et al., 2000; Hendy et al., 2002; Cobb et al., 2003a; McCulloch et al., 2003; Kilbourne et al., 2004; Sun et al., 2004; Nyberg et al., 2007). For centuries-old modern and young fossil corals, age uncertainties of ±1–5 yrs limit our ability to accurately determine the timing of climatic events and the precisely cross-correlate coral records to other high resolution proxy records.

Coral chronology can be determined by bulk annual density band counting (e.g., Dodge and Brass, 1984; Cole and Fairbanks, 1990; Crowley et al., 1997; Linsley et al., 1999; Kilbourne et al., 2004), or by tuning tracer records using methods adapted from dendrochronology and sediment core chronostratigraphy (e.g., Gagan and Chivas, 1995; Linsley et al., 1999; Cobb et al., 2003b; Hendy et al., 2003). Difficulty arises when using these methods for precise absolute chronological control in the following cases: (1) living corals with banding discontinuities caused by climatic and/or tectonic anomalies (e.g., Sieh et al., 1999; Hendy et al., 2003; Natawidjaja et al., 2004), (2) corals living in the equatorial oceans with intrinsically small seasonal climatic cycles (as low as 0–2 °C of seasonal temperature change), and (3) dead coral heads and fossils without absolute ages and/or mortality event-related age markers (Glynn et al., 1983; Yu et al., 2004).

The ^{230}Th dating method provides an ideal absolute chronological tool for coral because of high uranium levels of 2–3 parts per million (ppm) in their skeletons (Bateman, 1910; Barnes et al., 1956; Broecker and Thurber, 1965; Kaufman and Broecker, 1965; Edwards et al., 1987, 1988, 2003). The ^{230}Th age equation, including initial ^{230}Th/^{232}Th, is reported by Edwards et al. (2003) (modified from Bateman (1910) and Broecker (1963))

$$\frac{^{230}\mathrm{Th}}{^{238}\mathrm{U}} = 1 + \left(\left(\frac{^{232}\mathrm{Th}}{^{238}\mathrm{U}}\right)\left(\frac{^{230}\mathrm{Th}}{^{232}\mathrm{Th}}\right)_i - 1\right)\mathrm{e}^{-\lambda_{230}t} + \frac{\delta^{234}\mathrm{U}_m}{1000}\left(\frac{\lambda_{230}}{\lambda_{230}-\lambda_{234}}\right)\left(1-\mathrm{e}^{(\lambda_{234}-\lambda_{230})}\right), \quad (1)$$

where all isotope ratios are activity ratios, the λ's are decay constants, t is the ^{230}Th age, and $(^{230}\mathrm{Th}/^{232}\mathrm{Th})_i$ is the initial ^{230}Th/^{232}Th ratio. The ^{234}U/^{238}U ratio has been formulated into δ-notation, which denotes the fractionational enrichment in the ^{234}U/^{238}U ratio at secular equilibrium in parts per thousand. The observed value is given by $\delta^{234}\mathrm{U}_m = \{[(^{234}\mathrm{U}/^{238}\mathrm{U})_m/(^{234}\mathrm{U}/^{238}\mathrm{U})_{\mathrm{eq}}] - 1\} \times 10^3$ where $(^{234}\mathrm{U}/^{238}\mathrm{U})_m$ is the measured activity ratio and $(^{234}\mathrm{U}/^{238}\mathrm{U})_{\mathrm{eq}}$ is the ratio of 1 at secular equilibrium (Edwards et al., 1987). As $(^{232}\mathrm{Th}/^{238}\mathrm{U})$ can be measured, an accurate ^{230}Th age can be determined if $(^{230}\mathrm{Th}/^{232}\mathrm{Th})_i$ is known.

The first high accuracy young coral ^{230}Th dating techniques with precisions of ±3 yrs were developed using thermal ionization mass spectrometry by Edwards et al. (1988). Their study suggested the initial ^{230}Th ($^{230}\mathrm{Th}_0$) is not significant within errors of ±3 yrs in typical shallow-water corals with ^{232}Th levels less than 100 parts per trillion (ppt) and low initial ^{230}Th/^{232}Th (^{230}Th/^{232}Th) of 2–4 × 10^{-6} (atomic ratio, hereafter). However, development of a coral ^{230}Th dating method with a precision better than ±1–2 yrs is difficult with uncertainties mainly affected by the thorium levels and the uncertainty of the correction for $^{230}\mathrm{Th}_0$ (Zachariasen et al., 1999; Cobb et al., 2003b). For example, uncertainties of 25%, 50%, and 100% for a $^{230}\mathrm{Th}/^{232}\mathrm{Th}_0$ value of 4 × 10^{-6}, give approximate age errors of ±3, ±5, and ±10 yrs, respectively, for a decades-centuries-old coral with 2.4 ppm uranium and 1000 ppt thorium.

The initial thorium in the coralline structure is influenced both by scavenging processes between seawater and the coral skeleton, and by thorium association with detrital material incorporated into the crystal matrix (Cobb et al., 2003b; Edwards et al., 2003). Cobb et al. (2003b) proposed different potential sources of coral $^{230}\mathrm{Th}_0$, including (1) wind-blown dust with a ^{230}Th/^{232}Th ratio of 4 × 10^{-6}; (2) surface seawater containing dissolved and particulate thorium with a ^{230}Th/^{232}Th ratio of 5–10 × 10^{-6}; (3) deep seawater Th with a ^{230}Th/^{232}Th ratio of up to 2 × 10^{-4} (Moran et al., 2002); and (4) carbonate sands with ^{230}Th/^{232}Th ratios as high as 1 × 10^{-2}. Different sources and the non-conservative property of thorium in seawater (e.g., Broecker et al., 1973) could result in diverse coral $^{230}\mathrm{Th}/^{232}\mathrm{Th}_0$ ratios. The range of $^{230}\mathrm{Th}/^{232}\mathrm{Th}_0$ values observed in intertidal corals at different sites near Sumatra is 6.5 ± 6.5 × 10^{-6} (Zachariasen et al., 1999). High values of 10–20 × 10^{-6} are documented in Palmyra living corals (Cobb et al., 2003b). Modern Bahamas corals have 60–80 × 10^{-6} of $^{230}\mathrm{Th}/^{232}\mathrm{Th}_0$ values, intermediate between those of normal surface water and of bank-top water (Robinson et al., 2004). Clearly, the $^{230}\mathrm{Th}_0$ incorporated into a growing aragonitic skeleton needs to be well-constrained or its uncertainty may lead to significant error in the ^{230}Th ages of young corals.

The precision and accuracy of coral ^{230}Th dating techniques are affected by not only ^{232}Th content and variability of $^{230}\mathrm{Th}_0$, but also by the ^{230}Th introduced during sample collection and treatment. The previously published lowest procedural ^{230}Th blank, 0.0015 ± 0.0015 femtomole (fmol) (Cheng et al., 2000), is equivalent to an uncertainty of ±0.4 yr. Coupled with instrumental constraints (Goldstein and Stirling, 2003), the best coral U–Th dating procedures yielded an accuracy and precision of ±2–3 yrs (after Edwards et al., 1987; Edwards et al., 2003).

Four novel approaches were taken in this study to better understand the natural variability of coral $^{230}\mathrm{Th}/^{232}\mathrm{Th}_0$ in the oceans and to establish a high precision ^{230}Th dating method. First, chemical and analytical techniques were refined. The procedural ^{230}Th blank was reduced to as low as 0.0008 fmol, corresponding to an error of ±0.2 yr for a

1-g coral sample. Analytical uncertainty in ^{230}Th using inductively coupled plasma sector-field mass spectrometry (ICP-SF-MS) techniques (Shen et al., 2002) was reduced to an equivalent age uncertainty of about ±0.2–0.3 yr. Second, concentrations and isotopic compositions of dissolved and particulate thorium were analyzed to distinguish the contributions of the two phases to the coral skeletal matrix. Third, the variability of ^{230}Th/^{232}Th$_0$ at different hydrological settings was evaluated. Subtidal and intertidal modern and fossil corals, 24 in total, from the continental shelf sites of Nanwan in the western Pacific and Son Tra in the South China Sea, the open-ocean site of Santo in the western tropic Pacific, and six sites among the Sumatran islands in the eastern Indian Ocean, were analyzed to investigate the influences of terrestrial input, ^{230}Th ingrowth from the underlying substrate, and different water masses on ^{230}Th/^{232}Th$_0$. Finally, comparisons of the corals' ^{230}Th ages and independently-derived absolute ages, as well as isochron plots, were used to constrain spatial and temporal variations of ^{230}Th/^{232}Th$_0$ values on annual to millennial timescales at the selected sites.

2. MATERIALS AND METHODS

2.1. Field collection

Seawater and massive *Porites* coral samples were collected at sites with different hydrological settings from Nanwan, Taiwan, Son Tra Island, central Vietnam, southern Espiritu Santo Island, Vanuatu, and Sumatran islands (Figs. 1, A1–A4).

2.1.1. Nanwan

Nanwan (21°55′N, 120°47′E) is a semi-enclosed basin on the southern tip of Taiwan (Fig. A1). Two subtidal coral heads, NW0310 and NW0402, each 30–40 cm in diameter, were collected from the water intake channel of the nuclear power plant located at the northeastern corner of Nanwan in October 2003 and February 2004 at depths of 4 and 2 m, respectively.

A hydrological diagram of seawater Sr/Ca versus (vs.) salinity shows that Nanwan water is composed mainly of three endmembers: 25% offshore surface water, 75% tidally-induced upwelled subsurface cold water from depths of 100–200 m offshore, and an additional 0–2.5% fresh water in the summer (Lee et al., 1997; Shen et al., 2005b). In order to understand the influences of upwelled seawater and tide height on the local seawater ^{232}Th level and ^{230}Th/^{232}Th ratio, 21 consecutive 500-ml samples of filtered seawater were collected from the water intake channel of the Third Nuclear Power Plant, Nanwan, on July 31 and August 1, 2004, at a depth of 1 m (Fig. A1 and Table A1). Seawater was filtered with an acid-cleaned 0.45-μm acetate cellulose filter and stored acidified in an acid-cleaned polyethylene bottle by adding 0.5–1 g 14 N HNO_3 in the field (Fig. A1). Eight samples of suspended particulate matter, filtered from 5 L seawater with 0.45-μm acetate cellulose filters, were collected between October 28 and 30, 2004, at the same position where filtered seawater samples were collected (Fig. A1 and Table A2). Suspended particulate matter samples were stored in acid-cleaned polyethylene bags at 5 °C in a refrigerator before chemical analysis. The same seawater sampling process was applied at other sites. One calibrated underwater

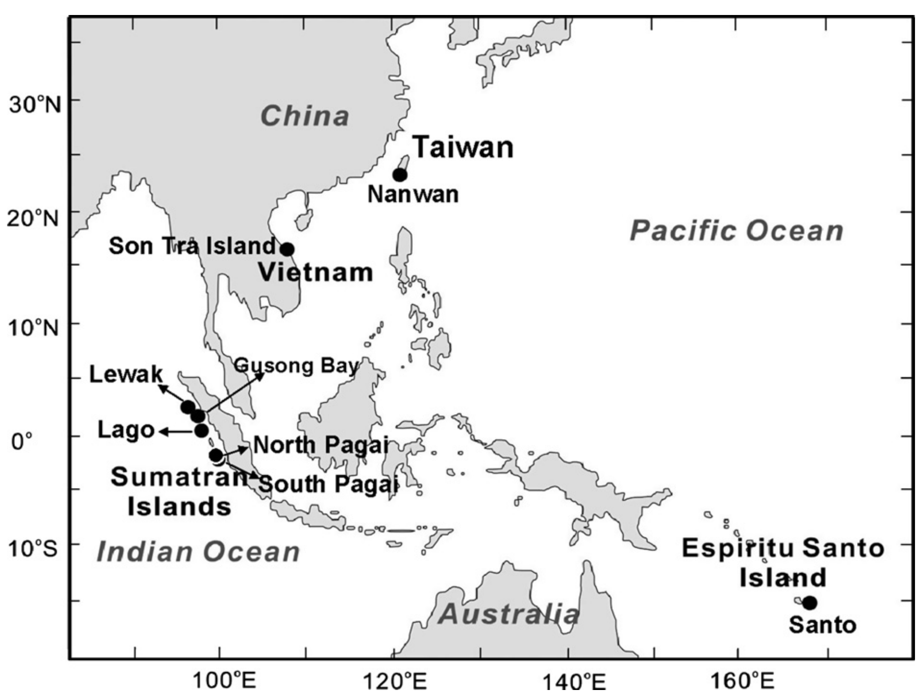

Fig. 1. Map of sample collection sites. Modern and fossil corals were collected from Nanwan, Taiwan, Son Tra Island, Vietnam, southern Espiritu Santo Island, Vanuatu, and the Sumatran islands. Surface seawater samples were collected from Nanwan, Son Tra, and North Pagai of the Sumatran islands.

thermometer with precision of 0.05 °C was placed next to the NW0402 coral sampling site to record sea surface temperature and monitor the timing of cold upwelled water intrusion. Tide height data monitored at Houbihu, 2 km south of the sample collection site (Fig. A1), are from the Central Weather Bureau.

2.1.2. Son Tra and Santo

One living 35-cm *Porites* coral head, ST0506, and 2 filtered 1-L seawater samples from a depth of 4 m below sea level were collected at Son Tra Island, a near-shore island in central Vietnam (16°13′N, 108°12′E) on June 14, 2005 (Fig. A2). The site is located at the north tip of Vung Da Nang Bay with terrestrial material influxes mainly delivered to the southern corner of the bay by the Han River. Two 1-L filtered seawater samples were also collected from a depth of 2 m at the same site.

The Santo subtidal coral core, 92MC, is 130 cm in length and 8 cm in diameter. It was drilled from a *Porites lutea* head living at a depth of 1.5 m at an open-ocean site, with notable lack of riverine influence, in the passage between Malo Island and Espiritu Santo Island (15°42′S, 167°12′E), in the western tropical Pacific Ocean, in June 1992 (Kilbourne et al., 2004) (Fig. A3).

2.1.3. Sumatran islands

The Sumatran islands are located along the Sunda subduction zone, an area associated with frequent earthquakes (e.g., Briggs et al., 2006; Subarya et al., 2006). The subduction zone and Sumatran fault separate the Indian and Australian plates from the Southeast Asian plate (Fitch, 1972; McCaffrey, 1991). Modern and fossil *Porites* slabs with thicknesses of 7–9 cm were cut with a chain saw from microatolls on shallow reefs within the intertidal zone at sites near Lewak (2°56′N, 95°48′E) and Gusong Bay (2°23′N, 96°20′E) on Simeulue Island; Lago (0°03′N, 94°32′E) in the Batu islands; North Pagai Island (2°35′S, 100°06′E); and Bulasat (3°07.6′S, 100°18.7′E), and Saumang (3°07.7′S, 100°18.6′E) on South Pagai Island (Fig. A4). One slab, LWK05, was collected from Lewak, and two slabs, GSG05YNG and GSG05OLD, were collected from Gusong Bay between the 1st and 3rd of June 2005; the two sites are 80 km apart, on the northern tip and the southern southwest coast of Simeulue Island, respectively. Two contiguous slabs, LG99A1 and LG00A1, were collected from the northeastern flank of Lago in 1999 and 2000, respectively (Natawidjaja et al., 2004). The Lago site is a landward pool characterized by a wide intertidal flat with coral rubble on a carbonate-enriched sandy substrate. Two slabs, NP00A1 and NP00A2, were collected from the eastern coast of North Pagai. Nine samples were collected from microatolls at Bulasat and Saumang on the southwestern coast of South Pagai. Following the same sampling procedure as at Nanwan, two 500-ml filtered seawater samples were collected at depths of 1 and 2 m at the coral collection site in North Pagai in January 2004.

2.2. Sample storage

General storage rooms for Quaternary carbonates can have ^{230}Th blanks higher than 0.002 fmol, which could bias dates for coral samples by as much as 30 yrs (Table A3). This cross-contamination, mainly from fine powder of Quaternary samples with high ^{230}Th content, may not be easy to remove from a porous coral skeleton, even using ultrasonic cleaning methods. Subsequently, we now bag coral samples individually and isolate young and old corals from each other in our storage rooms. In addition, we isolate coral samples from other types of natural carbonate samples, such as speleothem and tufa. These procedures effectively keep storage-related ^{230}Th background levels to 2×10^{-4} fmol or less.

2.3. Coral subsampling

Modern corals were subsampled in a separate class-100 laminar-flow clean working bench. For Nanwan, Son Tra, and Santo coral slabs, subsamples 0.5–1.5 cm in width were cut using a surgical blade, along growth layers, based on X-ray photographs. The widths are equivalent to 0.5–1 yr of coral growth. For Sumatran coral slabs, subsamples were collected by either cutting with a blade or drilling with a hole-drill bit 1 cm in diameter. The drilled cylindrical subsamples were 0.8 cm in diameter. Weights of coral subsamples ranged from 0.3 to 3 g (Tables A3–A12). All were ultrasonicated with deionized water 4–5 times until there was no visible powder or detrital material, and then dried at 70 °C. To avoid possible cross-contamination in the pretreatment process, all steps were performed on class-100 laminar-flow benches.

