Quaternary Research 71 (2009) 354–360

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Short Paper

Microatoll record for large century-scale sea-level fluctuations in the mid-Holocene

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ARTICLE INFO

Article history:
Received 25 March 2008

Keywords:
Microatoll
Sea level
Mid-Holocene
South China Sea
U-series
Coral reef

ABSTRACT

Coral microatolls have been long used as precise indicators of past sea level, but their use for precise definition of detailed sea-level fluctuations is still rare. Here we report twelve high-precision thermal ionization mass spectrometric ^{230}Th ages for twelve rims of five mid-Holocene microatolls from an emerged reef terrace at Leizhou Peninsula, northern South China Sea. This is a tectonically stable area, enabling us to reconstruct both the timing and trajectory of local sea-level fluctuations accurately. The elevations of these microatoll rims and cores were accurately determined relative to the surface of modern living microatolls at the same site. The results indicate that the sea level during the period of 7050–6600 yr bp (years before AD 1950) was about 171 to 219 cm above the present, with at least four cycles of fluctuations. Over this 450 yr interval, sea level fluctuated by 20–40 cm on century scales.

Introduction

Understanding the extent and timing of decadal- to century-scale sea-level fluctuations during the mid-Holocene could potentially help us to evaluate present and future changes under the influence of anthropogenic global warming. There is a strong evidence that the mid-Holocene was warmer than present (Gagan et al., 1998; Yu et al., 2005) and that relative sea level then was higher than now (Chappell, 1983; Mitrovica and Milne, 2002). But until now, little quantitative information has been known on this topic, due to the lack of a high-resolution and high-precision sea-level proxy. Living microatolls on intertidal reef flats are circular coral colonies with a flat-topped, dead core surrounded by a living rim. They have great potential as sea-level proxies, because it is prolonged subaerial exposure at low tide that kills the coral's upper surface as it grows vertically, and constrains subsequent growth to the horizontal plane (Fig. 1). Accordingly, the absolute elevation of the upper rim of live coral tissue is determined by the relative durations of submersion and subaerial exposure, which are in turn strongly linked to sea level (Habrant and Lathuiliere, 2000; Scoffin and Stoddart, 1978; Taylor et al., 1987; Woodroffe and McLean, 1990; Zachariasen et al., 1999; Zachariasen et al., 2000).

There are other causes of microatoll formation, such as excessive sedimentation (Guilcher, 1988), nutrient uptake (Steven and Atkinson, 2003) and currents (Stoddart and Scoffin, 1979). However in reef-flat settings, sea level is often the unambiguous and dominant driver of microatoll formation (Scoffin and Stoddart, 1978; Smithers and Woodroffe, 2000; Stoddart and Scoffin, 1979; Zachariasen et al., 2000). For instance, detailed analyses of 282 microatolls on 19 separate reef sites in Cocos (Keeling) Islands (Smithers and Woodroffe, 2000) show that the upper surfaces of individual microatolls were relatively horizontal and, in the case of those microatolls with their vertical growth clearly controlled by sea level alone, their mean height variation is only 2–3 cm. Because of this precise relationship between low tide level and coral rim height, the topographies of microatolls have been successfully used to detect detailed sea-level fluctuations and considered as tide gauges for the past tens to hundred years (Flora and Ely, 2003; Smithers and Woodroffe, 2001; Spencer et al., 1997; Woodroffe and McLean, 1990). However, although the emergence (above present low tide) of microatolls has been widely acknowledged as an indicator of high Holocene sea level (Chappell, 1983; McLean et al., 1978; Nott, 2003; Nunn, 2000; Nunn and Peltier, 2001; Woodroffe and McLean, 1990; Woodroffe and Gagan, 2000; Woodroffe et al., 1999), few studies have used the rims of mid-Holocene microatolls to reconstruct detailed sea-level oscillations. In this paper, we focus on detailed sea-level history by using accurate surveying of elevation and high-precision thermal ionization mass spectrometric (TIMS) U-series dating of individual rims of mid-Holocene microatolls.

