Palaeogeography, Palaeoclimatology, Palaeoecology 292 (2010) 465–473

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

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

# Sea-level rise and coral-reef development of Northwestern Luzon since 9.9 ka

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ARTICLE INFO

*Article history:*
Received 20 October 2009
Received in revised form 7 April 2010
Accepted 11 April 2010
Available online 24 April 2010

*Keywords:*
Holocene
Sea level
Coral reef
Philippines
South China Sea

ABSTRACT

Coral reef growth and relative sea-level record for the early mid-Holocene are established from three boreholes drilled on a raised Holocene reef at Currimao, northwestern Luzon, Philippines. Age control is provided by $^{230}$Th dates of 13 corals mostly in living position. The cores cover a depth interval from 3.8 m above to 26.7 m below present mean sea level (MSL) and consist of four lithofacies including (1) reef facies, (2) bioclastic facies, (3) clayey facies and (4) tuffaceous facies. The ages of dated corals vary from 6588 ± 27 ya at 1.4 m below MSL to 9855 ± 42 ya at 22 m below MSL. Results of this study indicate that the reef started growing about 9.9 ka when the minimum sea level, relative to the western Luzon coast, was about 27 m below MSL after tectonic correction. During 9.2–8.2 ka, reef accretion rate was as high as 10–13 m/ky. Coral reef developed to near paleo-sea level at about 6862 ± 28 ya and emerged due to tectonic uplift. The sea-level curve of Currimao is generally similar to that of the Western Australia coast but at least 8–11 m higher than that of Tahiti from 10 to 8.5 ka.

## 1. Introduction

Holocene reefs have long been a focus of geological research because they serve as an analogue of ancient reefs and preserve the archives of eustatic sea-level changes and neotectonics (Montaggioni and Macintyre, 1991; Ota and Chappell, 1999; Cabioch et al., 2003; Taylor et al., 2008). Although explorations started as early as 19th century and continued to this century (see reviews by Steers and Stoddart, 1977; Montaggioni, 2005; Hopley, et al., 2007, p.5–14), tropical Pacific reefs remain far less understood than their Atlantic counterparts except for the Great Barrier Reef (GBR) (Camoin and Davies, 1998; Kennedy and Woodroffe, 2002; Montaggioni, 2005).

Among the Indo-Pacific Holocene reefs, the Philippines has received particularly little attention compared to other Indo-Pacific sites such as the GBR, the Ryukyu Islands, Hawaiian Islands and Polynesian islands. Montaggioni (2005) provided an extensive review of case studies of Indo-Pacific coral reefs, none of which were located in the Philippines. There are two reasons why Philippine coral reefs are important. First, the Philippines is located in the Indo-Pacific center of coral diversity (Veron and Fenner, 2000; Licuanan and Capili, 2004). Second, the Philippines is located within the Western Pacific Warm Pool (WPWP) where the temperature was still suitable for coral growth even during the early Holocene when seawater was colder than present (Pelejero et al., 1999; Gagan et al., 2004). The Holocene reefs in the Philippines may provide valuable information toward a better understanding of reef growth responding to early Holocene sea-level rise in the Indo-Pacific region. The Philippines, however, presents some challenges for sea-level study. First, the region is an active island arc where vertical tectonics potentially has displaced paleosea-level indicators and influenced reef growth. Fortunately, it is possible to estimate the tectonic signal by comparing the reconstructed sea-level record with those established in tectonically stable regions. Second, modern Philippine coral reef studies are scarce, and they usually focus on fishery or reef management when available. Analogues for environmental interpretation of fossil corals are still lacking in the Philippines. Interpretations are especially challenging because many reefs have already been modified by human activities.

In most cases, only the tops of Holocene reefs are exposed, thus it is important to drill the reef sequences to study the tectonic or sea-level history. This study examined three cores drilled into Holocene reefs at Currimao, Ilocos Norte. Lithological facies and sequence of the cores were identified and selected corals were $^{230}$Th-dated. The objectives of this paper are to reconstruct: (1) the Holocene reef growth at Currimao and (2) the Holocene sea-level record using coral reef stratigraphy. This work is the first shallow drilling in Philippine coral reefs since Grobe and other's (1985) pioneering effort and the first coral-based sea-level record in the South China Sea.

## 2. Geological settings

Luzon is bounded by the Manila Trench on the west and the Philippine Trench on the east (Yang et al., 1996; Yumul et al., 2003),

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doi:10.1016/j.palaeo.2010.04.007

and consists of a complex of volcanic arcs and accreted terranes resulting from subduction and strike-slip faulting (Fig. 1). Between the two trenches, the strike-slip Philippine Fault extends from southern Mindanao to northern Luzon (Barrier et al., 1991). All three major tectonic elements of the Philippines are still active in the Quaternary (Yumul et al., 2003).

Currimao is located at 18°02′N, 120°28′E on the coast of northwestern Luzon, facing the South China Sea (Fig. 1). Tides in the area are mixed diurnal and semi-diurnal with a tidal range of 0.57 m (NAMRIA, 2001). The dry season is from October to May with an average temperature of 30 °C and the wet season falls during the months of June to September. Annual rainfall is about 2000 mm.