2.4. Chemistry

U–Th chemistry was performed in the High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC) of the Department of Geosciences, National Taiwan University (NTU) and in the Minnesota Isotope Laboratory of the Department of Geology and Geophysics, University of Minnesota (UMN). Chemistry for seawater samples was conducted following the procedures described in Moran et al. (2002) and Shen et al. (2003). Coral subsamples were prepared with chemical methods similar to those described by Edwards et al. (1988) and Shen et al. (2002, 2003). Samples were spiked with a ^{229}Th–^{233}U–^{236}U tracer. Uranium and thorium were separated with Fe coprecipitation and anion-exchange chromatography. The uranium and thorium aliquots were dissolved in 1% HNO_3 + 0.005 N HF for instrumental measurements (Shen et al., 2002).

2.5. Instrumental analysis

Determinations of uranium and thorium isotopic compositions and concentrations were performed using two ICP-SF-MS: a Thermo Electron ELEMENT II, housed at the Department of Geosciences, NTU, and a Finnigan ELEMENT, at the Minnesota Isotope Laboratory, UMN, with analytical techniques described by Shen et al. (2002). Spiked NBL-112A standard solution was measured to correct for multiplier intensity bias every day (Cheng et al., 2000). Pairs of the separated thorium and uranium fractions were sequentially analyzed by ICP-SF-MS. Both thorium and uranium mass biases were normalized to a $^{236}U/^{233}U$ atomic ratio of 1.01057 ± 0.00050 (Cheng et al., 2000). The accuracy of measurements of different thorium standards within error of accepted values suggests that there is no significant mass bias difference between thorium and uranium (Shen et al., 2002). Typical $^{230}Th^{+}$ ion beam intensities were just tens of counts per second (cps) for corals younger than 20 yrs and for filtered seawater and suspended particulate material. Sources of background noise include multiplier dark noise, memory blanks, tailing of $^{238}U^{+}$ and $^{232}Th^{+}$, and isobaric spectral interferences. The dark noise of the multiplier (0.05–0.1 cps), instrumental memory blanks (typically 0.1–0.2 cps at $m/z = 230$, for example), and background from the $^{238}U^{+}$ and $^{232}Th^{+}$ tails were subtracted during off-line data processing. Spectral interferences of 0–10 cps at $m/z = 229–237$ could be generated from polyatomic organics and/or complexes, which cause a high noise/signal ratio of 20–50% for low ^{230}Th analyses. This contamination was effectively removed by oxidation treatment with perchloric acid in chemistry, reducing the interferences to less than 0.1 cps at $m/z = 230$ (Shen et al., 2002). Resultant analytical uncertainty in ^{230}Th corresponded to an age uncertainty of 0.2–0.3 yrs. All errors given are two standard deviations (2σ) unless otherwise noted.

2.6. Blanks

Procedural blanks were 0.02 ± 0.01 pmol ^{238}U, 0.003 ± 0.003 pmol ^{232}Th, and 0.0008 ± 0.0008 fmol ^{230}Th for coral. The low ^{230}Th procedural blank corresponds to an age uncertainty of $\pm 0.1–0.2$ yr. The isotopic composition in the spike solution was carefully re-quantified. The value of the $^{230}Th/^{229}Th$ ratio in the $^{229}Th–^{233}U–^{236}U$ spike solution is 0.000050 ± 0.000002. The uncertainty corresponds to an error of $\pm 0.1–0.2$ yr for 1–2-g coral samples. The improved chemical procedure results in an overall age error of only $\pm 0.2–0.3$ yr. Procedural blanks of ^{238}U, ^{232}Th, and ^{230}Th for filtered seawater samples had the same as the values for corals. For the particulate fraction, the use of an acetate cellulose filter caused a relatively high procedural ^{232}Th blank of 0.06 ± 0.03 pmol.

3. RESULTS AND DISCUSSION

3.1. Uranium and thorium data

U–Th data for all seawater and coral samples are listed in Tables A1–A12. Uncertainties in the ^{235}U, ^{234}U, ^{232}Th, and ^{230}Th data are calculated at the 2σ level and include corrections for blanks, multiplier dark noise, abundance sensitivity, and errors associated with quantifying the isotopic composition in the spike solution. The ^{238}U level was calculated from measurement of ^{235}U and the assumed natural $^{238}U/^{235}U$ atomic ratio of 137.88 (Cowan and Adler, 1977; Steiger and Jager, 1977).

The decay constants used are $9.1577 \times 10^{-6}\ yr^{-1}$ for ^{230}Th and $2.8263 \times 10^{-6}\ yr^{-1}$ for ^{234}U (Cheng et al., 2000), and $1.55125 \times 10^{-10}\ yr^{-1}$ for ^{238}U (Jaffey et al., 1971). Ages are corrected for $^{230}Th_0$ by estimating $^{230}Th/^{232}Th_0$ with 3-D ($^{232}Th/^{238}U$-$^{230}Th/^{238}U$–$^{234}U/^{238}U$) isochron techniques and with seawater data for coral sample ST0506 from Son Tra. The initial $\delta^{234}U$ value is calculated from the measured $\delta^{234}U$ value using the corrected ^{230}Th age. Intercepts, isochron ages, and isochron plot errors were calculated with an Excel macro, *Isoplot* 3.00, by K.R. Ludwig of the Berkeley Geochronology Center, California, USA (Ludwig and Titterington, 1994; Ludwig, 2003).

3.2. Seawater uranium and thorium at Nanwan and other sites

Dissolved ^{238}U concentration is 3.1 ± 0.1 ppb for Nanwan seawater (Fig. 2 and Table A1) with a salinity of 33.8–34.0, measured by H.J. Lee of the Department of Marine Environmental Informatics, National Taiwan Ocean University. Our observations support the conservative behavior of the ^{238}U concentration in this coastal ocean (Chen et al., 1986; Robinson et al., 2004), although Taiwan experiences a high erosion rate of 3–6 mm/yr and supplies 300–500 Mt/yr of suspended sediment to the ocean (Dadson et al., 2003). Particulate ^{238}U concentration ranges from 0.6 to 2.0 ppt (Fig. 3 and Table A2), representing 0.02–0.06% of the respective dissolved concentrations.

For Nanwan water, the measured dissolved $\delta^{234}U$ of 147.4 ± 2.0 (Fig. 2 and Table A1) is within the open-ocean interval of 146 ± 2 (Chen et al., 1986). $\delta^{234}U$ of suspended particulate matter is 34 ± 36 in Nanwan seawater (Fig. 3 and Table A2). The calculated $\delta^{234}U$ of bulk (or unfiltered)

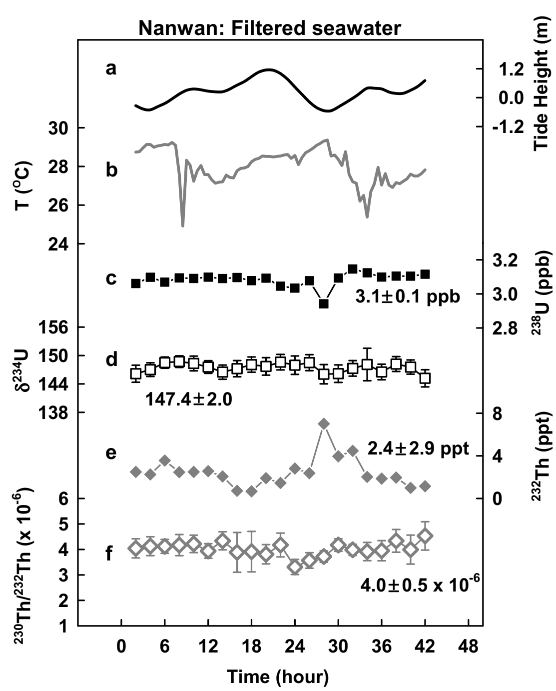

Fig. 2. Time series of (a) tide height, (b) temperature, (c) ^{238}U concentration, (d) $\delta^{234}U$, (e) ^{232}Th concentration, and (f) $^{230}Th/^{232}Th$ ratio for filtered Nanwan seawater collected from July 31, 06:00 AM to August 1, 10:00 PM, 2004. Means and 2σ errors of U–Th data are given.

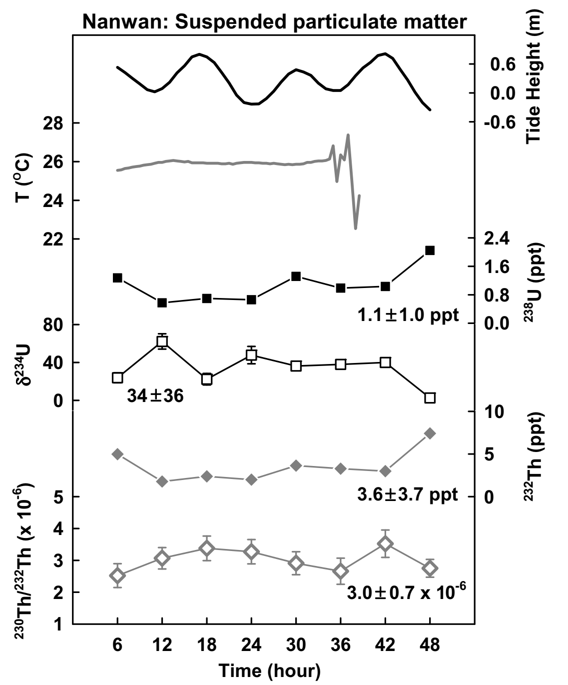

Fig. 3. Time series of (a) tide height, (b) temperature, (c) ^{238}U concentration, (d) δ^{234}U, (e) ^{232}Th concentration, and (f) ^{230}Th/^{232}Th ratio for the suspended particulate matter of Nanwan seawater collected from October 28, 7:00 AM to October 30, 1:00 AM, 2004. Average values and 2σ errors of U–Th data are listed by record.

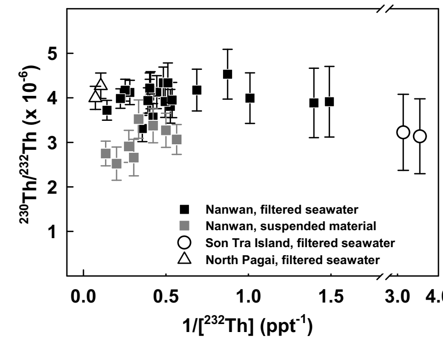

Fig. 4. A plot of ^{230}Th/^{232}Th vs. 1/^{232}Th for the dissolved fraction (solid cubes) and suspended particulate matter (gray cubes) of Nanwan seawater, dissolved fraction of Son Tra seawater (hollow circles), and dissolved fraction of intertidal seawater of North Pagai (hollow triangles).

seawater is 146.1–146.5, which is not significantly different from dissolved δ^{234}U values. With an analytical precision of 1–2‰, the influence of suspended particulate matter on the dissolved δ^{234}U value is not observable. The dissolved δ^{234}U is 146.6 in North Pagai and 145.0 in Son Tra (Table A1), both within the range observed in the open ocean (Chen et al., 1986).

Consecutive measurements of dissolved ^{232}Th range from 4–7 ppt at low tide to 0.7–3 ppt at high tide (Fig. 2 and Table A1), 10–100 times higher than the open-ocean bulk values from the central Pacific (Roy-Barman et al., 1996). The averaged particulate ^{232}Th of 3.6 ppt (Fig. 3) is 150% of the dissolved fraction. This proportion is higher, by 10–30%, than those at open-ocean sites in the Labrador Sea and Atlantic (Moran et al., 2002). This is likely the result of high thorium fluxes associated with terrestrial material input at Nanwan. The dissolved ^{230}Th/^{232}Th ratio, $4.0 \pm 0.5 \times 10^{-6}$, is slightly higher than that ($3.0 \pm 0.7 \times 10^{-6}$) of the particulate fraction (Fig. 3). It indicates that thorium is coming not only from terrestrial sources, but also from the open ocean which has high ^{230}Th/^{232}Th (Roy-Barman et al., 1996) or is derived from the ingrowth of ^{230}Th by uranium decay (e.g., Robinson et al., 2004).

There is no observable periodic trend of ^{230}Th/^{232}Th ratios for either the dissolved fraction or suspended particulate matter (Figs. 2 and 3). For neither fraction do ^{230}Th/^{232}Th ratios correlate with tide height or cold water intrusion, indicating that near-shore water ^{230}Th/^{232}Th is not affected by either tide height or upwelled subsurface cold water. Plots of ^{230}Th/^{232}Th vs. 1/^{232}Th for both the dissolved and suspended particulate fractions support the observation of no additional distinguishable sources of thorium at Nanwan (Fig. 4).

3.3. Uranium in corals

^{238}U concentrations range from 2.4 to 2.7 ppm for modern *Porites* coral samples from Nanwan, Son Tra, and Santo (Tables A3–A6). *Porites* coral skeletal Ca content is 38.2–38.5% by mass in the South China Sea and western Pacific (Sun et al., 1999). The calculated molar coral U/Ca ratio, $[U/Ca]_{coral}$, is $1.0–1.2 \times 10^{-6}$. Seawater Ca concentration is 10.3 mmol/g at a salinity of 35 (Chen, 1990; Shen et al., 1996, 2005b). We calculate a molar U/Ca ratios for Nanwan water to be 1.3×10^{-6}. The distribution coefficient of U between *Porites* coral and seawater at the three sites is estimated as: $D[U/Ca] = [U/Ca]_{coral}/[U/Ca]_{sea} = 0.80–0.90$, consistent with the values reported by Swart and Hubbard (1982) and Shen and Dunbar (1995). For all corals from Nanwan, Son Tra, Santo, and the Sumatran islands, molar U/Ca ratios are within 30%, agreeing with previous observations (Min et al., 1995; Shen and Dunbar, 1995).

For Nanwan corals, δ^{234}U averages 147.7 ± 3.2, matching the local dissolved value of 147.6 ± 2.7 (Fig. 2). δ^{234}U in corals of Son Tra and North Pagai also matches the seawater value of 145–147 (Table A1). There is no distinguishable difference of coral δ^{234}U from dissolved value at the sites with tremendous input of terrestrial material, which supports the conclusion that marine uranium is incorporated into the coral skeleton without isotopic fractionation and that the initial δ^{234}U is a reliable parameter for estimating diagenesis (Edwards et al., 2003).

3.4. Thorium in corals

3.4.1. Distribution coefficient

Coral skeletal ^{232}Th content is a function of oceanographic setting. For *Porites* corals, it increases from

10 s–100 s ppt in the open ocean, such as at the Santo site, to 100 s–1000 s ppt on the continental shelf, such as at the Son Tra and Nanwan sites, characterized by input of high-^{232}Th terrestrial material. For the intertidal corals at sites in the Sumatran islands with similar geological settings, skeletal ^{232}Th level varies from 100 s–10,000 s ppt. Even at the same site, such as Gusong Bay, ^{232}Th content in *Porites* GSG05OLD is 3000–7800 ppt, 10 times higher than that in *Porites* GSG05YNG (Table A8). Tenfold variation in skeletal ^{232}Th levels of 1000 s–10,000 s ppt is also observed in eight modern and Holocene corals from Bulasat, South Pagai. Unlike uranium that has a long residence time of 300–500 kyr (Dunk et al., 2002) and displays conservative behavior (Ku et al., 1977; Chen et al., 1986), thorium is non-conservative and a residence time of 0.1–0.7 yr in surface water (Broecker et al., 1973; Okubo, 1982). These features, along with the fact that different sources of thorium have various $^{230}Th/^{232}Th$ ratios (Cobb et al., 2003b), result in a wide range of coral ^{232}Th levels in different hydrological settings.

Thorium partitioning, similar to uranium (Cross and Cross, 1983), appears to be species dependent. The molar Th/Ca ratio is $1.0 \pm 1.2 \times 10^{-9}$ in the dissolved fraction of seawater and $2.2 \pm 2.2 \times 10^{-10}$ in *Porites* from Nanwan. A distribution coefficient, D[Th/Ca], of ~0.2 suggests *Porites* excludes thorium during growth (Edwards et al., 2003). Based on our measurements and previous reports (Edwards et al., 1987; Zachariasen, 1998; Zachariasen et al., 1999, 2000; Cobb et al., 2003b; Edwards et al., 2003; Natawidjaja et al., 2004; Robinson et al., 2004), *Acropora* corals have high D[Th/Ca] values $\geqq 1$. Thorium is effectively excluded by *Goniastrea* with an estimated D[Th/Ca] of 0.02 or less.

3.4.2. Dissolved phase of seawater and detrital materials

Three isochrons with ages of 4.1 ± 1.2, 5.1 ± 3.0 and 15.56 ± 0.56 yrs, for two Nanwan coral slabs, NW0310 and NW0402, are shown in Fig. 5a. All regression *y*-intercept values, with uncertainties of $1–2 \times 10^{-6}$, overlap with each other at 5×10^{-6} (Fig. 5a). An excellent fit to straight lines illustrates that there is no significant difference of the isotopic composition of associated thorium in the skeletal lattice between the three growth bands of the two coral heads in the same hydrographic environment. All intercepts are consistent with a value of $4.0 \pm 0.5 \times 10^{-6}$ in the dissolved fraction of seawater (Fig. 2) and higher than the value of $3.0 \pm 0.7 \times 10^{-6}$ in the suspended particulate matter (Fig. 3). A $^{230}Th/^{232}Th_0$ value of $4.7 \pm 1.0 \times 10^{-6}$ for growth banding of a modern coral, NP00A1 (Fig. 5f), from North Pagai captures the dissolved values of $4.0–4.3 \times 10^{-6}$ at that site. At the Son Tra site, using a dissolved $^{230}Th/^{232}Th$ value of $3.20 \pm 0.32 \times 10^{-6}$ as the initial thorium isotopic composition, the ^{230}Th ages of three bands of the Son Tra *Porites*, ST0506, match the absolute ages (Table A5).