Sample selection, analytical methods and results

The study was undertaken on the Leizhou Peninsula on the northern coast of the South China Sea. The emerged coral reef

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0033-5894/$ – see front matter.
doi:10.1016/j.yqres.2009.02.003

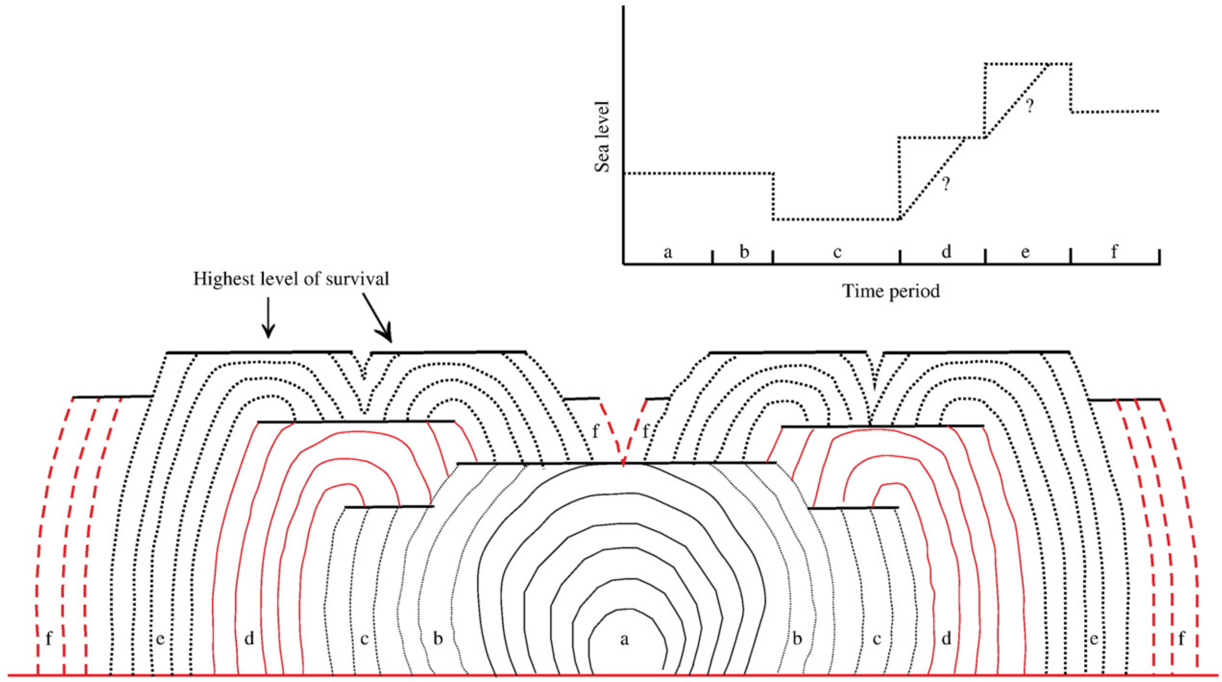

Figure 1. Relationship between microatoll developments and sea-level fluctuations. This figure shows detailed process of microatoll responses to sea-level change (after Woodroffe and McLean, 1990; Zachariasen et al., 1999). Usually, when a coral reaches the lowest tide level or the highest level of coral survival (HLS) (a), its upward growth will cease (because the coral tissue will die of exposure) but the horizontal growth will continue (b); then, as sea level drops, the HLS will also drop and coral will grow laterally at a relatively lower level (c). Later, if sea level rises again, coral will grow both upward and outward until it reaches the HLS (d); If sea level rises continuously, coral will continue the growth and even cover the old surface until it reaches the HLS (e); later, if sea level drops, coral will grow only laterally (f).