Holocene reefs crop out at Currimao, extending about 3.2 km along the coast, and 100 to 150 m perpendicular to the coast. The coastal geomorphology is characterized by three terraces (Figs. 1 and 2). The outer and lowest terrace, Terrace 3, lies at mean sea level (MSL) and is now covered mainly by seaweeds. The highest terrace, Terrace 2, is located just landward of Terrace 3 with a well-defined flat top and an elevation up to 3.7–3.9 m above sea level in its northern portion and descending to about 3.1 m southward. The surface of the previous reef flat is very well preserved with most corals in their original living positions. There are no signs of erosion on the surface. Detailed features of corallites are well preserved. The representative corals are *Acropora robusta* and *Pocillopora eydouxi*, both extensively observed on the top and on inner (landward) cliff of the terrace. Terrace 1 occurs at 1.2–1.5 m above sea level along the coastline and is separated from Terrace 2 by a depression. Terrace 1 is not as well defined as the other two terraces, and is capped by erosional surfaces, patch reefs, or beachrock depending on the location. *Heliopora coerulea* and *Porites* are the most common corals on Terrace 1. Pleistocene limestones are exposed along road cut of the coastal road but cannot be dated because fossil corals are already calcified.

Maeda et al. (2004) reported two notches, one at 2.3 m and another at 0.5 m above sea level respectively, on the seaward cliff of Terrace 2 and used them to identify Holocene sea-level standstills in the area. The upper notch is comparable to notches 2.3 to 2.8 m above present MSL in several locations in Palawan, which were dated to be 5466 and 5758 cal BP at Miniloc Island, Palawan (Maeda, et al., 2004), and probably represent the mid-Holocene highstand. The lower notch may correlate to a notch 0.5 m above MSL in Bacuit Bay, Palawan, on the floor of which a fossil coral was dated to be 3.58 ka (Maeda, et al., 2004).

A Pliocene unit, Laoag Formation, occurs as the basement below the Quaternary units and outcrops along the coastal road of Currimao. The typical lithology is calcareous siltstone and claystone interbedded with tuffaceous sandstone, and occasional limestone.

## 3. Material and methods

This study recovered three cores, each 6 cm in diameter, from each of the three terraces with a geotechnical rig (Fig. 1). The depths of cores CRM-1, CRM-2 and CRM-3 are 15.0 m, 22.2 m and 26.7 m from ground surface respectively. Two supplementary short cores were drilled by a portable electrical driller, CRM-1a next to CRM-1, and CRM-2C on top of Terrace 2 next to CRM-2 to provide data from above sea level for Terrace 2. Cores were split, photographed and described. Thin sections were made to aid core examination. Fossil coral oriented in growth position and relatively larger size were selected for U–Th chemistry (Shen et al., 2003) and $^{230}$Th dating (Frohlich et al., 2009; Shen et al., 2009). A sample for analysis was carefully picked and cut from each selected coral with its aragonitic composition confirmed by X-Ray diffractometry.

The U–Th isotopic compositions of fossil corals, physically cleaned with ultrasonic methods (Shen et al., 2008), were determined on a multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) with single secondary electron multiplier protocols in the High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University. The developed MC-ICP-MS technique offers an accurate determination of uranium and thorium isotopic ratios and concentrations with a precision of ±1–2‰ (2σ) for abundance determinations of 50–200-fg $^{234}$U (1–4-ng $^{238}$U) or $^{230}$Th (Frohlich et al., 2009; Shen