Robinson et al. (2004) showed the seawater $^{230}Th/^{232}Th$ value should be used for $^{230}Th_0$ correction with coral and bulk seawater data. The similarity between the dissolved $^{230}Th/^{232}Th$ values and the respective initial ratios in corals from Nanwan, North Pagai, and Son Tra, further supports that the idea that $^{230}Th_0$ is mainly from the dissolved fraction of seawater. The data from all three sites show that the ^{230}Th age should be corrected for $^{230}Th_0$ using the dissolved $^{230}Th/^{232}Th$ ratio. Precise and accurate correction for $^{230}Th_0$ content in coral can be achieved by understanding the spatial and temporal variability of $^{230}Th/^{232}Th_0$; this can be accomplished with isochron techniques as described in Sections 3.5 and 3.6.

Three discordant ages were observed from isochrons (Fig. 5) and the 1:1 line of the ^{230}Th age vs. growth band age plot (Fig. 6). The ^{230}Th age of one subsample, NW0310-5#3 (Table A4), is 3.8 ± 1.0 yrs older than the other three coeval subsamples. Two $^{230}Th/^{232}Th–^{234}U/^{232}Th$ data points, 92MC-1#4 (Table A6) and NP00A1–1#5 (Table A10), do not lie on isochrons (Fig. 5b and f). The ^{230}Th age of 92MC-1#4 is 5.0 ± 1.4 yrs older than the isochron age of 14.0 ± 1.1 yrs, constructed with the other three coeval subsamples. The ^{230}Th age of NP00A1–1#5 is 23 ± 6 yrs younger than the isochron age of 8.1 ± 1.9 yrs, established with four coeval subsamples (Table A10). The discordant ages are proposed to be caused by detrital materials with different thorium concentrations and $^{230}Th/^{232}Th$ ratios that were incorporated into the growing lattice during crystallization. The positive age bias for NW0310-5#3 and 92MC-1#4 could be due to carbonate detritus with low thorium concentration and a high $^{230}Th/^{232}Th$ ratio. Terrestrial particulates with a high thorium level and a low $^{230}Th/^{232}Th$ ratio of $1–2 \times 10^{-6}$ could result in the negative age bias of NP00A1–1#5.

3.5. Variability of $^{230}Th/^{232}Th_0$ in coral skeletons

3.5.1. Subtidal corals at continental shelf sites: Nanwan and Son Tra

3.5.1.1. Nanwan. The $^{230}Th/^{232}Th_0$ values derived from three isochrons of two modern Nanwan corals, $5.2 \pm 1.1 \times 10^{-6}$ and $4.86 \pm 0.27 \times 10^{-6}$ for NW0310 and $5.1 \pm 1.9 \times 10^{-6}$ for NW0402, collected 60 m apart, are consistent with each other (Fig. 5a). Plots of ^{230}Th age, calculated with the $^{230}Th/^{232}Th_0$ value of $4.86 \pm 0.27 \times 10^{-6}$ from NW0310-6, vs. banding age for three subsamples of NW940617 and five layers of NW0310, including bulk and three crushed fractions of <840, 840–1410, and 1410–2380 μm (Table A4), are shown in Fig. 6. All points, except for NW0310-5#3 with high $^{230}Th/^{232}$Th-detritus, plot within error of a 1:1 line for both bulk subsamples and crushed fractions, indicating that the $^{230}Th/^{232}Th_0$ ratios on different growth layers vary less than $\pm 0.27 \times 10^{-6}$. A single $^{230}Th/^{232}Th_0$ value can be used to determine different ^{230}Th ages on annual to decadal timescales for Nanwan samples. The results and measurements of seawater thorium isotopic composition at Nanwan (Figs. 2 and 3) indicate that inter-annual variability of the $^{230}Th/^{232}Th$ ratio in the dissolved fraction is not resolvable, even though there is a large daily intrusion of cold upwelled subsurface water mass at the Nanwan site (Lee et al., 1997; Shen et al., 2005b).

3.5.1.2. Son Tra. All six subsamples of three layers of the modern Son Tra coral lie on a 1:1 line in Fig. 6 using a seawater $^{230}Th/^{232}Th$ value of $3.20 \pm 0.32 \times 10^{-6}$ as the initial

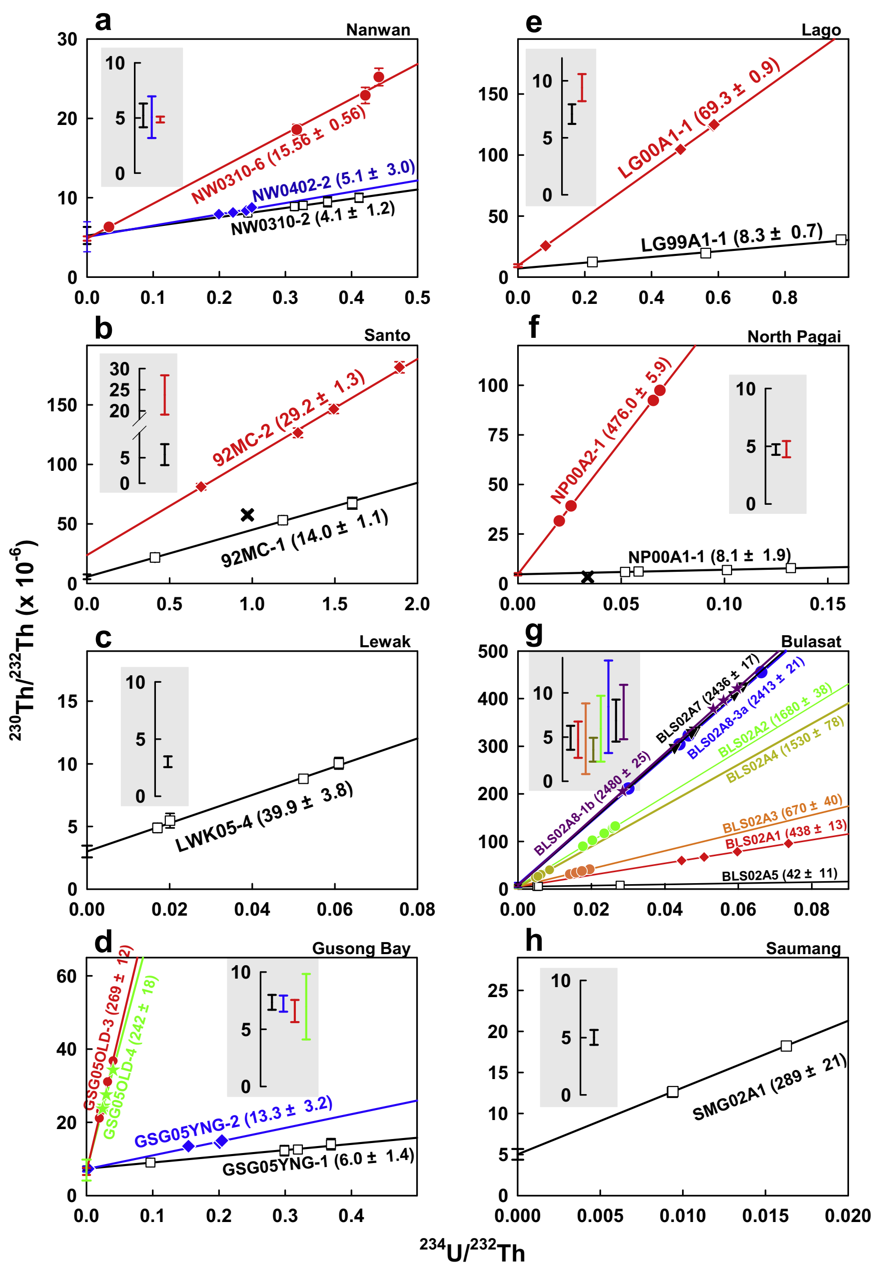

Fig. 5. Isochron plots of $^{230}Th/^{232}Th$ vs. $^{234}U/^{232}Th$ (atomic ratios) for 23 coeval sets of subsamples from (a) three growth bands of two Nanwan coral slabs, NW0310 and NW0402, (b) two growth bands of the Santo 92MC coral, and (c–h) 18 horizons of corals from the Sumatran islands. Isochron-inferred $^{230}Th/^{232}Th_0$ ratios (*y*-intercepts with 2σ errors) are enlarged in insets.

value, indicating no significant annual change of the initial thorium isotopic composition at this site. There is a distinguishable difference in $^{230}Th/^{232}Th_0$ values of $1.66 \pm 0.42 \times 10^{-6}$ between Son Tra and Nanwan (Fig. 7), suggesting that a terrestrial source with low thorium isotopic composition and high ^{232}Th levels of 1000 s ppt is more dominant at Son Tra.

Located on the continental shelf with a large influx of inland material, the Nanwan and Son Tra sites in the western Pacific yield isochron-inferred $^{230}Th/^{232}Th_0$ ratios of $3–5 \times 10^{-6}$ (Fig. 5), consistent with an average crustal value (Richards and Dorale, 2003). Results of seawater analyses and isochrons, and the consistency of ^{230}Th and absolute ages, show that the variability of $^{230}Th/^{232}Th$ ratios in the dissolved fraction of seawater and initial values in corals is $\pm 0.25–0.35 \times 10^{-6}$, which is within 10% of the mean value at the two local sites. These small temporal and spatial variations suggest that the crust-derived mean value of $4–5 \times 10^{-6}$ with an arbitrary uncertainty of 50% or 100% is practical for the continental shelf region in the western Pacific. The observation of resolvable differences in the $^{230}Th/^{232}Th_0$ values between Nanwan and Son Tra indicates that a site-specific $^{230}Th/^{232}Th_0$ ratio is important for high precision and accurate ^{230}Th dating.

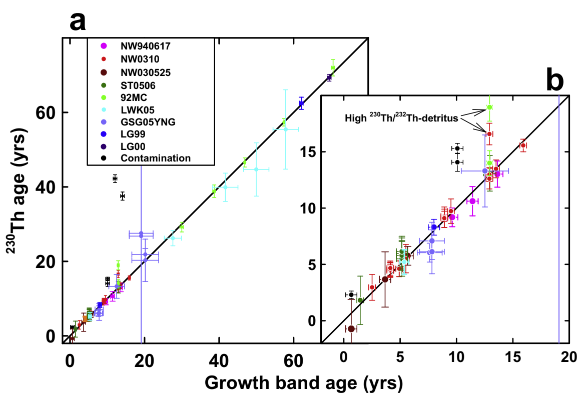

Fig. 6. ^{230}Th age vs. growth band age plots of over 50 data points for coral subsamples of Nanwan, Son Tra, Santo, and the Sumatran islands. Eight of the ^{230}Th ages are inferred from isochron techniques and the other ages are calculated with different ^{230}Th/^{232}Th$_0$ ratios (see text and Appendices). Note that subsample NP00A1–1#5, which yielded a ^{230}Th age 23 ± 6 yrs younger than the isochron age of 8.1 ± 1.9 yrs, is not shown on this plot. Data for subsamples that may have acquired high ^{230}Th in the storage room or during the subsampling process are given in black.

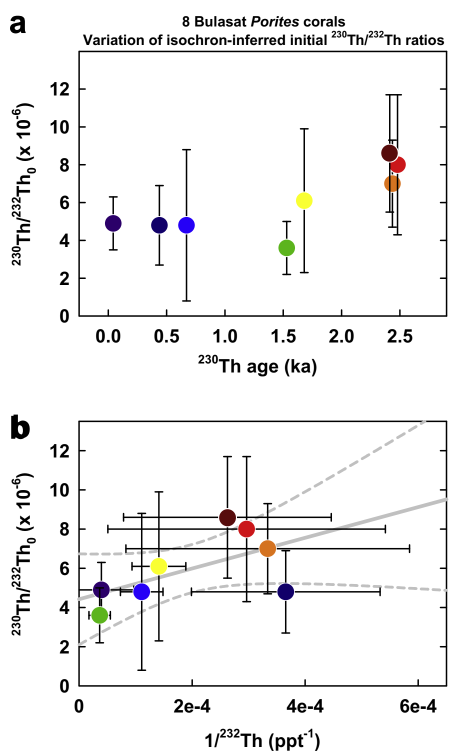

Fig. 7. (a) Temporal variation of isochron-inferred ^{230}Th/^{232}Th$_0$ ratios for eight corals collected from Bulasat of the Sumatran islands over 2.5 ka. (b) An endmember plot of ^{230}Th/^{232}Th$_0$ vs. 1/^{232}Th shows a mixing trend (gray line) with an intercept of $4.4 \pm 2.3 \times 10^{-6}$ at the 95% confidence (dashed lines).

3.5.2. *Subtidal corals at open-ocean site: Santo*

Data of ^{230}Th age vs. growth band age for subsamples of the Santo 92MC coral, except for subsample 1#4, and subsamples 2#1 through 2#4 (Table A6), reside on a 1:1 line using the isochron-inferred ^{230}Th/^{232}Th$_0$ value of $5.62 \pm 2.05 \times 10^{-6}$ from the coeval subsamples on layer 92MC-1 (Fig. 5b). This initial value at this open-ocean site, with minor terrestrial influence, is higher than 3.2×10^{-6} measured at the continental shelf site of Son Tra (Fig. 5). The discordant age of subsample 1#4 was discussed earlier in Section 3.4.2. The isochron plot of layer 92MC-2 shows a much higher ^{230}Th/^{232}Th$_0$ ratio of $23.8 \pm 4.7 \times 10^{-6}$ and the isochron age of 29.2 ± 1.3 yrs matches the absolute date (Table A6). If we use the initial value inferred from the layer 92MC-1, however, the ^{230}Th ages of subsamples of 2#1–2#4 are 2.9–8.7 yrs older than the absolute age of 30.0 ± 0.5 yrs.

The high ^{230}Th/^{232}Th$_0$ value of layer 92MC-2 in AD 1974.6 ± 0.5 (growth band age) could be attributed to substantial upwelling of cold water in the eastern Pacific during a predominant La Niña episode between AD 1973 and 1976. In terms of the magnitude of the Southern Oscillation Index, the three La Niña years, AD 1974, 1975, and 1976, are historically ranked as the 1st, 15th, and 4th, respectively, during the interval from 1951 to 1996 (Clark et al., 2001). A monthly sea surface temperature anomaly (SSTA) of −2 °C over the Niño-3.4 region (5°S–5°N, 170–120°W; http://www.cpc.noaa.gov/data/indices/) in the central equatorial Pacific was observed in both La Niña episodes of AD 1973/74 and 1975/76. During a similar SSTA during the 1998/99 La Niña event, shoaling of the thermocline in the eastern equatorial Pacific was induced by a strong westward near-surface (0–15 m) current of 1 m/s (Grodsky and Carton, 2001; Bonjean and Lagerloef, 2002). A high seawater ^{230}Th/^{232}Th value of $20–200 \times 10^{-6}$ was measured at a depth of 25 m at the Aloha Station in the central Pacific (22°45′N, 158°00′W) in September 1994 (normal El Niño/Southern Oscillation (ENSO) condition; Roy-Barman et al., 1996). Notably, in the 1944 La Niña event, a high ^{230}Th/^{232}Th$_0$ ratio of $22–25 \times 10^{-6}$, calculated with U–Th data from the Modern-2 coral in Table 2 of Cobb et al. (2003b), was also observed at Palmyra Island, in the central tropical Pacific (5°51′N, 162°8′W). The high ^{230}Th/^{232}Th$_0$ value of 24×10^{-6} found in layer 92MC-2 of the Santo coral could likely be attributed to cold upwelled water delivered by the persistent westward current. An alternate possibility might be local changes in current circulation and/or wind strength and direction at the Santo site that were tied to ENSO.

In Santo coral 92MC, an initial isotopic ratio of $5.6 \pm 2.1 \times 10^{-6}$ is observed in 4 of 5 bands and a high value of $23.8 \pm 4.7 \times 10^{-6}$ observed in AD 1974–1975 during a strong La Niña episode. The fluctuation of ^{230}Th/^{232}Th$_0$ values at Santo, an open-ocean site in the western tropical Pacific, could be related to mixing of water masses. Also taking into consideration the case at Palmyra Island in the central tropical Pacific (Cobb et al., 2003b), isochron techniques are suggested for determining accurate and precise ^{230}Th dates. High-^{230}Th/^{232}Th thorium, delivered by the upwelled water, can be taken up by the coral skeleton. The magnitude of ^{230}Th/^{232}Th$_0$ variation at these regions should therefore be understood in advance for high precision coral ^{230}Th dating.