(20°13'N–20°17'N, 109°54'E–109°58'E), named Dengloujiao, 10 km long and 0.5–1.0 m wide (~2 km at the most), is a well-preserved fringing reef dominated by *Porites* and *Goniopora* species. Tectonically, the study area has been relatively stable with negligible vertical movements since the mid-Holocene (Nie et al, 1997; Lu, 1997). A historical disastrous earthquake (with magnitude M_w ~7.5) striking the neighboring Hainan Island in 1605 AD resulted in subsidence of the surrounding area (Zhang et al, 2008). However, no evidence was found to show it had any obvious impact on Leizhou Peninsula, as the two areas are separated by Qiongzhou Strait (with water depth ~100 m and width ~30 km). The tectonic stability with minimal vertical movements since mid-Holocene enables us to reconstruct both timing and trajectory of detailed local sea-level fluctuations precisely. Previous studies (Yu et al., 2002b) revealed that the coral reef formed its geomorphological framework during the mid-Holocene. Its morphology contains signatures of multiple Holocene sea-level highstands (Zhao and Yu, 2002, 2007) and also records high-frequent winter cooling and mass coral mortalities (cold-bleaching) during the Holocene climate optimum (7.5–7.0 ka) (Yu et al., 2002a; Yu et al., 2004), and a general decreasing trend in sea-surface temperature (SST) from ~6.8 to 1.5 ka with mean Sr/Ca-SSTs from 6.8 to 5.0 ka being 0.9–0.5°C higher than at present (Yu et al., 2005).

Dead microatolls, mainly *Porites* with diameters up to 9.6 m, are widespread on the emerged reef flat. Modern living *Porites* microatolls, with diameters about 0.6–1.2 m, are developing sporadically around the inner (landward) part of the modern reef flat. Thirteen samples were collected from twelve rims of five *Porites* microatolls, and their individual elevations were surveyed relative to the average elevation of the rims of modern living *Porites* microatolls, which vary within ±8.5 cm (corresponding to a maximum range of 17 cm).

The ±8.5 cm variation in elevations of the modern microatoll surfaces is similar to those observed for reef-flat microatolls at Cocos Island (from ±1.5 to ±13 cm at different sites, with a mean of ±5.5 cm) (Smithers and Woodroffe, 2001) and for microatolls near 3°S (±5 cm) (Natawidjaja et al, 2004). Smithers and Woodroffe (2001) attributed the relatively large variation in the elevations of individual microatoll colonies from different sites as mainly due to ponding as well as spatial variation in the tidal curve generated by geomorphological and hydrodynamic setting. However, they found that the mean height of living coral (HLC) within each microatoll colony shows very little variation, only 3.3±1.7 cm for the entire 282 microatolls surveyed. Based on this observation, it can be reasonably inferred that any height change in the rims of different ages within an individual fossil microatoll should mainly reflect sea-level variation, as the geomorphological and hydrodynamic setting of that specific colony should remain relatively unchanged.

The mid-Holocene samples were taken from precisely recorded positions on the colonies, and their ^{230}Th ages determined to ±0.3–1.0% precision (2 sigma) by thermal ionization mass spectrometry (TIMS) U-series method (see Table 1). The results show that the U-series ages of these microatoll rims range from 7050±32 to 6603±41 yr bp (years before AD 1950) and their elevations vary from 178.5 to 218.5 cm above the modern *Porites* microatoll surfaces. The micro-geomorphology of these microatolls suggests that the elevation differences between these rims mainly resulted from sea-level fluctuations.

The TIMS U-series analytical procedures were those described in Zhao et al. (2001) and Yu et al. (2006). Unaltered coral chips free of any weathered surfaces were extracted from each of the coral specimens, cleaned ultrasonically, and spiked with a ^{229}Th–^{233}U–^{236}U mixed tracer. The ^{233}U–^{236}U double spike with precisely known ^{233}U/^{236}U ratio was used to monitor and correct for U mass-fractionation to improve the analytical precision of U isotope ratio measurements. After total dissolution in nitric acid, concentrated hydrogen peroxide was added to decompose any organic matter and to ensure complete mixing between the spike and the sample. U and Th were co-precipitated with iron hydroxide, and then redissolved