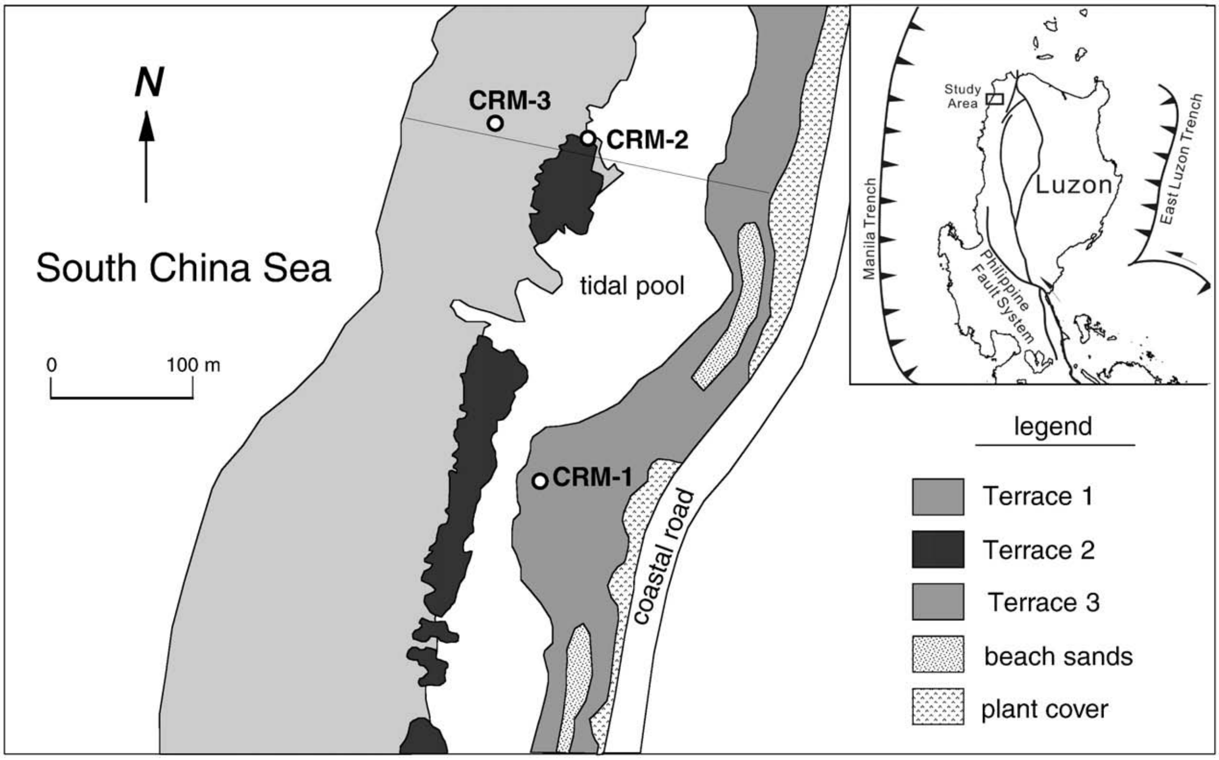


**Fig. 1.** Location of the study area and boreholes drilled on three terraces. Location of the profile in Fig. 2 is indicated by the straight line.

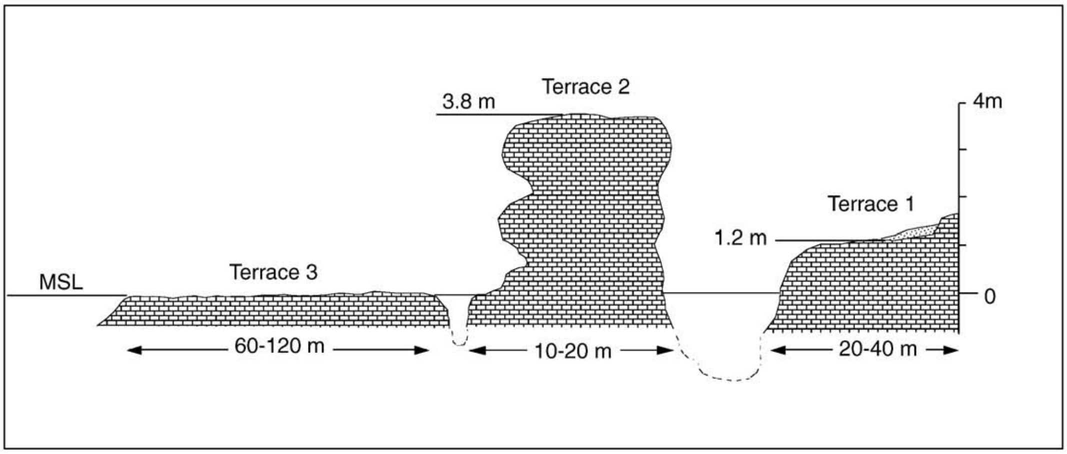


**Fig. 2.** Coastal geomorphologic profile in Currimao, modified from Maeda et al. (2004). See Fig. 1 for its location.

et al., 2009). The observation that there is no significant difference between standards measurement compared to the coral and speleothem samples on ICP-sector-field-MS (ICP-SF-MS; Shen et al., 2002) and on MC-ICP-MS certifies the validity of the MC-ICP-MS methodology. Uncertainties in the U–Th isotopic data and $^{230}$Th dates given in this paper are calculated at the $2\sigma$ level or two standard deviations of the mean ($2\sigma_m$) unless otherwise noted.

## 4. Lithofacies

Four lithofacies were defined from the borehole cores: reef facies, bioclastic facies, clayey facies and tuffaceous facies. Lithofacies delineation was based on biolithologic components and fabric of rock or sediments.

### 4.1. Reef facies

The Reef facies consists of coral boundstones and coral floatstones/rudstones (Fig. 3A,B). Corals are often bored. The matrix between coral skeletons or in bored cavities may be micritic, red algal encrustation, or loose bioclastics. Two subfacies can be distinguished in terms of coral fauna. In the robust branching subfacies, the major coral components are robust branching corals such as *Acropora robusta*, *A. digitifera* and *Pocillopora eydouxi* (Fig. 3A), while the domal/*Heliopora* subfacies includes mostly domal corals, such as *Porites* and Faviids as well as *Heliopora* (Fig. 3B). The robust branching subfacies is best developed in Terrace 2 as shown in the short borehole CRM-2C. It also occurs in the lower and upper part of borehole CRM-3, and sparsely in Terrace 1 as shown in CRM-1a. This subfacies is equivalent to the Robust branching coral facies as described by Montaggioni (2005), and is interpreted to represent the outer reef flat, upper reef slope or patch reef where the current was relatively strong as suggested by general habitat of *A. robusta*, *A. digitifera* and *P. eydouxi* (Wallace, 1999; Veron, 2000). In their modern coral reefs of two nearby areas, Palau and Papua New Guinea, the coral assemblage are typical of high energy reef-crest environment (Nakamori et al., 1995; Kayanne et al., 2002).

The domal/*Heliopora* subfacies, best developed in the uppermost part of CRM-3, is interpreted to occur in deeper and calmer water in the lagoon or the fore-reef environment.

### 4.2. Bioclastic facies

The Bioclastic facies is characterized by unconsolidated bioclastic packstones and coral rubbles with a winnowed bioclastics matrix (Fig. 3C). The dominant constituents are finger-like corals, mostly *Acropora* and *Heliopora*, mollusk fragments and benthic foraminifera, especially *Calcarina sp.* This facies typically occurs in association with the reef facies as infilling in crevices between reef frameworks or as back-reef sands. This facies is best represented in the upper part of CRM-1.