3.5.3. Intertidal corals at sites in the Sumatran islands

3.5.3.1. Gusong Bay and Lewak of Simeulue. At the Gusong Bay site of southwestern Simeulue, there is no significant difference between four isochron-inferred $^{230}Th/^{232}Th_0$ values, $7.35 \pm 0.65 \times 10^{-6}$ and $7.24 \pm 0.70 \times 10^{-6}$ from modern coral GSG05YNG, and $6.59 \pm 0.97 \times 10^{-6}$ and $6.97 \pm 2.86 \times 10^{-6}$ from fossil GSG05OLD (Fig. 5d). Using an initial value of $7.35 \pm 0.65 \times 10^{-6}$, six additional ^{230}Th age vs. band counting age points lie on a 1:1 line (Fig. 6 and Table A8). Gusong Bay data show that the $^{230}Th/^{232}Th_0$ ratio remains steady at this site. A similar case of a steady but lower $^{230}Th/^{232}Th_0$ value of $3.01 \pm 0.47 \times 10^{-6}$, inferred from a LWK05 coral isochron (Fig. 5c and Table A7) and supported by the concordance between the banding ages and the ^{230}Th ages calculated using the initial value (Fig. 6), is observed at the Lewak site in northern Simeulue, 80 km from the Gusong Bay site. The discrepancy between the initial values at the two sites, on the same island, clearly shows the $^{230}Th/^{232}Th_0$ ratio is dependent on local hydrology.

3.5.3.2. Lago. A $^{230}Th/^{232}Th_0$ ratio of $9.4 \pm 1.2 \times 10^{-6}$ is observed for band LG00A1-1 of coral LG00A1, from the northeastern side of Lago island (Fig. 5e). An age of AD 1935.1 ± 0.9, determined with this initial value, is identical to a band age of AD 1935.0 ± 0.5 on the slab (Fig. 5e). Calculated with the same $^{230}Th/^{232}Th_0$ value, a date of AD 1942.1 ± 1.6 is calculated, identical to the absolute age (AD 1942.5 ± 0.5), for horizon LG99A1-3 of a contiguous coral slab, LG99A1, from the same coral head (Table A9). This indicates that the high $^{230}Th/^{232}Th_0$ value did not change after the earthquake in December 1935 (Mw = 7.7; Rivera et al., 2002). The carbonate-enriched sandy substrate could supply ^{230}Th and a high $^{230}Th/^{232}Th$ ratio source to coral skeletons (Robinson et al., 2004). A different initial value of $7.08 \pm 0.86 \times 10^{-6}$ is found using an isochron from an AD 1996 layer, LG99A1-1. This low initial value could likely be attributed to either a different thorium isotopic composition in seawater or a lower proportion of ^{230}Th to the coral skeleton.

3.5.3.3. North Pagai. The isochron-derived $^{230}Th/^{232}Th_0$ ratios for one modern coral, NP00A1, and one 475-year-old fossil, NP00A2, sampled near Simanganya village along the northeastern coast of North Pagai are indistinguishable (Fig. 5f). The value of $4.7 \pm 1.0 \times 10^{-6}$ is identical to that of the dissolved fraction of ambient seawater, 4.0–4.3×10^{-6}, supporting the finding that the dissolved seawater thorium is the main source of thorium to the coral skeleton. Dissolved ^{232}Th concentrations at the North Pagai site range from 9.5 to 13.8 ppt, which is even higher than those at the Nanwan site. Coupled with low $^{230}Th/^{232}Th$ ratios of 4.0–4.3×10^{-6}, this indicates that the site in North Pagai also experiences a high flux of terrestrial matter.

3.5.3.4. Bulasat and Saumang of South Pagai. The Bulasat and Saumang sites have similar hydrological settings and are 10 km apart on the southwestern coast of South Pagai. The $^{230}Th/^{232}Th_0$ ratios of two modern coral slabs, BLS02A5 and SMG02A1, are $4.9 \pm 1.4 \times 10^{-6}$ and $5.02 \pm 0.65 \times 10^{-6}$, respectively (Figs. 5g and h). The identical $^{230}Th/^{232}Th_0$ values of the two slabs suggest that there is no spatial variation of thorium isotopic composition at the sites in South Pagai. Temporal variation of $^{230}Th/^{232}Th_0$ values at the Bulasat site is characterized with eight isochrons going back 2.5 thousand years (Figs. 5g and 7a). Despite 2σ uncertainties of 1.4–3.8×10^{-6}, the graphs show that the means of the initial values ranged from 7–8×10^{-6} at 2.5 thousand years ago (ka) to 3.6×10^{-6} at 1.5 ka, with intermediate values of 4.8–4.9×10^{-6} during the past 0.7 ka. An endmember plot of $^{230}Th/^{232}Th_0$ vs. $1/^{232}Th$ displays a mixing trend with an intercept of $4.4 \pm 2.3 \times 10^{-6}$ at the 95% confidence level (Fig. 7b), which agrees with the crust-derived mean value of 4.5–4.7×10^{-6} (Richards and Dorale, 2003). Terrestrial sources with low $^{230}Th/^{232}Th$ dominated in the four coral heads since 1.5 ka. High $^{230}Th/^{232}Th_0$ ratios recorded in the other four fossil corals, older than 1.5 ka, can be attributed to different sources such as open ocean water masses and carbonate-enriched substrate with high ^{230}Th (Robinson et al., 2004).

3.5.3.5. $^{230}Th/^{232}Th_0$ variation between sites. The natural dynamics of $^{230}Th/^{232}Th_0$ values in the different intertidal zones at sites of the Sumatran islands are more complicated and governed by variability of four sources: (1) terrestrial influx, (2) in-situ ingrowth ^{230}Th, (3) open-ocean surface seawater, and (4) upwelled cold seawater. Terrestrial sources appear to be dominant at the Lewak and North Pagai sites with low $^{230}Th/^{232}Th$ values of 3–4×10^{-6}. The Lago site, away from sources of significant terrestrial input and with a carbonate sandy substrate, shows high $^{230}Th/^{232}Th_0$ values of 7–9×10^{-6}. The regional seawater $^{230}Th/^{232}Th$ value is affected by the upwelling of cold seawater, which has been observed in the eastern Indian Ocean. For example, three strong positive Indian Ocean Dipole events, in 1877, 1994 and 1997, caused a 4 °C drop of sea surface temperature in the Mentawai reefs (Abram et al., 2003). The offshore islands have also experienced frequent rupture of active faults (Zachariasen et al., 1999; Sieh et al., 1999; Natawidjaja et al., 2004; Briggs et al., 2006). The proportion of the different thorium sources could plausibly be altered by uplift or subsidence associated with seismic displacements. A wide isochron-inferred initial range of 3.0–9.4×10^{-6} is shown in Fig. 5. The observed spatiotemporal variation of the means of the isochron-inferred $^{230}Th/^{232}Th_0$ ratios is $6.2 \pm 3.2 \times 10^{-6}$ at the sites, which sprawl across 800 km of the Sumatran islands (Figs. 5c–h). The range, consistent with the previous value of $6.5 \pm 6.5 \times 10^{-6}$ published by Zachariasen et al. (1999), can be applied to ^{230}Th dating of intertidal corals in the Sumatran islands. However, high precision and accurate ^{230}Th dates will require well-constrained $^{230}Th/^{232}Th_0$ values specific to each site.

3.6. Limitations of high precision coral ^{230}Th dating

3.6.1. Prerequisites

High precision coral ^{230}Th dating with a precision of ±1 yr requires an appropriate quality control with a careful sampling procedures, cross-contamination-free sample storage, and proper subsampling methods. The level and uncertainty of ^{230}Th blank in the chemical procedure and instrumental analysis should be effectively reduced. In this study, the procedural ^{230}Th blank of 0.0008 ± 0.0008 fmol ^{230}Th corresponds to an uncertainty of only ± 0.1–0.2 yr for 1-g coral samples.

3.6.2. Usage of appropriate $^{230}Th/^{232}Th_0$ values

A bulk Earth crustal Th/U atomic ratio of 3.6–3.8 (Taylor and McLennan, 1985, 1995) and an assumed secular equilibrium between ^{230}Th and ^{238}U in the terrestrial upper or bulk continental crust is generally used to determine a $^{230}Th/^{232}Th$ value of $4–5 \times 10^{-6}$ (Richards and Dorale, 2003); this, coupled with an arbitrary uncertainty of 50% or 100%, is often considered as the initial value for the age calculation in the ^{230}Th dating equation (Eq. (1)). This study of modern and fossil coral and seawater samples indicates that the dissolved fraction of seawater is the primary thorium source for the coral skeleton. Variability of seawater $^{230}Th/^{232}Th$ values may result from mixing of sources with different thorium isotopic compositions. The use of the continental crust-derived values is valid where the dominant source of thorium is terrestrial. However, a positive age bias can be generated if the crustal value is used for sites with high $^{230}Th/^{232}Th$ sources. Isochron techniques can offer an accurate $^{230}Th/^{232}Th_0$ value and a date with precision as good as ± 1 yr for corals younger than 100 yrs (Fig. 5). A high precision date can also be achievable using site-specific $^{230}Th/^{232}Th_0$ ratios (Fig. 6 and Tables A3–A12).

3.6.3. Duplicate measurements

Three discordant ages in 141 U–Th points indicate additional ^{230}Th and ^{232}Th sources, presumably high-$^{230}Th/^{232}Th$ carbonate sands and low-$^{230}Th/^{232}Th$ terrestrial materials, which cause occasional biases of 4–23 yrs from the true age (Fig. 6 and Tables A4, A6, A10). Coeval subsamples with different dating results indicate that heterogeneous coprecipitation places limits on high precision ^{230}Th dating. In our study, these discordant ages were relatively rare (2.1% of the 141 total subsamples). Duplicate measurement of coeval subsamples is suggested to verify the accuracy of high precision dates if $^{230}Th/^{232}Th_0$ can be well estimated.

This issue is not critical for Quaternary samples, for which a ^{230}Th dating precision of ± 30–50 yrs is satisfactory. For young corals, the occasional problem of detrital material with $^{230}Th/^{232}Th$ ratios significantly different from the dissolved value in seawater can be resolved by duplicate measurements of ^{230}Th ages at 2–3 coeval loci on a single growth band as a concordance test to rule out the influence of detrital material contributing an anomalous $^{230}Th/^{232}Th$ value.

4. CONCLUSIONS

Measurements of U–Th isotopic compositions in suspended particulate material and the dissolved fraction of seawater and in modern and fossil corals from sites in the western Pacific Ocean, South China Sea, and eastern Indian Ocean were performed to understand the natural variation of $^{230}Th/^{232}Th_0$ in shallow seawater corals and its effects on coral ^{230}Th dating. To approach this objective, sample preparation procedures and chemical procedures have been refined, resulting in an equivalent age uncertainty of only ± 0.2–0.3 yr.

Coral isochron-derived $^{230}Th/^{232}Th_0$ ratios, comparison of ^{230}Th ages and absolute ages, and thorium analyses in seawater samples demonstrate that coral skeletal thorium originates mainly from the dissolved fraction of seawater. The $^{230}Th/^{232}Th_0$ value is strongly influenced by local hydrological setting. $^{230}Th/^{232}Th_0$ values are low ($3–5 \times 10^{-6}$) at Son Tra and Nanwan, two continental shelf sites with intense terrestrial material input. The variation of initial values at each site is ~10%. The crustal U–Th composition-inferred $^{230}Th/^{232}Th$ values can be used for age calculation. At the open-ocean site of Santo in the western Pacific, a value of 5.6×10^{-6} is observed at 4 horizons, and one high value of 24×10^{-6} is documented during a La Niña event in AD 1973–1976. The initial values recorded in the intertidal corals at the sites in the Sumatran islands vary significantly from 3.0 to 9.4×10^{-6}. Accordingly, isochron techniques should be applied for high precision dating at these sites with a variety of $^{230}Th/^{232}Th_0$ ratios. Detrital material with anomalously low or high $^{230}Th/^{232}Th$ ratios causes biases ranging from -23 to $+4$ yrs in this study. Duplicate measurement of coeval subsamples is recommended to verify the age accuracy.

Band-counted and tracer-tuned chronologies are usually characterized by compounded age errors of at least ± 2–3 yrs by AD 1800–1900. Using site-specific $^{230}Th/^{232}Th_0$ values or isochron techniques, our study demonstrates that a coral ^{230}Th dating method with a precision as high as ± 1 yr is achievable for corals with ages less than 100 yrs. The ability to obtain high precision and accuracy ages on young coral will be useful in diverse fields within the broad area of global change, including oceanography, tectonic evolution, anthropogenic pollution history, paleoclimate and paleo-environment. This ^{230}Th dating methodology can also be applied to different carbonate samples, such as speleothem and tufa.

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APPENDIX A

See Figs. A1–A4 and Tables A1–A12.

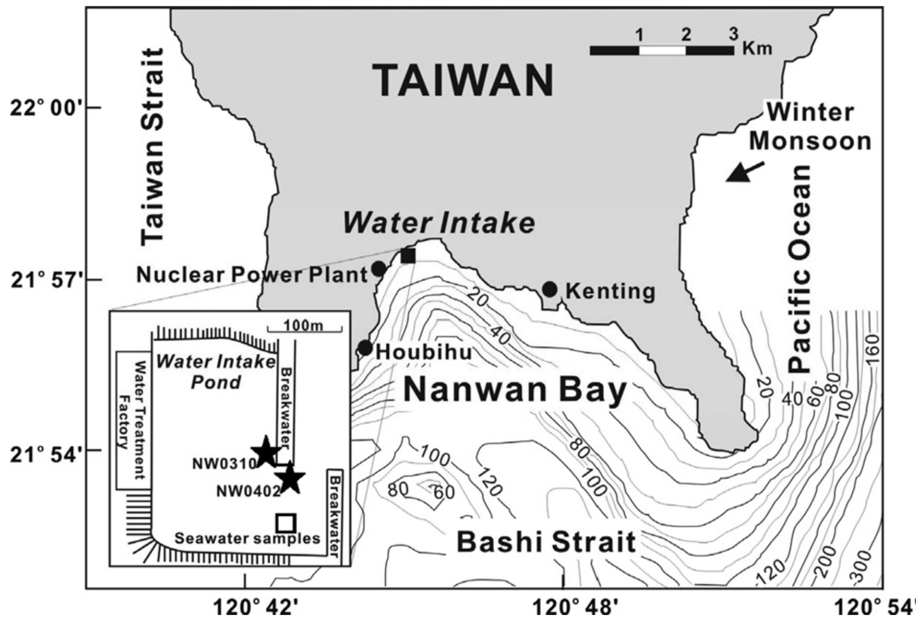

Fig. A1. Map of collection sites of corals (stars) and seawater samples (square) at Nanwan, Taiwan.

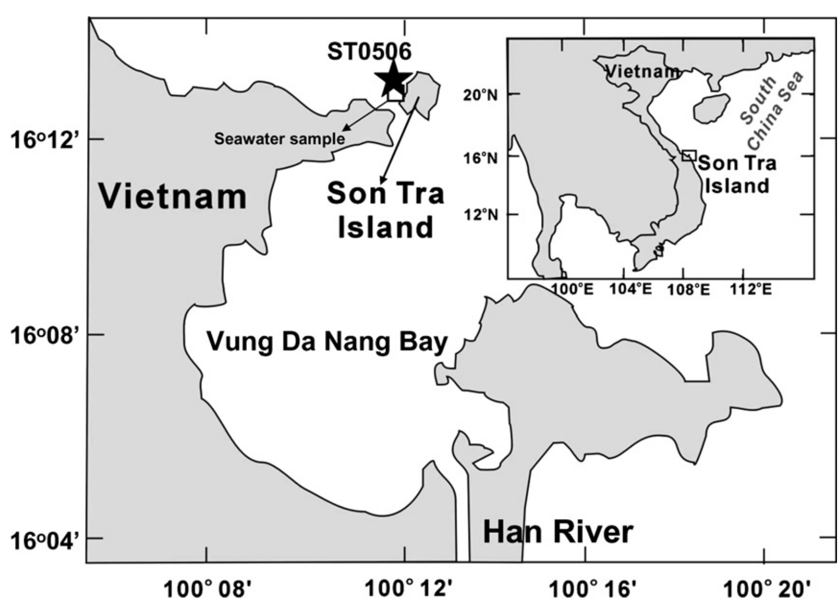

Fig. A2. The collection site of a living *Porites* coral (star) and seawater (square) at Son Tra Island, Vietnam.

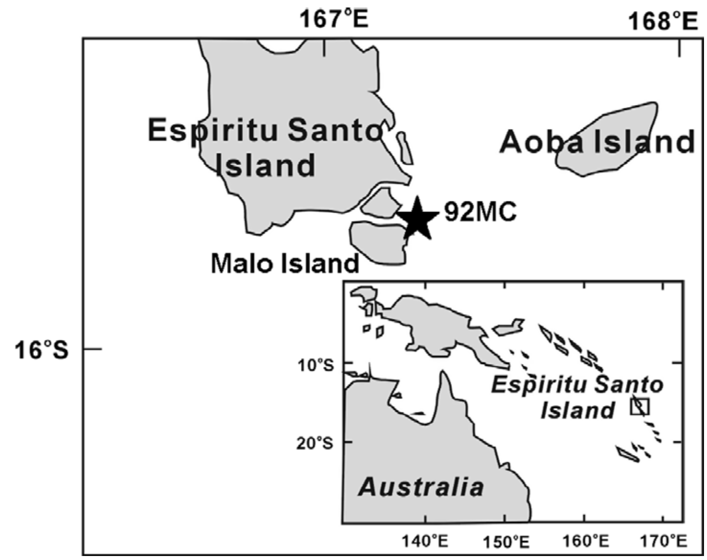

Fig. A3. The coral coring site of sample 92MC (star) on southern Espiritu Santo Island of Vanuatu.

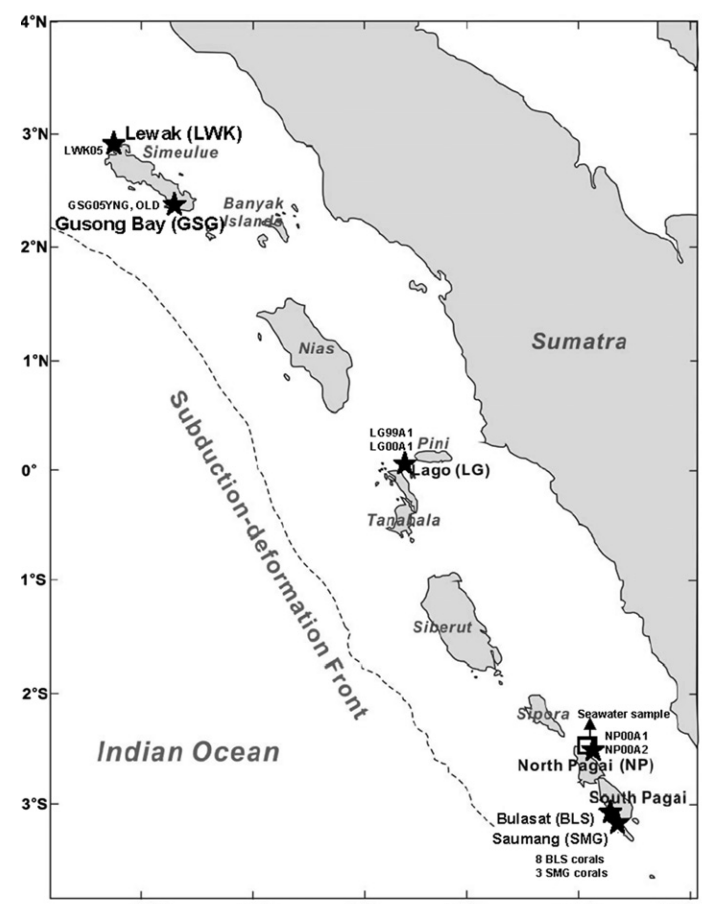

Fig. A4. The collection sites of modern and fossil corals (stars) and seawater (square) in the Sumatran islands.

Table A1
U–Th data for dissolved fractions of seawater samples from Nanwan, North Pagai and Son Tra

Sample ID[a]	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	$\delta^{234}U$	($^{230}Th/^{238}U$) activity ratio	$^{230}Th/^{232}Th \times 10^{-6}$
NS1	536.88	3.061 ± 0.005	2.492 ± 0.006	146.2 ± 1.8	0.00020 ± 0.00002	4.04 ± 0.38
NS2	539.24	3.098 ± 0.004	2.251 ± 0.005	147.0 ± 1.4	0.00018 ± 0.00002	4.13 ± 0.37
NS3	536.74	3.069 ± 0.003	3.557 ± 0.008	148.5 ± 1.2	0.00029 ± 0.00002	4.12 ± 0.27
NS4	534.31	3.094 ± 0.004	2.460 ± 0.006	148.7 ± 1.2	0.00020 ± 0.00002	4.17 ± 0.42
NS5	541.01	3.090 ± 0.004	2.490 ± 0.006	148.3 ± 1.6	0.00021 ± 0.00002	4.22 ± 0.34
NS6	539.33	3.099 ± 0.004	2.561 ± 0.005	147.6 ± 1.3	0.00020 ± 0.00001	3.94 ± 0.29
NS7	537.08	3.090 ± 0.004	2.064 ± 0.004	146.5 ± 1.5	0.00018 ± 0.00001	4.34 ± 0.35
NS8	534.77	3.096 ± 0.005	0.716 ± 0.002	147.2 ± 1.7	0.00005 ± 0.00001	3.89 ± 0.78
NS9	533.95	3.078 ± 0.004	0.671 ± 0.002	148.1 ± 1.6	0.00005 ± 0.00001	3.91 ± 0.79
NS10	536.91	3.092 ± 0.005	1.899 ± 0.005	147.7 ± 1.9	0.00014 ± 0.00001	3.81 ± 0.38
NS11	538.77	3.045 ± 0.004	1.456 ± 0.004	148.6 ± 1.6	0.00012 ± 0.00001	4.17 ± 0.47
NS12	539.74	3.034 ± 0.005	2.803 ± 0.006	148.0 ± 1.9	0.00019 ± 0.00002	3.31 ± 0.30
NS13	535.66	3.077 ± 0.004	2.371 ± 0.005	148.5 ± 1.7	0.00017 ± 0.00001	3.57 ± 0.30
NS14	543.20	2.942 ± 0.005	7.004 ± 0.019	146.0 ± 2.0	0.00054 ± 0.00003	3.72 ± 0.22
NS15	538.38	3.093 ± 0.005	3.953 ± 0.008	146.2 ± 1.9	0.00032 ± 0.00002	4.17 ± 0.25
NS16	487.17	3.146 ± 0.005	4.463 ± 0.009	147.3 ± 1.7	0.00034 ± 0.00002	3.98 ± 0.22
NS17	534.88	3.124 ± 0.010	2.020 ± 0.004	148.1 ± 3.4	0.00015 ± 0.00001	3.92 ± 0.36
NS18	538.08	3.099 ± 0.004	1.861 ± 0.004	146.5 ± 1.6	0.00014 ± 0.00001	3.95 ± 0.40
NS19	537.00	3.104 ± 0.004	1.955 ± 0.005	148.2 ± 1.6	0.00017 ± 0.00002	4.34 ± 0.45
NS20	539.29	3.104 ± 0.004	0.991 ± 0.003	147.6 ± 1.5	0.00008 ± 0.00001	3.99 ± 0.57
NS21	542.62	3.116 ± 0.005	1.145 ± 0.003	145.2 ± 1.8	0.00010 ± 0.00001	4.53 ± 0.56
NPSW1	487.42	3.026 ± 0.005	9.503 ± 0.029	147.7 ± 1.8	0.00081 ± 0.00005	4.27 ± 0.29
NPSW2	539.59	3.052 ± 0.009	13.755 ± 0.057	145.5 ± 3.1	0.00109 ± 0.00007	4.00 ± 0.26
VTSW1	991.20	2.872 ± 0.015	0.282 ± 0.001	146.3 ± 2.9	0.000019 ± 0.000005	3.14 ± 0.84
VTSW2	1012.01	3.371 ± 0.009	0.318 ± 0.001	143.6 ± 1.7	0.000018 ± 0.000005	3.23 ± 0.85

[a] NS1–NS21: Nanwan samples; NPSW1–NPSW2: North Pagai samples; VTSW1–VTSW2: Son Tra Island samples. Nanwan samples were collected every 2 h from July 31, 6:00 AM to August 1, 10:00 PM, 2004. North Pagai samples were collected in January 2004, and Son Tra Island samples on June 14, 2005.

Table A2
U–Th data in the suspended particulate matter of 5-L Nanwan seawater samples

Sample ID[a]	^{238}U (ppb)	^{232}Th (ppt)	$\delta^{234}U$	($^{230}Th/^{238}U$) activity ratio	$^{230}Th/^{232}Th \times 10^{-6}$
SP1	1.276 ± 0.008	4.98 ± 0.05	23.9 ± 5.3	0.60 ± 0.09	2.52 ± 0.37
SP2	0.576 ± 0.007	1.77 ± 0.01	62.3 ± 8.1	0.57 ± 0.06	3.06 ± 0.34
SP3	0.696 ± 0.008	2.37 ± 0.01	22.3 ± 6.1	0.70 ± 0.08	3.38 ± 0.39
SP4	0.660 ± 0.007	1.99 ± 0.01	47.8 ± 9.3	0.60 ± 0.07	3.27 ± 0.38
SP5	1.319 ± 0.008	3.63 ± 0.09	36.2 ± 3.8	0.49 ± 0.06	2.91 ± 0.36
SP6	0.988 ± 0.008	3.28 ± 0.03	38.0 ± 4.6	0.53 ± 0.08	2.66 ± 0.41
SP7	1.035 ± 0.008	2.99 ± 0.02	40.0 ± 4.3	0.62 ± 0.08	3.52 ± 0.43
SP8	2.048 ± 0.010	7.41 ± 0.05	2.6 ± 3.7	0.60 ± 0.06	2.75 ± 0.28

[a] Samples were collected from October 28, 7:00 AM to October 30, 1:00 AM, 2004.

Table A3
U–Th data and ^{230}Th ages for subsamples of Nanwan NW030525, NW940101, and NW940617 corals

Coral ID[a]	Subsample ID[b]	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[c]	^{230}Th date AD	Banding date AD	Chemistry date AD
NW030525	*1#1*	1.046	2538 ± 5	470.6 ± 2.1	147.1 ± 2.0	0.000047 ± 0.000027	4.2 ± 2.4	147.1 ± 2.0	4.5 ± 2.6	−0.7 ± 2.6	2004.3 ± 2.6	2002.9 ± 0.5	2003.58
	1#2	2.578	2336 ± 6	148.2 ± 0.4	146.0 ± 2.4	0.000043 ± 0.000003	11.1 ± 0.9	146.0 ± 2.4	4.1 ± 0.3	2.3 ± 0.3	*2001.3* ± 0.3	2002.9 ± 0.5	2003.58
	2	0.966	2851 ± 5	380.7 ± 1.8	148.1 ± 1.9	0.000078 ± 0.000026	9.6 ± 3.2	148.1 ± 1.9	7.4 ± 2.4	3.7 ± 2.5	1999.9 ± 2.5	1999.9 ± 0.5	2003.58
	3	0.985	2649 ± 5	388.2 ± 1.3	146.6 ± 2.1	0.000104 ± 0.000008	11.7 ± 1.0	146.6 ± 2.1	9.9 ± 0.8	5.8 ± 0.8	1997.8 ± 0.8	1997.9 ± 0.5	2003.58
NW940101	*1#1*	1.003	2363 ± 5	227.2 ± 0.9	145.4 ± 2.0	0.000176 ± 0.000008	30.2 ± 1.4	145.4 ± 2.0	16.8 ± 0.8	14.1 ± 0.8	*1989.5* ± 0.8	1993.5 ± 0.5	2003.58
	1#2	2.505	2411 ± 5	263.3 ± 0.3	146.7 ± 2.2	0.000193 ± 0.000004	29.1 ± 0.7	146.7 ± 2.2	18.4 ± 0.4	15.3 ± 0.5	*1988.3* ± 0.5	1993.5 ± 0.5	2003.58
	2	0.795	2640 ± 5	489.8 ± 1.4	145.1 ± 1.9	0.000497 ± 0.000011	44.3 ± 0.9	144.3 ± 1.9	47.4 ± 1.0	42.2 ± 1.0	*1961.4* ± 1.0	1991.5 ± 0.5	2003.58
	3	0.850	2524 ± 5	388.0 ± 1.2	144.9 ± 2.0	0.000439 ± 0.000011	47.1 ± 1.2	144.9 ± 2.0	41.9 ± 1.1	37.5 ± 1.1	*1966.0* ± 1.1	1989.5 ± 0.5	2003.58
NW940617	1	1.459	2442 ± 5	328 ± 1	146.3 ± 2.1	0.000136 ± 0.000008	16.7 ± 1.0	146.3 ± 2.1	13.0 ± 0.8	9.2 ± 0.8	1994.4 ± 0.8	1994.0 ± 0.5	2003.58
	2	0.844	2403 ± 4	1109 ± 2	145.6 ± 1.9	0.000247 ± 0.000011	8.8 ± 0.4	145.6 ± 1.9	23.6 ± 1.1	10.6 ± 1.3	1993.0 ± 1.3	1992.2 ± 0.5	2003.58
	3	0.847	2535 ± 5	888 ± 2	145.0 ± 2.0	0.000240 ± 0.000011	11.3 ± 0.5	145.0 ± 2.0	22.9 ± 1.0	13.0 ± 1.2	1990.6 ± 1.2	1990.0 ± 0.5	2003.58

[a] Samples, NW030525 and NW940617, were stored in plastic bags and NW940101 was stored uncovered with Quaternary samples.
[b] The subsamples, 1#2 of NW030525 and all of NW940101 shown in italic, cut on a class-100 bench in a general Quaternary carbonate preparation room, were contaminated.
[c] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $4.86 \pm 0.27 \times 10^{-6}$, inferred from the isochron with subsamples 6#1–6#4 of NW0310 (see A8).

Table A4
U–Th data and ^{230}Th ages for subsamples of Nanwan NW0310 and NW0402 corals

Coral ID	Subsample ID	Crushed size (μm)	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th date AD	Banding date AD	Chemistry date AD
NW0310	1	Bulk	0.696	2446 ± 4	320.3 ± 1.8	145.6 ± 1.5	0.000070 ± 0.000012	8.8 ± 1.5	145.6 ± 1.5	6.6 ± 1.1	3.0 ± 1.1	2001.6 ± 1.1	2002.0 ± 0.3	2004.54
	2#1	Bulk	2.326	2620 ± 9	442.1 ± 1.4	147.1 ± 2.2	0.000097 ± 0.000006	9.2 ± 0.6	147.1 ± 2.2	9.2 ± 0.6	4.5 ± 0.7	2000.5 ± 0.7	2000.8 ± 0.3	2004.96
	2#2	Bulk	2.258	2646 ± 9	519.9 ± 1.5	151.7 ± 2.4	0.000106 ± 0.000006	8.9 ± 0.5	151.7 ± 2.4	10.0 ± 0.6	4.6 ± 0.6	2000.4 ± 0.6	2000.8 ± 0.3	2004.96
	2#3	Bulk	3.066	2596 ± 9	388.3 ± 1.2	150.0 ± 2.0	0.000091 ± 0.000005	10.0 ± 0.6	150.0 ± 2.0	8.6 ± 0.5	4.4 ± 0.5	2000.5 ± 0.5	2000.8 ± 0.3	2004.96
	2#4	Bulk	2.868	2647 ± 10	497.9 ± 1.5	148.9 ± 2.2	0.000103 ± 0.000006	9.0 ± 0.5	148.9 ± 2.2	9.8 ± 0.5	4.5 ± 0.6	2000.4 ± 0.6	2000.8 ± 0.3	2004.96
	2#5	Bulk	2.356	2520 ± 9	637.9 ± 1.4	150.8 ± 2.4	0.000124 ± 0.000005	8.1 ± 0.3	150.8 ± 2.4	11.7 ± 0.5	4.7 ± 0.6	2000.3 ± 0.6	2000.8 ± 0.3	2004.96
	3#1	840–1410	0.807	2662 ± 5	321.3 ± 1.2	147.5 ± 1.5	0.000084 ± 0.000007	11.5 ± 1.0	147.5 ± 1.5	8.0 ± 0.7	4.6 ± 0.7	1999.3 ± 0.7	1999.0 ± 0.3	2003.95
	3#2	1410–2380	0.836	2664 ± 7	328.2 ± 1.2	147.2 ± 2.2	0.000085 ± 0.000007	11.4 ± 0.9	147.2 ± 2.2	8.1 ± 0.7	4.6 ± 0.7	1999.3 ± 0.7	1999.0 ± 0.3	2003.95
	3#3	Bulk	0.758	2622 ± 5	440.8 ± 2.5	146.7 ± 1.6	0.000107 ± 0.000013	10.5 ± 1.3	146.7 ± 1.6	10.2 ± 1.2	5.5 ± 1.3	1999.0 ± 1.3	1999.0 ± 0.3	2004.54
	4#1	<840	2.324	2626 ± 5	465.5 ± 0.7	145.9 ± 1.6	0.000149 ± 0.000004	13.9 ± 0.3	145.9 ± 1.6	14.2 ± 0.4	9.3 ± 0.5	1994.7 ± 0.5	1995.0 ± 0.3	2003.95
	4#2	840–1410	0.742	2657 ± 5	340.5 ± 1.4	146.9 ± 2.0	0.000134 ± 0.000009	17.3 ± 1.2	146.9 ± 2.0	12.8 ± 0.9	9.2 ± 0.9	1994.8 ± 0.9	1995.0 ± 0.3	2003.95
	4#3	1410–2380	0.733	2621 ± 6	334.1 ± 1.5	146.7 ± 2.2	0.000133 ± 0.000008	17.2 ± 1.1	146.7 ± 2.2	12.7 ± 0.8	9.1 ± 0.8	1994.9 ± 0.8	1995.0 ± 0.3	2003.95
	4#4	Bulk	0.622	2727 ± 5	427.7 ± 1.7	146.7 ± 1.7	0.000148 ± 0.000011	15.6 ± 1.2	146.7 ± 1.7	14.1 ± 1.1	9.7 ± 1.1	1994.8 ± 1.1	1995.0 ± 0.3	2004.54
	5#1	<840	2.009	2534 ± 5	395.9 ± 1.1	149.6 ± 2.1	0.000183 ± 0.000006	19.3 ± 0.6	149.6 ± 2.1	17.3 ± 0.6	13.0 ± 0.6	1991.0 ± 0.6	1991.0 ± 0.3	2003.95