### 4.3. Clayey facies

The Clayey facies consists of algal–coral boundstones, coral rubbles and bioclastics in a clayey matrix. The representative corals are *Heliopora* in boundstones, or *Heliopora* and *Acropora* corals as coral rubbles (Fig. 3D,E). Encrusting red algae also occurs in this facies with occasional rhodolith. In some intervals, the clayey matrix is cemented, but in other intervals it is still soft and thus could have been washed away during the drilling operation. This facies is best developed in the middle part of borehole CRM-3, the lower part of CRM-1, and upper part of CRM-2. We interpret this facies corresponds to a protected, back-reef environment. The boundstones with clayey matrix are interpreted to be patch reefs in the back-reef environment where the current was weak.

### 4.4. Tuffaceous facies

The Tuffaceous facies consists of volcanic ash and bioclastics with occasional red algal binding (Fig. 3F). Other than the volcanic sediments and better lithification, it appears similar to the clayey facies. This facies, with maximum thickness of 1.3 m in borehole CRM-1, overlies the Laoag Formation and underlies the other carbonate facies. The volcanics imply a large volcanic eruption in the early Holocene or late Pleistocene in northern Luzon.

## 5. Coral ages and facies geometry

The U–Th measurement results are summarized in Table 1. The absence of secondary carbonates in the intra-skeletal structure, the $^{238}$U levels of 2.3–3.6 ppm, and the initial $\delta^{234}$U values of 144.5–149.5‰ as in modern corals, suggest that the selected coral samples are well preserved. Agreement of duplicate $^{230}$Th dates for sample 7.8 m of CRM-3 (CRM-3-7.8 m-R, Table 1), also confirms our U–Th methodology and sample quality. Fig. 4 gives the lithocolumn with ages of fossil corals. The depth error of each coral is determined with the thicknesses of covered and unrecovered interval in each coring run. The oldest sample is dated as 9855 ± 42 ka at a depth of 22 m in borehole CRM-3, and youngest as 6588 ± 27 ka at 1.4 m below sea level of CRM-3.

Interpreted facies geometry and time lines are displayed in Fig. 5. Coral-reef development in Currimao started at least as early as 9.86 ka on a bioclastic substrate (Figs. 4 and 5, Table 1). The reef accreted vertically with the crest near the site of CRM-3. A back-reef environment with some patch reefs developed behind the reef crest