(*continued on next page*)

Table A4 (*continued*)

Coral ID	Subsample ID	Crushed size (μm)	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th date AD	Banding date AD	Chemistry date AD
	5#2	840–1410	0.655	2543 ± 6	331.9 ± 2.0	147.8 ± 2.6	0.000171 ± 0.000009	21.6 ± 1.2	147.8 ± 2.6	16.3 ± 0.9	12.6 ± 0.9	1991.3 ± 0.9	1991.0 ± 0.3	2003.95
	5#3	1410–2380	0.664	2545 ± 6	348.0 ± 1.3	146.8 ± 2.4	0.000214 ± 0.000010	25.9 ± 1.2	146.8 ± 2.4	20.4 ± 0.9	16.6 ± 1.0	1987.4 ± 1.0	1991.0 ± 0.3	2003.95
	5#4	Bulk	0.956	2588 ± 5	317.7 ± 1.1	145.8 ± 1.7	0.000171 ± 0.000008	23.0 ± 1.1	145.8 ± 1.7	16.9 ± 0.8	13.5 ± 0.8	1991.1 ± 0.8	1991.0 ± 0.3	2004.54
	6#1	<840	1.964	2508 ± 6	485.3 ± 1.5	147.3 ± 2.6	0.000218 ± 0.000008	18.6 ± 0.7	147.7[b] ± 2.7	20.7 ± 0.8	15.56[c] ± 0.56	1988.4 ± 0.6	1988.0 ± 0.3	2003.95
	6#2	840–1410	0.985	2445 ± 6	356.9 ± 1.7	148.3 ± 2.5	0.000202 ± 0.000009	22.9 ± 1.0		19.3 ± 0.9			1988.0 ± 0.3	2003.95
	6#3	1410–2380	1.090	2497 ± 6	347.3 ± 1.5	147.6 ± 2.5	0.000213 ± 0.000009	25.2 ± 1.1		20.2 ± 0.9			1988.0 ± 0.3	2003.95
	6#4	Bulk	0.991	2443 ± 6	4547 ± 15	148.3 ± 2.1	0.000713 ± 0.000028	6.3 ± 0.2		67.8 ± 2.7			1988.0 ± 0.3	2003.95
NW0402	2#1	Bulk	2.932	2435 ± 9	677.5 ± 1.7	147.2 ± 2.3	0.000137 ± 0.000006	8.1 ± 0.4	147.3 ± 2.3	13.1 ± 0.6	5.3 ± 0.7	1999.7 ± 0.7	No clear banding	2004.96
	2#2	Bulk	2.495	2443 ± 8	752.9 ± 1.8	147.9 ± 2.2	0.000148 ± 0.000006	7.9 ± 0.3	147.9 ± 2.2	14.1 ± 0.5	5.5 ± 0.7	1999.5 ± 0.7		2004.96
	2#3	Bulk	3.179	2468 ± 8	629.4 ± 1.3	147.5 ± 2.1	0.000130 ± 0.000005	8.4 ± 0.3	147.5 ± 2.1	12.3 ± 0.5	5.2 ± 0.6	1999.8 ± 0.6		2004.96
	2#4	Bulk	3.173	2513 ± 10	618.2 ± 1.7	145.3 ± 2.1	0.000131 ± 0.000006	8.8 ± 0.4	145.3 ± 2.1	12.5 ± 0.6	5.6 ± 0.7	1999.4 ± 0.7		2004.96

[a] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $4.86 \pm 0.27 \times 10^{-6}$, inferred from the isochron with subsamples 6#1–6#4 of NW0310.
[b] Isochron-derived initial δ^{234}U value.
[c] Isochron age for the subsamples, 6#1, 6#2, 6#3, and 6#4, of NW0310.

Table A5
U–Th data and ^{230}Th ages for subsamples of the ST0506 coral slab from Son Tra Island, Vietnam

Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th date AD	Banding date AD	Chemistry date AD
1	1.573	2501 ± 10	1246 ± 12	146.4 ± 2.5	0.00012 ± 0.00002	3.8 ± 0.7	146.4 ± 2.5	11.0 ± 1.9	1.8 ± 2.1	2003.7 ± 2.1	2004.1 ± 0.3	2005.56
2#1	2.333	2427 ± 11	1062 ± 3	143.3 ± 2.6	0.00015 ± 0.00001	5.6 ± 0.4	143.3 ± 2.6	14.1 ± 1.1	6.0 ± 1.4	1999.6 ± 1.4	2000.4 ± 0.5	2005.56
2#2	1.913	2587 ± 6	1191 ± 5	147.5 ± 2.5	0.00015 ± 0.00001	5.3 ± 0.5	147.5 ± 2.5	14.0 ± 1.3	5.5 ± 1.5	2000.1 ± 1.5	2000.4 ± 0.5	2005.56
2#3	2.208	2461 ± 10	1102 ± 3	146.3 ± 2.4	0.00015 ± 0.00001	5.4 ± 0.4	146.3 ± 2.4	14.1 ± 1.0	5.8 ± 1.3	1999.8 ± 1.3	2000.4 ± 0.5	2005.56
2#4	2.376	2405 ± 11	1045 ± 3	147.2 ± 2.6	0.00015 ± 0.00001	5.7 ± 0.4	147.2 ± 2.6	14.2 ± 1.1	6.1 ± 1.4	1999.4 ± 1.4	2000.4 ± 0.5	2005.56
3	2.273	2410 ± 11	1388 ± 5	148.7 ± 2.5	0.00025 ± 0.00001	7.2 ± 0.4	148.7 ± 2.5	23.8 ± 1.2	13.1 ± 1.6	1992.4 ± 1.6	1992.6 ± 0.6	2005.56

[a] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $3.20 \pm 0.32 \times 10^{-6}$, estimated from seawater thorium data.

Table A6
U–Th data and ^{230}Th ages for subsamples of the Santo 92MC coral

Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th date AD	Banding date AD	Chemistry date AD
1#1	0.928	2460 ± 4	366.3 ± 1.1	145.2 ± 1.9	0.00020 ± 0.00001	21.8 ± 1.3	147.3[b] ± 2.8	18.8 ± 1.1	14.0[c] ± 1.1	1990.6 ± 1.1	1991.7 ± 0.3	2004.58
1#2	1.101	2522 ± 4	96.4 ± 0.7	146.5 ± 1.7	0.00016 ± 0.00001	67.4 ± 4.8		14.9 ± 1.1				2004.58
1#3	1.343	2541 ± 4	131.5 ± 0.6	146.8 ± 1.6	0.00017 ± 0.00001	53.2 ± 2.7		15.9 ± 0.8				2004.58
1#4	0.960	2547 ± 3	160.9 ± 0.8	147.0 ± 1.6	0.00022 ± 0.00001	57.6 ± 2.7	147.1 ± 1.6	21.0 ± 1.0	19.0 ± 1.2	1985.6 ± 1.2	1991.7 ± 0.3	2004.58
2#1	1.289	2534 ± 4	82.1 ± 0.6	145.0 ± 1.8	0.00036 ± 0.00001	181.6 ± 4.6	146.1[b] ± 3.2	34.0 ± 0.8	29.2[c] ± 1.3	1975.4 ± 1.3	1974.6 ± 0.5	2004.58
2#2	1.025	2500 ± 3	120.3 ± 0.8	147.9 ± 1.6	0.00037 ± 0.00001	126.6 ± 4.0		35.1 ± 1.1				2004.58
2#3	1.203	2557 ± 4	105.0 ± 0.6	146.5 ± 3.7	0.00036 ± 0.00001	146.5 ± 3.7		34.7 ± 0.9				2004.58
2#4	0.869	2595 ± 3	230.4 ± 1.0	146.5 ± 1.7	0.00044 ± 0.00001	81.3 ± 2.6		41.6 ± 1.3				2004.58
3	1.511	2473 ± 5	204.5 ± 0.9	145.9 ± 1.9	0.00044 ± 0.00001	87.0 ± 2.9	145.9 ± 1.9	41.5 ± 1.4	38.9 ± 1.7	1965.7 ± 1.7	1965.9 ± 0.4	2004.58
4	1.139	2541 ± 4	28.9 ± 0.6	145.4 ± 1.8	0.00049 ± 0.00001	714 ± 24	145.4 ± 1.8	47.0 ± 1.2	46.6 ± 1.2	1958.0 ± 1.2	1957.7 ± 0.2	2004.58
5	1.601	2469 ± 4	90.9 ± 0.5	147.9 ± 1.6	0.00062 ± 0.00001	275.9 ± 4.4	147.9 ± 1.6	58.5 ± 0.9	57.3 ± 1.0	1947.2 ± 1.0	1947.2 ± 0.2	2004.58
6	1.320	2503 ± 4	368.8 ± 1.2	148.6 ± 1.7	0.00081 ± 0.00001	90.5 ± 1.6	148.6 ± 1.7	76.8 ± 1.3	72.0 ± 2.2	1932.6 ± 2.2	1934.0 ± 0.4	2004.58

[a] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $5.62 \pm 2.05 \times 10^{-6}$, inferred from the isochron with subsamples, 1#1, 1#2, and 1#3.
[b] Isochron-derived initial δ^{234}U value.
[c] Isochron ages.

Table A7
U–Th data and ^{230}Th ages for subsamples of the LWK05 coral collected from Lewak, northern Simeulue, Sumatran islands

Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th date AD	Banding date AD	Chemistry date AD
2a + 2b	2.074	2275 ± 5	497.2 ± 1.7	149.3 ± 2.3	0.00009 ± 0.00001	7.1 ± 0.7	149.3 ± 2.3	9.0 ± 0.9	5.2 ± 1.1	2000.8 ± 1.1	2000.6 ± 0.4	2005.96
3a	1.819	2138 ± 3	576.6 ± 2.0	142.9 ± 1.7	0.00032 ± 0.00002	19.8 ± 1.2	142.9 ± 1.7	30.9 ± 1.9	26.2 ± 2.0	1979.7 ± 2.0	1978.4 ± 2.3	2005.96
4a#1	1.438	2354 ± 4	2354 ± 8	146.0 ± 2.1	0.00061 ± 0.00003	10.0 ± 0.5	146.8[b] ± 3.2	58.4 ± 2.7	39.9[c] ± 3.8	1966.1 ± 3.8	1964.3 ± 3.4	2005.96
4a#2	1.170	2300 ± 5	7005 ± 33	143.4 ± 2.9	0.00101 ± 0.00011	5.5 ± 0.6		96 ± 10				2005.96
4b#1	1.792	2292 ± 5	2685 ± 10	146.8 ± 2.3	0.00063 ± 0.00002	8.8 ± 0.3		59.5 ± 2.2				2005.96
4b#2	1.063	2292 ± 4	8246 ± 55	145.6 ± 2.1	0.00107 ± 0.00008	4.9 ± 0.4		101.6 ± 7.8				2005.96
5a	1.403	2319 ± 5	4671 ± 33	144.0 ± 2.5	0.00084 ± 0.00005	6.8 ± 0.4	144.0 ± 2.5	79.7 ± 4.6	44.7 ± 7.2	1961.3 ± 7.2	1956.0 ± 5.0	2005.96
6a	1.598	2302 ± 5	6769 ± 49	145.5 ± 2.5	0.00112 ± 0.00007	6.3 ± 0.4	145.5 ± 2.5	106.5 ± 7.1	55 ± 11	1951 ± 11	1948.1 ± 5.0	2005.96

[a] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $3.01 \pm 0.47 \times 10^{-6}$.
[b] Isochron-derived initial δ^{234}U value.
[c] Isochron age for subsamples of 4a#1, 4a#2, 4b#1, and 4b#2.

Table A8
U–Th data and ^{230}Th ages for subsamples of coral slabs, GSG05YNG and GSG05OLD, collected from Gusong Bay of southwestern Simeulue, Sumatran islands

Coral ID	Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th date AD	Banding date AD	Chemistry date AD
GSG05YNG	1a#1	0.683	2253 ± 4	374 ± 2	146.5 ± 1.9	0.00014 ± 0.00002	14.0 ± 1.5	146.3[b] ± 1.4	13.4 ± 1.4	6.0[c] ± 1.4	2000.2 ± 1.4	1998.6 ± 1.1	2006.22
	1a#2	0.700	2264 ± 3	435 ± 2	145.3 ± 1.4	0.00015 ± 0.00001	12.6 ± 1.2		13.9 ± 1.3				2006.22
	1a#3	0.741	2201 ± 5	1395 ± 5	144.5 ± 1.8	0.00035 ± 0.00002	9.0 ± 0.6		33.1 ± 2.1				2006.22
	1a#4	0.589	2319 ± 5	476 ± 2	145.4 ± 2.0	0.00015 ± 0.00002	12.3 ± 1.4		14.6 ± 1.6				2006.22
	1b#1	0.482	2307 ± 5	263 ± 2	145.8 ± 2.0	0.00012 ± 0.00002	18.1 ± 2.4	145.8 ± 2.0	11.9 ± 1.6	7.1 ± 1.7	1999.1 ± 1.7	1998.4 ± 1.1	2006.22
	1b#2	0.551	2252 ± 4	655 ± 3	146.1 ± 1.8	0.00019 ± 0.00002	11.0 ± 1.0	146.1 ± 1.8	18.5 ± 1.6	6.1 ± 2.0	2000.1 ± 2.0	1998.4 ± 1.1	2006.22
	2a#1	0.640	2183 ± 4	665 ± 3	144.2 ± 1.7	0.00027 ± 0.00002	14.4 ± 0.9	146.5[b] ± 7.1	25.4 ± 1.6	13.3[c] ± 3.2	1992.9 ± 3.2	1993.7 ± 2.1	2006.22
	2a#2	0.752	2135 ± 4	52,670 ± 535	146.1 ± 2.3	0.01096 ± 0.00035	7.3 ± 0.2		1049 ± 34				2006.22
	2a#4	0.638	2247 ± 5	897 ± 8	148.8 ± 2.9	0.00033 ± 0.00003	13.5 ± 1.1		31.0 ± 2.5				2006.22
	2b#1	0.711	1984 ± 3	597 ± 4	148.7 ± 2.1	0.00027 ± 0.00002	15.0 ± 1.0		26.0 ± 1.8				2006.22
	3a#1	2.037	2257 ± 4	64,689 ± 933	146.8 ± 1.7	0.01304 ± 0.00055	7.5 ± 0.3	146.9 ± 1.7	1249 ± 53	28 ± 122	1978 ± 122	1986.9 ± 3.2	2005.99
	3a#2	1.410	2230 ± 4	40,714 ± 337	145.6 ± 1.9	0.00841 ± 0.00039	7.6 ± 0.4	145.6 ± 1.9	804 ± 37	27 ± 79	1979 ± 79	1986.9 ± 3.2	2005.99
	3b#1	1.375	2149 ± 4	2887 ± 7	148.6 ± 1.9	0.00081 ± 0.00003	10.0 ± 0.3	148.6 ± 1.9	77.2 ± 2.7	20.3 ± 5.7	1985.7 ± 5.7	1985.8 ± 3.6	2005.99
	3b#2	1.735	2172 ± 5	557 ± 2	144.7 ± 2.2	0.00034 ± 0.00001	22.1 ± 0.8	144.7 ± 2.2	32.8 ± 1.3	84.1 ± 1.6	1984.1 ± 1.6	1985.8 ± 3.6	2005.99
GSG05OLD	3a#1	1.181	2339 ± 3	3578 ± 15	146.0 ± 2.0	0.00341 ± 0.00006	36.8 ± 0.7	145.5[b] ± 4.4	325.3 ± 6.0	269[c] ± 12	1737 ± 12	Unknown[d]	2006.11
	3a#2	0.973	2440 ± 3	6959 ± 42	144.3 ± 1.9	0.00397 ± 0.00011	23.0 ± 0.6		380 ± 10				2006.11
	3a#3	0.804	2438 ± 4	7742 ± 29	146.9 ± 2.3	0.00407 ± 0.00009	21.1 ± 0.5		387.9 ± 8.4				2006.11
	3a#4	0.560	2359 ± 3	4529 ± 16	145.1 ± 2.0	0.00361 ± 0.00007	31.1 ± 0.6		345.1 ± 6.3				2006.11
	4a#1	0.461	2654 ± 4	6242 ± 22	143.5 ± 1.8	0.00349 ± 0.00008	24.5 ± 0.5	150.0[b] ± 7.9	333.6 ± 7.3	242[c] ± 18	1764 ± 18	Unknown[d]	2006.11
	4a#2	0.318	2488 ± 4	6282 ± 20	145.2 ± 1.8	0.00363 ± 0.00007	23.7 ± 0.4		346.3 ± 6.3				2006.11
	4a#3	0.362	2415 ± 6	3703 ± 12	148.3 ± 3.1	0.00319 ± 0.00006	34.3 ± 0.7		303.5 ± 6.1				2006.11
	4a#4	0.911	2381 ± 4	4879 ± 15	143.9 ± 1.8	0.00342 ± 0.00006	27.5 ± 0.5		326.8 ± 5.7				2006.11

[a] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $7.35 \pm 0.65 \times 10^{-6}$, inferred from the isochron with subsamples of 1a#1–1a#4 of GSG05YNG.
[b] Isochron-derived initial ^{234}U value.
[c] Isochron age.
[d] GSG05OLD is a fossil coral and banding dates could not be counted.

Table A9
U–Th data and ^{230}Th ages for subsamples of two coral slabs, LG00A1 and LG99A1, from Lago of the Sumatran islands

Coral ID	Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected	^{230}Th date AD	Banding date AD	Chemistry date AD
LG99A1	1#1	1.321	2720 ± 6	297.1 ± 1.0	148.3 ± 1.7	0.00013 ± 0.00001	19.7 ± 1.0	147.3[a] ± 2.8	12.4 ± 0.6	8.3[b] ± 0.7	1995.7 ± 0.7	1996.0 ± 0.5	2003.96
	1#2	1.130	2776 ± 6	176.3 ± 0.8	148.3 ± 1.8	0.00012 ± 0.00001	30.7 ± 1.7		11.2 ± 0.6				
	1#3	1.703	2692 ± 6	743.4 ± 2.4	150.6 ± 1.7	0.00021 ± 0.00001	12.4 ± 0.6		19.7 ± 0.9				
LG99A1	3a	1.175	2643 ± 6	133.4 ± 0.8	146.6 ± 1.8	0.00068 ± 0.00002	224.0 ± 5.6	146.6 ± 1.8	65.2 ± 1.6	63.1[c] ± 1.6	1941.4 ± 1.6	1942.5 ± 0.5	2004.56
										62.5[d] ± 1.6	1942.1 ± 1.6	1942.5 ± 0.5	2004.56
LG00A1	1#1	1.541	2747 ± 6	2036.5 ± 8.5	147.2 ± 1.7	0.00115 ± 0.00002	25.7 ± 0.5	150.2[a] ± 2.2	109.7 ± 2.1	69.3[b] ± 0.9	1935.3 ± 0.9	1935.0 ± 0.5	2004.56
	1#2	1.369	2691 ± 5	282.6 ± 0.9	148.6 ± 1.5	0.00079 ± 0.00001	123.8 ± 1.8		74.9 ± 1.1				2004.56
	1#3	1.628	2776 ± 6	290.7 ± 1.1	149.5 ± 1.6	0.00079 ± 0.00001	124.9 ± 2.4		75.3 ± 1.4				2004.56
	1#4	1.498	2843 ± 6	359.9 ± 1.3	151.6 ± 1.7	0.00080 ± 0.00001	104.6 ± 1.6		76.1 ± 1.1				2004.56

[a] Isochron-derived initial δ^{234}U value.
[b] Isochron ages, 1#1–1#3 of LG99A1 and 1#1–1#4 of LG00A1.
[c] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $7.08 \pm 0.86 \times 10^{-6}$, inferred from the isochron with subsamples, 1#1–1#3, of LG99A1.
[d] Age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $9.4 \pm 1.2 \times 10^{-6}$, inferred from the isochron with subsamples, 1#1–1#4, of LG00A1.

Table A10
U–Th data and ^{230}Th ages for subsamples of coral slabs, NP00A1 and NP00A2 from the east coast of North Pagai, Sumatran islands

Coral ID	Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected[a]	^{230}Th Age uncorrected	^{230}Th Age corrected[b]	^{230}Th Age AD	^{230}Th/$^{232}Th_{initial}$ $\times 10^{-6}$[c]	Chemistry Date AD
NP00A1	1#1	2.034	2391 ± 6	2513 ± 10	147.0 ± 2.0	0.00039 ± 0.00002	6.1 ± 0.3	143.9 ± 3.4	37.0 ± 2.1	8.1 ± 1.9	1,997.0 ± 1.9	4.72 ± 0.45	2,005.05
	1#2	1.264	2362 ± 6	1432.1 ± 3.6	146.9 ± 2.3	0.00025 ± 0.00001	6.9 ± 0.4		24.0 ± 1.3				2,005.05
	1#3	1.118	2444 ± 5	2886.7 ± 8.9	145.2 ± 2.0	0.00042 ± 0.00002	5.9 ± 0.3		40.3 ± 2.0				2,005.05
	1#4	0.915	2459 ± 3	1138.8 ± 1.9	144.1 ± 1.5	0.00022 ± 0.00001	7.8 ± 0.4		21.0 ± 1.0				2,005.05
	1#5	1.823	2342 ± 8	4257 ± 17	146.9 ± 2.5	0.00037 ± 0.00003	3.3 ± 0.3	146.9 ± 2.5	34.9 ± 3.1	−14.6 ± 5.6			2,005.05
NP00A2	1#1	2.118	2422 ± 8	7437 ± 39	149.3 ± 2.6	0.00588 ± 0.00011	31.6 ± 0.6	145.2 ± 3.6	560 ± 10	476.0 ± 5.9	1,529.1 ± 5.9	4.81 ± 0.70	2,005.06
	1#2	1.419	2476 ± 8	5908 ± 27	147.9 ± 2.7	0.00566 ± 0.00009	39.2 ± 0.6		539.7 ± 8.6				2,005.06
	1#3	1.732	2450 ± 9	2291.5 ± 6.4	146.1 ± 2.7	0.00523 ± 0.00004	92.3 ± 0.7		499.3 ± 4.4				2,005.06
	1#4	1.158	2488 ± 6	2219.3 ± 6.4	146.4 ± 2.4	0.00526 ± 0.00005	97.4 ± 0.9		502.4 ± 4.9				2,005.06

[a] Isochron-derived initial δ^{234}U values for subsamples, 1#1-1#4, of NP00A1 and subsamples of NP00A2.
[b] For subsample NP00A1-1#5, age corrected using an initial ^{230}Th/^{232}Th atomic ratio of $4.72 \pm 0.45 \times 10^{-6}$, inferred from subsamples 1#1-1#4 of NP00A1; isochron age for others.
[c] Isochron-inferred initial ^{230}Th/^{232}Th.

Table A11
U-Th data and ^{230}Th ages for subsamples of eight coral slabs from Bulasat of South Pagai, Sumatran islands

Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U	(^{230}Th/^{238}U) activity ratio	^{230}Th/^{232}Th $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected[a]	^{230}Th Age uncorrected	^{230}Th Age corrected[b]	^{230}Th Age AD	^{230}Th/$^{232}Th_{initial}$ $\times 10^{-6c}$	Chemistry Date AD
BLS02A1-3a	0.460	2394 ± 3	1991 ± 3	144.9 ± 1.3	0.00482 ± 0.00004	95.8 ± 0.8	146.6 ± 4.9	461 ± 4	438 ± 13	1,565 ± 13	4.8 ± 2.1	2,003.38
BLS02A1-3a	0.746	2518 ± 3	3042 ± 6	144.2 ± 1.5	0.00492 ± 0.00006	67.3 ± 0.8		471 ± 5				2,005.79
BLS02A1-3a	0.668	2432 ± 3	2492 ± 5	144.4 ± 1.7	0.00488 ± 0.00006	78.6 ± 0.9		466 ± 6				2,005.79
BLS02A1-3a	0.442	2487 ± 5	3415 ± 8	144.0 ± 2.4	0.00498 ± 0.00006	59.9 ± 0.8		477 ± 6				2,005.79
BLS02A2-3a	0.464	2605 ± 4	6191 ± 11	145.2 ± 1.6	0.01839 ± 0.00010	127.8 ± 0.7	149.0 ± 5.8	1,767 ± 10	1,680 ± 38	323 ± 3.8	6.1 ± 3.8	2,003.38
BLS02A2-3a	0.468	2572 ± 5	6011 ± 13	145.7 ± 2.2	0.01842 ± 0.00012	130.2 ± 0.9		1,770 ± 12				2,003.38
BLS02A2-3a	0.491	2726 ± 4	7107 ± 21	145.0 ± 1.6	0.01847 ± 0.00015	117.0 ± 1.0		1,775 ± 15				2,005.27
BLS02A2-3a	0.433	2595 ± 5	8973 ± 28	142.3 ± 2.1	0.01881 ± 0.00018	89.8 ± 0.9		1,812 ± 18				2,005.27
BLS02A2-3a	0.316	2647 ± 4	8000 ± 23	144.6 ± 2.0	0.01871 ± 0.00019	102.2 ± 1.1		1,799 ± 18				2,005.27
BLS02A2-3a	0.439	2696 ± 6	6213 ± 17	141.5 ± 2.3	0.01845 ± 0.00014	132.2 ± 1.0		1,779 ± 14				2,005.27
BLS02A3-1b	0.376	2271 ± 2	7113 ± 12	143.3 ± 1.2	0.00785 ± 0.00009	41.4 ± 0.5	142.0 ± 5.9	752 ± 8	670 ± 40	1,333 ± 40	4.8 ± 4.0	2,003.29
BLS02A3-1b	0.806	2491 ± 3	10770 ± 27	143.5 ± 1.4	0.00820 ± 0.00012	31.3 ± 0.5		786 ± 11				2,005.79
BLS02A3-1b	0.654	2459 ± 3	9543 ± 24	146.0 ± 1.6	0.00809 ± 0.00013	34.4 ± 0.6		774 ± 12				2,005.79
BLS02A3-1b	0.433	2473 ± 2	8698 ± 17	144.1 ± 1.7	0.00805 ± 0.00011	37.8 ± 0.5		771 ± 11				2,005.79
BLS02A4-4b	0.401	2498 ± 4	24362 ± 71	145.3 ± 1.9	0.01814 ± 0.00022	30.7 ± 0.4	143.0 ± 5.1	1,743 ± 21	1,530 ± 78	473 ± 78	3.6 ± 1.4	2,003.38
BLS02A4-4b	0.447	2722 ± 4	35211 ± 206	147.5 ± 1.9	0.01858 ± 0.00048	23.7 ± 0.6		1,782 ± 47				2,005.83
BLS02A4-4b	0.670	2690 ± 4	19129 ± 87	144.9 ± 1.9	0.01737 ± 0.00028	40.3 ± 0.7		1,669 ± 27				2,005.83
BLS02A4-4b	0.509	2768 ± 4	31223 ± 149	144.3 ± 1.8	0.01826 ± 0.00036	26.7 ± 0.5		1,756 ± 35				2,005.83
BLS02A5-3b	1.127	2568 ± 8	5675 ± 49	148.4 ± 3.0	0.00110 ± 0.00009	8.2 ± 0.7	149.0 ± 4.4	105 ± 9	42 ± 11	1,963 ± 11	4.9 ± 1.4	2,004.56
BLS02A5-3b	0.779	3519 ± 11	42154 ± 576	147.8 ± 2.8	0.00390 ± 0.00025	5.4 ± 0.4		372 ± 24				2,004.56
BLS02A5-3b	1.217	2558 ± 8	28213 ± 405	144.1 ± 2.9	0.00388 ± 0.00030	5.8 ± 0.5		371 ± 29				2,004.56
BLS02A7-1b	0.387	2176 ± 2	1057 ± 2	145.0 ± 1.2	0.02546 ± 0.00010	865.5 ± 3.7	146.2 ± 2.9	2,454 ± 10	2,436 ± 17	−433 ± 17	7.0 ± 2.3	2,003.29
BLS02A7-1b	0.823	2571 ± 6	2568 ± 7	143.2 ± 2.4	0.02582 ± 0.00016	426.8 ± 2.6		2,493 ± 16				2,005.27
BLS02A7-4b	0.461	2676 ± 4	2786 ± 7	145.7 ± 2.0	0.02574 ± 0.00012	408.3 ± 2.0		2,480 ± 12				2,003.38
BLS02A7-4b	0.427	2895 ± 3	4159 ± 11	144.3 ± 1.6	0.02587 ± 0.00013	297.4 ± 1.7		2,496 ± 13				2,005.83
BLS02A7-4b	0.620	2924 ± 4	3716 ± 9	143.7 ± 1.9	0.02571 ± 0.00015	334.0 ± 2.1		2,481 ± 16				2,005.83
BLS02A7-4b	0.675	2847 ± 4	3691 ± 8	145.2 ± 1.9	0.02581 ± 0.00015	328.7 ± 2.0		2,488 ± 15				2,005.83
BLS02A8-1b	0.404	2397 ± 3	2759 ± 4	147.7 ± 3.8	0.02637 ± 0.00011	378.2 ± 1.7	147.7 ± 3.8	2,546 ± 12	2,480 ± 25	−477 ± 25	80 ± 3.7	2,003.29
BLS02A8-1b	0.341	2408 ± 2	2474 ± 3	145.8 ± 1.4	0.02622 ± 0.00009	421.4 ± 1.5		2,527 ± 9				2,003.29
BLS02A8-1b	1.076	2539 ± 6	5457 ± 18	144.0 ± 2.4	0.02676 ± 0.00020	205.6 ± 1.6		2,584 ± 20				2,005.27
BLS02A8-1b	0.885	2559 ± 6	2802 ± 7	145.6 ± 2.4	0.02626 ± 0.00015	396.0 ± 2.3		2,531 ± 16				2,005.27
BLS02A8-3a	0.360	2542 ± 2	2350 ± 4	144.9 ± 1.1	0.02550 ± 0.00009	455.4 ± 1.7	146.0 ± 3.4	2,458 ± 9	2,413 ± 21	−410 ± 21	8.6 ± 3.1	2,003.38
BLS02A8-3a	0.993	2669 ± 4	3728 ± 8	147.5 ± 2.1	0.02571 ± 0.00014	304.0 ± 1.7		2,474 ± 14				2,005.83
BLS02A8-3a	0.576	2741 ± 4	5583 ± 13	144.7 ± 1.9	0.02606 ± 0.00016	211.3 ± 1.4		2,514 ± 16				2,005.83
BLS02A8-3a	0.698	2717 ± 3	3580 ± 7	144.2 ± 1.3	0.02575 ± 0.00012	322.7 ± 1.6		2,485 ± 12				2,005.83

[a] Isochron-derived initial δ^{234}U.
[b] Isochron age.
[c] Isochron-inferred initial ^{230}Th/^{232}Th.

Table A12
U–Th data and ^{230}Th ages for subsamples of three coral slabs from Saumang of South Pagai, Sumatran islands

Coral ID	Subsample ID	Weight (g)	^{238}U (ppb)	^{232}Th (ppt)	$\delta^{234}U$	$(^{230}Th/^{238}U)$ activity ratio	$^{230}Th/^{232}Th$ $\times 10^{-6}$	$\delta^{234}U_{initial}$ corrected	^{230}Th age uncorrected	^{230}Th age corrected[a]	^{230}Th age AD	$^{230}Th/^{232}Th_{initial}$ $\times 10^{-6}$	Chemistry date AD
SMG02A1	1a	0.951	2434 ± 4	9172 ± 19	145.1 ± 1.8	0.00416 ± 0.00008	18.2 ± 0.4	143.4[b] ± 4.8	397 ± 8	289[c] ± 21	1715 ± 21	5.02[d] ± 0.65	2004.42
	1b	0.903	2655 ± 5	17,398 ± 107	147.1 ± 1.5	0.00499 ± 0.00011	12.6 ± 0.3		476 ± 10				
	1c	0.477	2318 ± 2	15,122 ± 40	146.1 ± 1.2	0.00501 ± 0.00013	12.7 ± 0.3		478 ± 12				
SMG02A2	1a	1.275	2437 ± 4	10,717 ± 73	146.6 ± 1.4	0.00430 ± 0.00011	16.2 ± 0.4	146.7 ± 1.4	411 ± 10	283 ± 19	1721 ± 19		2004.56
	1b	0.457	2289 ± 3	9980 ± 20	146.3 ± 1.7	0.00447 ± 0.00008	16.9 ± 0.3	146.4 ± 1.7	427 ± 8	300 ± 18	1703 ± 18		2003.29
	3a	0.413	2290 ± 4	15,179 ± 50	148.2 ± 1.9	0.00614 ± 0.00016	15.3 ± 0.4	148.4 ± 2.0	586 ± 15	394 ± 29	1610 ± 29		2003.38
	3a	0.428	2435 ± 5	17,039 ± 48	145.3 ± 2.5	0.00622 ± 0.00018	14.7 ± 0.4	145.5 ± 2.5	595 ± 17	392 ± 31	1614 ± 31		2005.79
	3a	0.866	2327 ± 5	15,364 ± 58	144.0 ± 2.2	0.00619 ± 0.00015	15.5 ± 0.4	144.2 ± 2.2	592 ± 15	400 ± 29	1606 ± 29		2005.79
	3a	0.451	2380 ± 4	15,018 ± 44	143.7 ± 2.2	0.00589 ± 0.00016	15.4 ± 0.4	143.9 ± 2.2	563 ± 15	380 ± 28	1626 ± 28		2005.79
SMG02A3	1b	0.383	2290 ± 2	2943 ± 4	145.0 ± 1.2	0.00773 ± 0.00006	99.3 ± 0.7	145.3 ± 1.2	740 ± 6	703 ± 7	1301 ± 7		2003.29
	4b	0.416	2462 ± 2	1515 ± 3	146.4 ± 1.1	0.00801 ± 0.00005	214.8 ± 1.5	146.7 ± 1.1	765 ± 5	747 ± 6	1256 ± 6		2003.29

[a] Age corrected using an initial $^{230}Th/^{232}Th$ atomic ratio of $5.02 \pm 0.65 \times 10^{-6}$ estimated from SMG02A1 isochron.
[b] Isochron-derived initial ^{234}U value.
[c] Isochron age for the subsamples, 1a, 1b, and 1c, of SMG02A1.
[d] Isochron-inferred initial $^{230}Th/^{232}Th$ atomic ratio.