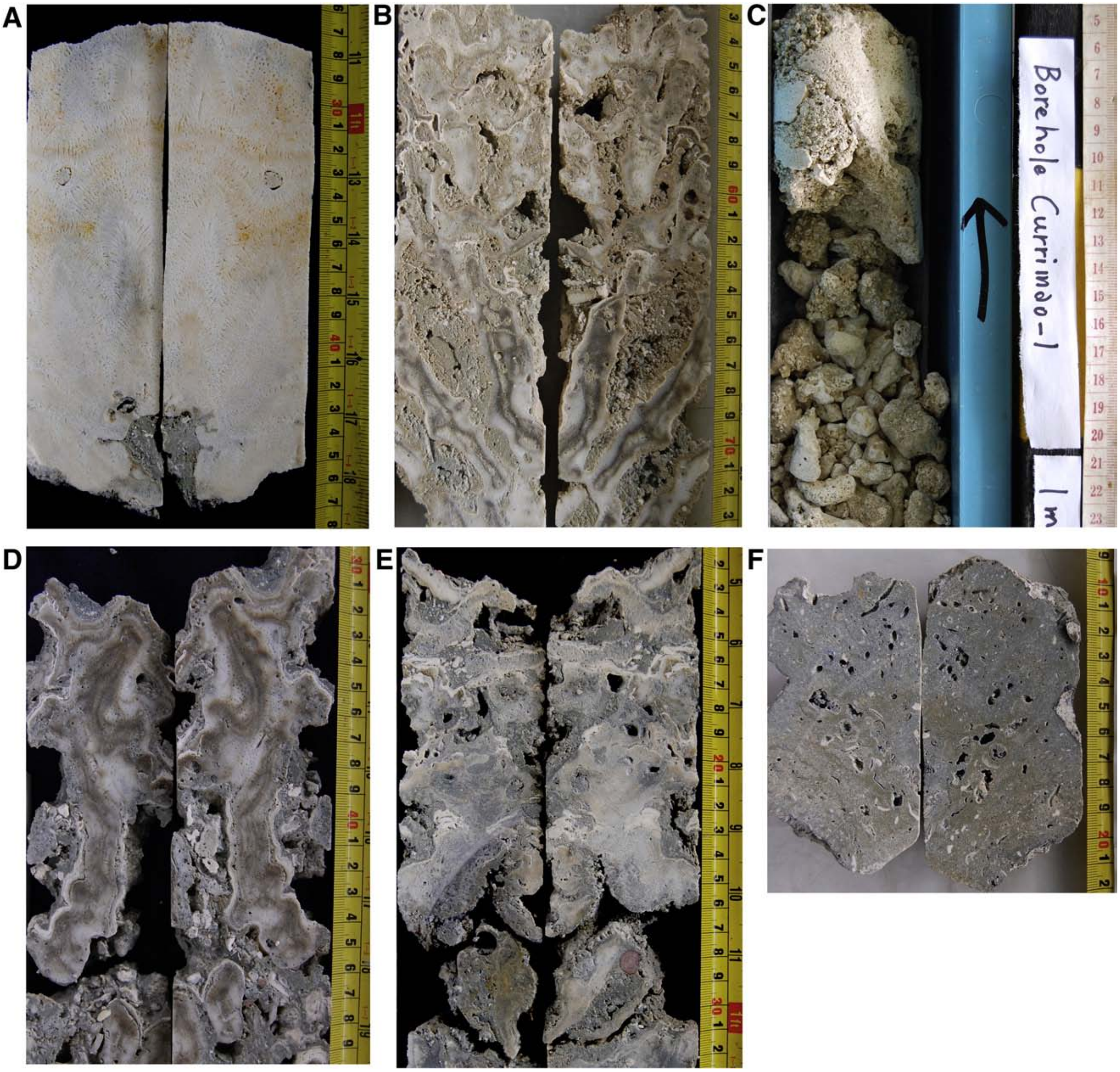


**Fig. 3.** Photographs of lithofacies of the Currimao cores. (A) The robust branching subfacies showing an *Acropora robusta*, CRM-3, 8.3–8.4 m. (B) The domal/*Heliopora* subfacies showing boundstone with a *Heliopora*, CRM-3, 4.6 m. (C) Bioclastic facies showing coral fragments, sand-sized bioclastics were washed away during drilling operation, CRM-1, 0.3 m. (D) Clayey facies, a *Heliopora* in clayey matrix, CRM-3, 10.3–10.5 m. (E) Clayey facies, bioclastics in clayey matrix and binded by red algae encrustations, CRM-3, 14.1–14.3 m. (F) Tuffaceous facies, CRM-1, 13.1–13.2 m.

as revealed in boreholes CRM-1 and CRM-2. The reef crest pro-graded seaward around 9 ka and shifted landward again toward 8 ka. The sea level and reef growth continued to rise till about 6.86 ka. The site was then uplifted to about 3.8 m above MSL. After that, the reef continued to develop at the site of CRM-3 till about 6.59 ka.

## 6. Discussion

### 6.1. Reef accretion rate

Holocene reefs throughout the world's tropical ocean have shown variable vertical accretion rates. Caribbean reefs typically exhibit higher vertical accretion rates with an average 6 m/ky (Dullo, 2005). The faster cases are: 12 m/ky in Alcaran, Mexico 8.9–7 ka (Macintyre et al., 1977), 13 m/ky in Barbados 8.8–7 ka (Fairbanks, 1989) and 15 m/ky in St. Croix 9.4–5 ka (Adey et al., 1977) with an average 6 m/ky in the Holocene (Dullo, 2005). In contrast, Indo-Pacific reefs typically grew at an average rate of 4.4 m/ky (Dullo, 2005). Apparently, Indo-Pacific reefs commonly developed at lower rates than Caribbean reefs. The faster growing reefs in the Indo-Pacific are: 8.57 m/ky in Mayotte 9.6–7.2 ka, (Dullo, 2005), 8 m/ky in central Great Barrier Reef 7.5 ka (Davies, et al., 1985), and 7.6 m/ky in Abrolhos Island 9.9–8.0 ka (Eisenhauer et al., 1993). Short-term vertical accretion rate of Palau could be 30 m in about 240 years in conventional $^{14}$C ages but the average is 8.5 m/ky in a 1-ky period (Kayanne et al., 2002). The exception is Tahiti where early Holocene reefs developed at a vertical accretion rate of about 12 m/ky during 10.8–8.5 ka in borehole P7, or even as high as 15 m/ky during a period from 10.1 to 9.5 ka in borehole P6 (Bard et al., 1996). However, all these data only reveal vertical accretion rates but not progradational rates due to the nature of cores.

Figs. 6 and 7 show that the CRM-3 reef grew upward at about 10 m/ky from 9.86 to 8.23 ka, or even 13 m/ky from 9.16 to 8.23 ka. CRM-2 exhibits a vertical accretion rate of about 10 m/ky from 9.2 ka

**Table 1**
U–Th isotopic compositions and $^{230}$Th ages for fossil coral samples of Currimao, Philippines by MC-ICPMS.