REFERENCES

Abram N. J., Gagan M. K., McCulloch M. T., Chappell J. and Hantoro W. S. (2003) Coral reef death during the 1997 Indian Ocean Dipole linked to Indonesian wildfires. *Science* **301**, 952–955.

Barnes J. W., Lang E. J. and Potratz H. A. (1956) The ratio of ionium to uranium in coral limestone. *Science* **124**, 175–176.

Bateman H. (1910) The solution of a system of differential questions occurring in the theory of radioactive transformations. *Proc. Camb. Philos. Soc.* **15**, 423–427.

Beck J. W., Recy J., Taylor F. W., Edwards R. L. and Cabioch G. (1997) Abrupt changes in early Holocene sea surface temperature derived from coral records. *Nature* **385**, 705–707.

Briggs R. W., Sieh K., Meltzner A. J., Natawidjaja D., Galetzka J., Suwargadi B., Hsu Y.-J., Simons M., Hananto N., Suprihanto I., Prayudi D., Avouac J.-P., Prawirodirdjo L. and Bock Y. (2006) Deformation and slip along the Sunda megathrust in the great 2005 Nias-Simeulue earthquake. *Science* **311**, 1897–1901.

Bonjean F. and Lagerloef G. S. E. (2002) Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean. *J. Phys. Oceanogr.* **32**, 2938–2954.

Broecker W. S. (1963) A preliminary evaluation of uranium series inequilibrium as a tool for absolute age measurement on marine carbonates. *J. Geophys. Res.* **68**, 2817–2834.

Broecker W. S. and Thurber D. L. (1965) Uranium-series dating of corals and oolites from Bahaman and Florida Key limestones. *Science* **149**, 58–60.

Broecker W. S., Kaufman A. and Trier R. M. (1973) The residence time of thorium in surface sea water and its implications regarding the rate of reactive pollutants. *Earth Planet. Sci. Lett.* **20**, 35–44.

Chen C.-T. A. (1990) Rates of calcium carbonate dissolution and organic carbon decomposition in the North Pacific Ocean. *J. Oceanogr. Soc. Jpn.* **46**, 201–210.

Chen J. H., Edwards R. L. and Wasserburg G. J. (1986) ^{238}U, ^{234}U and ^{232}Th in sea water. *Earth Planet. Sci. Lett.* **80**, 241–251.

Cheng H., Edwards R. L., Hoff J., Gallup C. D., Richards D. A. and Asmersom Y. (2000) The half-lives of uranium-234 and thorium-230. *Chem. Geol.* **169**, 17–33.

Clark M. P., Serreze M. C. and McCabe G. J. (2001) Historical effects of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River Basins. *Water Resour. Res.* **37**, 741–757.

Cobb K. M., Charles C. D., Cheng H. and Edwards R. L. (2003a) El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature* **424**, 271–276.

Cobb K. M., Charles C. D., Cheng H., Kastner M. and Edwards R. L. (2003b) U/Th-dating living and young fossil corals from the central tropical Pacific. *Earth Planet. Sci. Lett.* **210**, 91–103.

Cole J. E. and Fairbanks R. G. (1990) The Southern Oscillation recorded in the $\delta^{18}O$ of corals from Tarawa Atoll. *Paleoceanography* **5**, 669–683.

Cowan G. A. and Adler H. H. (1977) Variability of natural abundance of U-235. *Geochim. Cosmochim. Acta* **40**, 1487–1490.

Cross T. S. and Cross B. W. (1983) U, Sr, and Mg in Holocene and Pleistocene corals *A. Palmata* and *M. annularis*. *J. Sed. Petrol.* **53**, 587–594.

Crowley T. J., Quinn T. M., Taylor F. W., Henin C. and Joannot P. (1997) Evidence for a volcanic cooling signal in a 335-year coral record from New Caledonia. *Paleoceanography* **12**, 633–639.

Cutler K. B., Edwards R. L., Taylor F. W., Chen H., Adkins J., Gallup C. D., Cutler P. M., Burr G. S. and Bloom A. L. (2003) Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. *Earth Planet. Sci. Lett.* **206**, 253–271.

Dadson S. J., Hovius N., Chen H., Dade W. B., Hsieh M.-L., Willett S. D., Hu J.-C., Horng M.-J., Chen M.-C., Stark C. P., Lague D. and Lin J.-C. (2003) Links between erosion, runoff variability and seismicity in the Taiwan orogen. *Nature* **426**, 648–651.

Dodge R. E. and Brass G. W. (1984) Skeletal extension, density and calcification of the reef coral, *Montastrea annularis*: St Croix, US Virgin Islands. *Bull. Mar. Sci.* **34**, 288–307.

Dunk R. M., Mills R. A. and Jenkins W. J. (2002) A reevaluation of the ocean uranium budget for the Holocene. *Chem. Geol.* **190**, 45–67.

Edwards R. L., Chen J. H., Ku T.-L. and Wasserburg G. J. (1987) Precise timing of the last interglacial period from mass-spectrometric determination of Th-230 in corals. *Science* **236**, 1547–1553.

Edwards R. L., Taylor F. W. and Wasserburg G. J. (1988) Dating earthquakes with high-precision Th-230 ages of very young corals. *Earth Planet. Sci. Lett.* **90**, 371–381.

Edwards R. L., Gallup C. D. and Cheng H. (2003) Uranium-series dating of marine and lacustrine carbonates. In *Uranium-Series Geochemistry* (eds. B. Bourdon, G. M. Henderson, C. C. Lundstrom and S. P. Turner). Mineralogical Society of America, Washington, DC, pp. 363–405.

Evans M. N., Fairbanks R. G. and Rubenstone J. L. (1998) A proxy index of ENSO teleconnections. *Nature* **394**, 732–733.

Fitch T. J. (1972) Plate convergence, transcurrent fault, and internal deformation adjacent to Southeast Asia and western Pacific. *J. Geophys. Res.* **77**, 4432–4460.

Gagan M. K. and Chivas A. R. (1995) Oxygen isotopes in western Australian coral reveal Pinatubo aerosol-induced cooling in the Western Pacific Warm Pool. *Geophys. Res. Lett.* **22**, 1069–1072.

Gagan M., Ayliffe L. K., Hopley D., Cali J. A., Mortimer G. E., Chappell J., McCulloch M. T. and Head M. J. (1998) Temperature and surface-ocean water balance of the mid-Holocene tropical Western Pacific. *Science* **279**, 1014–1018.

Glynn P. W., Druffel E. M. and Dunbar R. B. (1983) A dead central American coral reef tract: possible link with the Little Ice Age. *J. Mar. Res.* **41**, 605–637.

Goldstein S. J. and Stirling C. H. (2003) Techniques for measuring uranium-series nuclides: 1992–2002. In *Uranium-Series Geochemistry* (eds. B. Bourdon, G. M. Henderson, C. C. Lundstrom and S. P. Turner). Mineralogical Society of America, Washington, DC, pp. 23–57.

Grodsky S. A. and Carton J. A. (2001) Intense surface currents in the tropical Pacific during 1996–1998. *J. Geophys. Res.* **106**, 16673–16684.

Hendy E. J., Gagan M. K., Alibert C. A., McCulloch M. T., Lough J. M. and Isdale P. J. (2002) Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* **295**, 1511–1514.

Hendy E. J., Gagan M. K. and Lough J. M. (2003) Chronological control of coral records using evidence for non-stationary ENSO teleconnections in northeast Australia. *The Holocene* **13**, 187–199.

Jaffey A. H., Flynn K. F., Glendenin L. E., Bentley W. C. and Essling A. M. (1971) Precision measurement of half-lives and specific activities of U-235 and U-238. *Phys. Rev.* **4**, 1889–1906.

Kaufman A. and Broecker W. S. (1965) Comparison of ^{230}Th and ^{14}C ages for carbonate materials from lakes Lahontan and Bonneville. *J. Geophys. Res.* **70**, 4039–4054.

Kilbourne K. H., Quinn T. M., Taylor F. W., Delcroix T. and Gouriou Y. (2004) El Niño-Southern Oscillation-related salinity variations recorded in the skeletal geochemistry of a *Porites* coral from Espiritu Santo, Vanuatu. *Paleoceanography* **19**. doi:10.1029/2004PA001033.

Ku T.-L., Knauss K. G. and Mathieu G. G. (1977) Uranium in open ocean: concentration and isotopic composition. *Deep-Sea Res.* **24**, 1005–1017.

Lee H.-J., Chao S.-Y., Fan K.-L., Wang Y.-H. and Liang N.-K. (1997) Tidally induced upwelling in a semi-enclosed basin: Nan Wan Bay. *J. Oceanogr.* **53**, 467–480.

Linsley B. K., Messier R. G. and Dunbar R. B. (1999) Assessing between-colony oxygen isotope variability in the coral *Porites lobata* at Clipperton Atoll. *Coral Reefs* **18**, 13–27.

Linsley B. K., Wellington G. M. and Schrag D. P. (2000) Decadal sea surface temperature variability in the subtropical South Pacific from 1726 to 1997 A.D. *Science* **290**, 1145–1148.

Ludwig K. R. and Titterington D. M. (1994) Calculation of ^{230}Th/U isochrons, ages, and errors. *Geochim. Cosmochim. Acta* **58**, 5031–5042.

Ludwig K. R. (2003) Mathematical–statistical treatment of data and errors for ^{230}Th/U geochronology. In *Uranium-Series Geochemistry* (eds. B. Bourdon, G. M. Henderson, C. C. Lundstrom and S. P. Turner). Mineralogical Society of America, Washington, DC, pp. 631–656.

McCaffrey R. (1991) Slip vectors and stretching of the Sumatran fore arc. *Geology* **19**, 881–884.

McCulloch M. T., Tudhope A. W., Esat T. M., Mortimer G. E., Chappell J., Pillans B., Chivas A. R. and Omura A. (1999) Coral record of equatorial sea-surface temperatures during the penultimate deglaciation at Huon Peninsula. *Science* **283**, 202–204.

McCulloch M. T., Fallon S., Wyndham T., Hendy E. J., Lough J. M. and Barnes D. (2003) Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. *Nature* **421**, 727–730.

Min G. R., Edwards R. L., Taylor F. W., Recy J., Gallup C. D. and Beck J. W. (1995) Annual cycles of U/Ca in coral skeletons and U/Ca thermometry. *Geochim. Cosmochim. Acta* **59**, 2025–2042.

Moran S. B., Shen C.-C., Edmonds H. N., Weinstein S. E., Smith J. N. and Edwards R. L. (2002) Dissolved and particulate ^{231}Pa and ^{230}Th in the Atlantic Ocean: constraints on intermediate/deep water ages, boundary scavenging, and ^{231}Pa/^{230}Th fractionation. *Earth Planet. Sci. Lett.* **203**, 999–1014.

Natawidjaja D. H., Sieh K., Ward S. N., Cheng H., Edwards R. L., Galetzka J. and Suwargadi B. W. (2004) Paleogeodetic records of seismic and aseismic subduction from central Sumatran microatolls, Indonesia. *J. Geophys. Res.* **109**. doi:10.1029/2003JB002398.

Nyberg J., Malmgren B. A., Winter A., Jury M. R., Kilbourne K. H. and Quinn T. M. (2007) Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* **447**, 698–702.

Okubo T. (1982) Radioactive disequilibrium of thorium series nuclides in surface waters of the Seto Inland Sea. *J. Oceanogr. Soc. Jpn.* **38**, 1–7.

Richards D. A. and Dorale J. A. (2003) Uranium-series chronology and environmental applications of speleothems. In *Uranium-Series Geochemistry* (eds. B. Bourdon, G. M. Henderson, C. C. Lundstrom and S. P. Turner). Mineralogical Society of America, Washington, DC, pp. 407–460.

Rivera L., Sieh K., Helmberger D. and Natawidjaja D. H. (2002) A comparative study of the Sumatran subduction-zone earthquakes of 1935 and 1984. *Bull. Seismol. Soc. Am.* **92**, 1721–1736.

Robinson L. F., Belshaw N. S. and Henderson G. M. (2004) U and Th concentrations and isotope ratios in modern carbonates and waters from the Bahamas. *Geochim. Cosmochim. Acta* **68**, 1777–1789.

Roy-Barman M., Chen J. H. and Wasserburg G. J. (1996) ^{230}Th–^{232}Th systematics in the central Pacific Ocean: the sources and the fates of thorium. *Earth Planet. Sci. Lett.* **139**, 351–363.

Shen C.-C., Lee T., Chen C.-Y., Wang C.-H., Dai C.-F. and Li L.-A. (1996) The calibration of D[Sr/Ca] versus sea surface temperature relationship for *Porites* corals. *Geochim. Cosmochim. Acta* **60**, 3849–3858.

Shen C.-C., Edwards R. L., Cheng H., Dorale J. A., Thomas R. B., Moran S. B., Weinstein S. E. and Edmonds H. N. (2002) Uranium and thorium isotopic and concentration measurements by magnetic sector inductively coupled plasma mass spectrometry. *Chem. Geol.* **185**, 165–178.

Shen C.-C., Cheng H., Edwards R. L., Moran S. B., Edmonds H. N., Hoff J. A. and Thomas R. B. (2003) Measurement of attogram quantities of ^{231}Pa in dissolved and particulate fractions of seawater by isotope dilution thermal ionization mass spectroscopy. *Anal. Chem.* **75**, 1075–1079.

Shen C.-C., Lee T., Liu K.-K., Hsu H.-H., Edwards R. L., Wang C.-H., Lee M.-Y., Chen Y.-G., Lee H.-J. and Sun H.-T. (2005a) An evaluation of quantitative reconstruction of past precipitation records using coral skeletal Sr/Ca and $\delta^{18}O$ data. *Earth Planet. Sci. Lett.* **237**, 370–386.

Shen C.-C., Liu K.-K., Lee M.-Y., Lee T., Wang C.-H. and Lee H.-J. (2005b) A novel method for tracing coastal water masses using Sr/Ca ratios and salinity: a case study in Nanwan Bay, Southern Taiwan. *Estuar. Coast. Shelf Sci.* **65**, 135–142.

Shen G. T. and Dunbar R. B. (1995) Environmental controls on uranium in reef corals. *Geochim. Cosmochim. Acta* **59**, 2009–2024.

Sieh K., Ward S. N., Natawidjaja D. and Suwargadi B. W. (1999) Crustal deformation at the Sumatran subduction zone revealed by coral rings. *Geophys. Res. Lett.* **26**, 3141–3144.

Steiger R. H. and Jager E. (1977) Subcommission on geochronology: convention on use of decay constants in Geochronology and Cosmochronology. *Earth Planet. Sci. Lett.* **36**, 359–362.

Subarya C., Chlieh M., Prawirodirdjo L., Avouac J. P., Bock Y., Sieh K., Meltzner A. J., Natawidjaja D. H. and McCaffrey R. (2006) Plate-boundary deformation associated with the great Sumatra-Andaman earthquake. *Nature* **440**, 46–51.

Sun M., Chiu C.-H., Shen C.-C. and Lee T. (1999) Sr thermometer for *Porites* corals; little need to measure Ca? *Geochem. J.* **33**, 351–354.

Sun Y., Sun M., Wei G., Lee T., Nie B. and Yu Z. (2004) Strontium content of a *Porites* coral from Xisha Island, South China Sea: a proxy for sea surface temperature of the 20th century. *Paleoceanography* **19**, 1–10.

Swart P. K. and Hubbard J. A. E. B. (1982) Uranium in scleractinian coral skeletons. *Coral Reefs* **1**, 13–19.

Taylor S. R. and McLennan S. M. (1985) *The Continental Crust: Its Composition and Evolution*. Blackwell, Oxford.

Taylor S. R. and McLennan S. M. (1995) The geochemical evolution of the continental crust. *Rev. Geophys.* **33**, 241–265.

Thompson W. G. and Goldstein S. L. (2005) Open-system coral ages reveal persistent suborbital sea-level cycles. *Science* **308**, 401–404.

Urban F. E., Cole J. E. and Overpeck J. T. (2000) Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record. *Nature* **407**, 989–993.

Wellington G. M. and Dunbar R. B. (1995) Stable isotopic signature of El Niño-Southern Oscillation events in eastern tropical Pacific reef corals. *Coral Reefs* **14**, 5–25.

Yu K.-F., Zhao J.-X., Liu T.-S., Wei G.-J., Wang P.-X. and Collerson K. D. (2004) High-frequency winter cooling and reef coral mortality during the Holocene climatic optimum. *Earth Planet. Sci. Lett.* **224**, 143–155.

Zachariasen J. (1998) Paleoseismology and Paleogeodesy of Sumatran Subduction Zone: A Study of Vertical Deformation Using Coral Microatolls. Ph.D. Thesis, Calif. Inst. Technol., Pasadena, California.

Zachariasen J., Sieh K., Taylor F. W., Edwards R. L. and Hantoro W. S. (1999) Submergence and uplift associated with the giant 1833 Sumatran subduction earthquake: evidence from coral microatolls. *J. Geophys. Res.* **104**, 895–919.

Zachariasen J., Sieh K., Taylor F. W. and Hantoro W. S. (2000) Modern vertical deformation above the Sumatran subduction zone: Paleogeodetic insights from coral microatolls. *Bull. Seismol. Soc. Am.* **90**, 897–913.

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