| Sample ID | Depth (m) | $^{238}$U (ppb) | $^{232}$Th (ppt) | $\delta^{234}$U Measured[a] | [$^{230}$Th/$^{238}$U] Activity[c] | [$^{230}$Th/$^{232}$Th] (ppm)[d] | Age Uncorrected | Age Corrected[c,e] | $\delta^{234}$U$_{initial}$ Corrected[b] |
|---|---|---|---|---|---|---|---|---|---|
| CRM-1a-0.5m | +0.7 | 3396.8 ± 2.7 | 59.1 ± 2.4 | 143.3 ± 1.4 | 0.07404 ± 0.00013 | 70221 ± 2809 | 7301 ± 16 | 7300 ± 16 | 146.3 ± 1.4 |
| CRM-1-3.4m | −2.8 ± 0.6 | 2306.6 ± 1.7 | 366.6 ± 2.2 | 144.7 ± 1.5 | 0.07659 ± 0.00013 | 7958 ± 49 | 7552 ± 16 | 7548 ± 17 | 147.8 ± 1.5 |
| CRM-1-5.1m | −5.1 | 3424.2 ± 3.4 | 81.3 ± 3.4 | 141.8 ± 1.6 | 0.08263 ± 0.00014 | 57480 ± 2424 | 8191 ± 19 | 8191 ± 19 | 145.1 ± 1.7 |
| CRM-1-12.4m | −12.2 ± 0.2 | 2753.3 ± 2.8 | 212 ± 11 | 141.6 ± 1.6 | 0.08957 ± 0.00020 | 19164 ± 962 | 8909 ± 25 | 8907 ± 25 | 145.2 ± 1.7 |
| CRM-2C-top | +3.8 | 2258.4 ± 4.4 | 42.3 ± 1.9 | 144.4 ± 2.6 | 0.06979 ± 0.00022 | 61568 ± 2775 | 6863 ± 28 | 6862 ± 28 | 147.2 ± 2.7 |
| CRM-2-2.2m | −1.8 ± 0.4 | 3321.0 ± 2.8 | 196.4 ± 2.7 | 141.5 ± 1.5 | 0.07573 ± 0.00012 | 21149 ± 296 | 7486 ± 16 | 7485 ± 16 | 144.5 ± 1.5 |
| CRM-2-7.3m | −7.1 ± 0.2 | 3568.8 ± 3.4 | 501.4 ± 8.2 | 144.1 ± 1.6 | 0.08317 ± 0.00017 | 9774 ± 160 | 8228 ± 21 | 8225 ± 21 | 147.5 ± 1.7 |
| CRM-2-17.5m | −16 ± 1.5 | 3248.3 ± 2.8 | 1508.5 ± 6.2 | 143.5 ± 1.4 | 0.09261 ± 0.00027 | 3293 ± 16 | 9207 ± 30 | 9196 ± 32 | 147.3 ± 1.5 |
| CRM-3-1.4m | −1.2 ± 0.2 | 2394.5 ± 3.7 | 28.0 ± 1.1 | 143.6 ± 2.4 | 0.06703 ± 0.00022 | 94671 ± 3825 | 6588 ± 27 | 6588 ± 27 | 146.3 ± 2.4 |
| CRM-3-5.7m | −5.3 ± 0.4 | 3292.7 ± 3.1 | 1231 ± 11 | 142.3 ± 1.7 | 0.08317 ± 0.00020 | 3673 ± 33 | 8242 ± 24 | 8233 ± 25 | 145.7 ± 1.7 |
| CRM-3-7.8m | −7.6 ± 0.2 | 3535.0 ± 2.9 | 112.2 ± 2.1 | 145.5 ± 1.4 | 0.08285 ± 0.00013 | 43114 ± 820 | 8185 ± 16 | 8185 ± 16 | 148.9 ± 1.4 |
| CRM-3-7.8m-R | −7.6 ± 0.2 | 3653.5 ± 3.6 | 1576.0 ± 2.8 | 142.4 ± 1.7 | 0.08273 ± 0.00019 | 3167 ± 9 | 8196 ± 23 | 8186 ± 25 | 145.8 ± 1.7 |
| CRM-3-18.7m | −18.4 ± 0.3 | 3226.1 ± 2.8 | 230.4 ± 1.7 | 144.0 ± 1.7 | 0.09225 ± 0.00012 | 21330 ± 162 | 9165 ± 19 | 9164 ± 19 | 147.8 ± 1.7 |
| CRM-3-22.2m | −21.8 ± 0.4 | 3281.5 ± 6.3 | 1644.8 ± 7.0 | 145.4 ± 2.8 | 0.09913 ± 0.00030 | 3265 ± 16 | 9866 ± 41 | 9855 ± 42 | 149.5 ± 2.9 |

Depth annotated with "−"or "+" sign indicates depth below or above present sea level after tectonic correction.

Chemistry was performed during November 2008–March 2009 and instrumental analyses on MC-ICP-MS (Shen et al., 2009). Analytical errors are 2σ of the mean.

[a] $\delta^{234}\mathrm{U} = ([^{234}\mathrm{U}/^{238}\mathrm{U}]_{\mathrm{activity}} - 1) \times 1000$.

[b] $[^{230}\mathrm{Th}/^{238}\mathrm{U}]_{\mathrm{activity}} = 1 - e^{-\lambda 230T} + (\delta^{324}{}_{\mathrm{measured}}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda_{230} - \lambda_{234})T})$, where $T$ is the age. Decay constants are $9.1577 \times 10^{-6}$ yr$^{-1}$ for $^{230}$Th, $2.8263 \times 10^{-6}$ yr$^{-1}$ for $^{234}$U, and $1.55125 \times 10^{-10}$ yr$^{-1}$ for $^{238}$U (Cheng et al., 2000).

[c] The degree of detrital $^{230}$Th contamination is indicated by the [$^{230}$Th/$^{232}$Th] atomic ratio instead of the activity ratio.

[d] Age corrections were calculated using an estimated atomic $^{230}$Th/$^{232}$Th ratio of 4 ± 4 ppm. Those are the values estimated from shallow corals with an arbitrarily assumed error of 100% (Shen et al., 2008).

[e] $\delta^{234}{}_{\mathrm{initial}}$ corrected was calculated based on $^{230}$Th age ($T$), i.e., $\delta^{234}\mathrm{U}_{\mathrm{initial}} = \delta^{234}{}_{\mathrm{measured}} X\, e^{\lambda 234 * T}$, and $T$ is corrected age.

to 8.23 ka. CRM-1 also displays a vertical accretion rate of about 10 m/ky from 8.9 ka to 8.19 ka. Such fast rates, exhibited in 3 cores by 6 to 7 fossil corals based on accurate $^{230}$Th ages, indicate that the chance of sampling artifact is very slim. The rates are among the fastest vertical accretion rate in the western Pacific and Indian Ocean, and are comparable to the fastest rates of the Caribbean region or the early Holocene reefs of Tahiti.

This study suggests that the apparent lower accretion rate of Indo-Pacific reefs is still an open question at least for the early Holocene. The area, including Indonesia, New Guinea and the Philippines, has the highest coral diversity and is referred to as "coral triangle" where Holocene reefs occurred extensively yet very few studies have been conducted. Higher vertical accretion rates could be established in the area with more data available.

### 6.2. Landward shift of the reef crest at 7.48 ka

Figs. 5 and 6 show a landward shift of the reef crest of about 40 m from the CRM-3 site to the CRM-2 site some time after 7.48 ka. This shift is revealed by the change of lithology in CRM-2 change from bioclastics in a clayey matrix to coral boundstone dominated by robust branching corals (Fig. 4). These robust branching corals are also observed along Terrace 2 that extends for almost 3 km. In the meantime, the coral fauna of CRM-3 shifts from a very shallow-water species *Acropora robusta* to domal corals and blue coral, and the accretion rate declined significantly after 8.18–8.23 ka (Figs. 4 and 6).

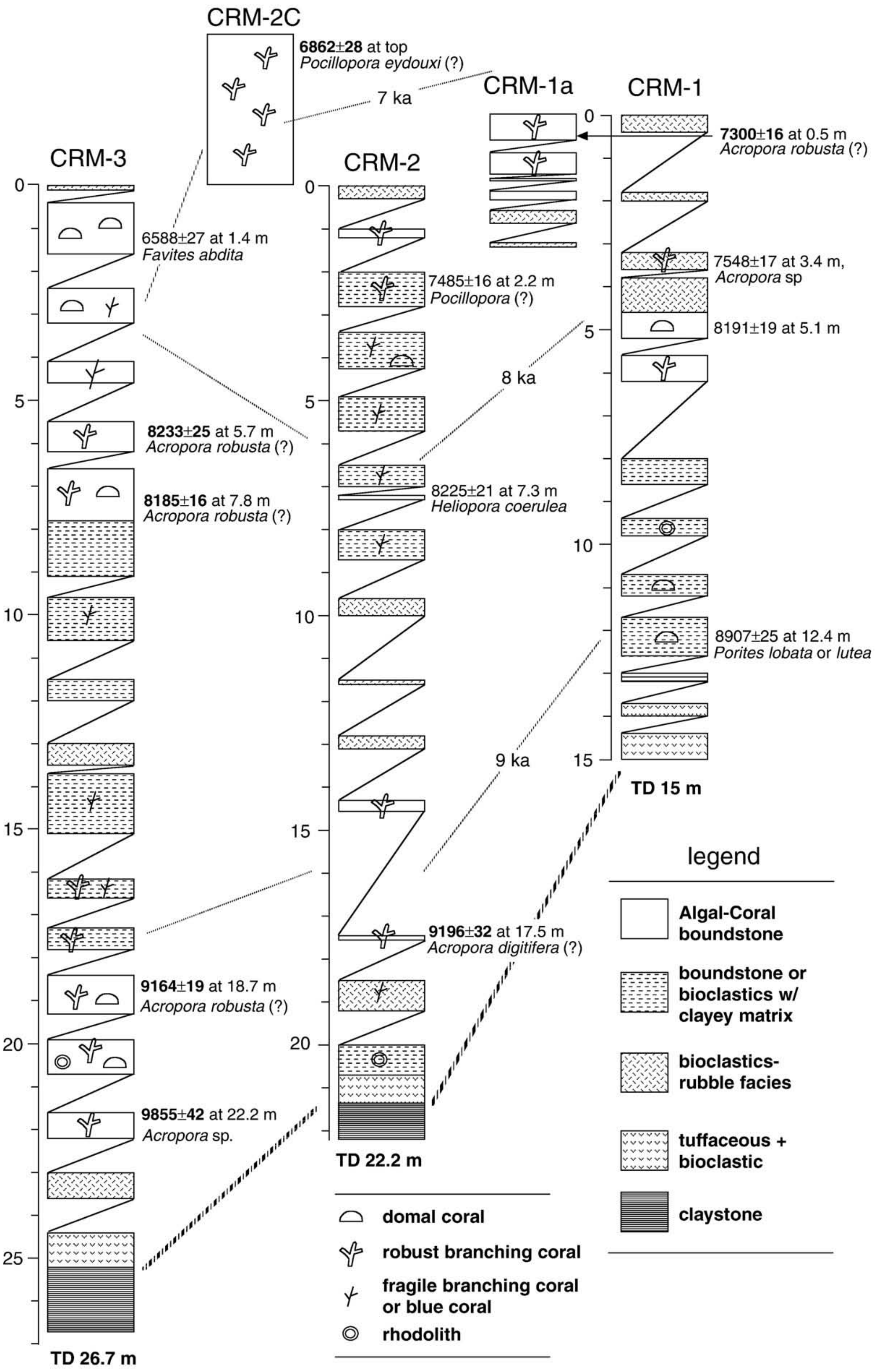
Reef backstepping has been reported at some time during the interval 8–7 ka in Caribbean Sea (Blanchon and Shaw, 1995; Blanchon et al., 2002) and in the Pacific (Kayanne et al., 2002; Engels et al., 2004), and attributed to a pulse of sea-level rise about 7.6 ka (Woodroffe and Horton, 2005), although there is uncertainty in the timing and amplitude of the event. Other studies questioned the importance of a sea-level event at 7.6 ka (Bard et al., 1996; Hubbard et al., 1997; Montaggioni et al., 1997; Toscano and Lundberg, 1998) and even considered it a sampling artifact (Toscano and Lundberg, 1998). The landward shift of the reef crest in Currimao can be explained by the same event that caused the reef backstepping documented in other places (Blanchon and Shaw, 1995; Blanchon et al., 2002; Kayanne et al., 2002; Engels et al., 2004). However, the older reef crest is only shown in one core. Further studies must be done to confirm the existence of an older reef crest near the edge of Terrace 1.

### 6.3. Deglacial sea-level rise

Fig. 6 plots the ages and depths of corals in all three cores. All cores show that ages generally increase with increasing depth, and the three cores agree with each other in general. This pattern certainly reduces the possibility of redeposited corals or sampling artifact to a large degree. However the curves should be considered as accumulation curves rather than sea-level curves.

Corals do not always live just below sea level. Some species may live in water below 20 m deep. In addition, Luzon is still tectonically active, and tectonic effects must be addressed before any meaningful discussion of Holocene sea-level history. To represent paleo-sea level as much as possible, only *Acropora robusta*, *A. digitifera* and *Pocillopora eydouxi* ((highlighted in Table 1 and printed in bold in Fig. 4) were selected as a sea-level proxy because these species typically live on the outer reef flat or upper reef slope and are therefore considered better sea-level indicators than others (Wallace, 1999, p.115; Veron, 2000, v.1, p.216, 328; v.2, p.44). The only exception is the *Acropora* at 22 m of CRM-3 where we cannot determine the species. This sample is still included because it is the oldest and deepest datable coral. A total of seven coral ages, printed in bold in Fig. 4, are included in a sea-level reconstruction. Even though the corals were carefully selected, the coral depths should be considered to be the minimum sea level. The paleo-sea level could be a few of meters higher than the depths of the dated corals.

The site of CRM-2, a 6.86-ky-old reef flat is now emerged to 3.8 m above sea level, which could be attributed to two possible scenarios; either the paleo-sea level was near +3.8 m above MSL around 6.86 ka, or the reef flat was mainly uplifted by tectonic activity, or a combination of both. Among the Philippines sites where mid-Holocene sea-level records are available, Palawan is considered relatively stable in terms of active faulting and seismic activities (Bautista and Oike, 2000; PHIVOLCS, 2001a,b). That the elevation of MIS 5e sea level is at 6.8 m above MSL in northwest Palawan (Omura et al., 2004) is a strong argument for a very minimal uplift since late Pleistocene. Sea-level records of Palawan with ages similar to Terrace 2 were identified at the Caparri as 0.5 m above MSL at 6.7 ± 0.1 ka with $^{230}$Th/$^{234}$U dating, and 0.3 m above MSL in Lagen Island at 6.8 ± 0.1 ka with $^{14}$C dating (Maeda et al., 2004). By comparing the sea-level records of Palawan, a scenario in which most of the 3.8 m of reef emergence due to tectonic uplift is preferred. The observations


CRM-2C
6862±28 at top
Pocillopora eydouxi (?)
7 ka
CRM-1a
CRM-1
7300±16 at 0.5 m
Acropora robusta (?)
CRM-3
CRM-2
6588±27 at 1.4 m
Favites abdita
7485±16 at 2.2 m
Pocillopora (?)
7548±17 at 3.4 m,
Acropora sp
8191±19 at 5.1 m
8 ka
8233±25 at 5.7 m
Acropora robusta (?)
8225±21 at 7.3 m
Heliopora coerulea
8185±16 at 7.8 m
Acropora robusta (?)
8907±25 at 12.4 m
Porites lobata or lutea
9 ka
TD 15 m
9196±32 at 17.5 m
Acropora digitifera (?)
9164±19 at 18.7 m
Acropora robusta (?)
9855±42 at 22.2 m
Acropora sp.
TD 22.2 m
TD 26.7 m
0
5
10
15
20
25
legend
Algal-Coral boundstone
boundstone or bioclastics w/ clayey matrix
bioclastics-rubble facies
tuffaceous + bioclastic
claystone
domal coral
robust branching coral
fragile branching coral or blue coral
rhodolith

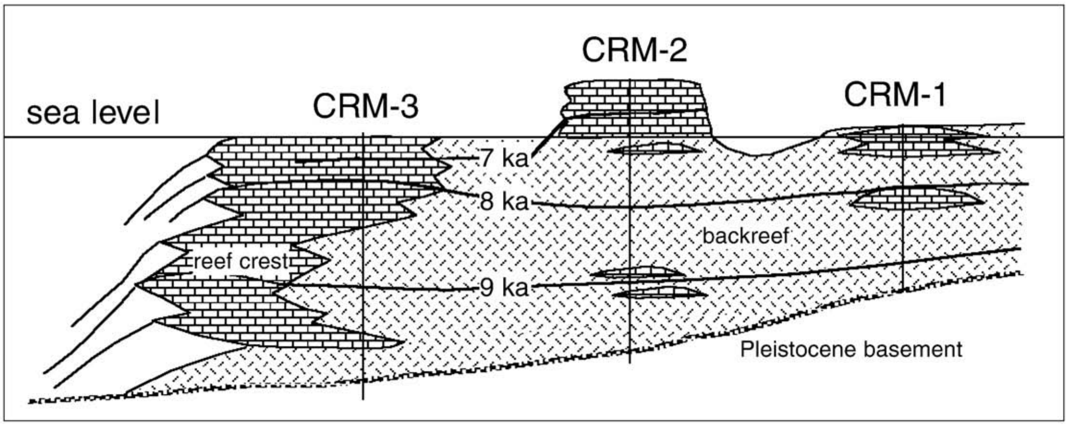


**Fig. 5.** Schematic profile of facies geometry with time lines reconstructed from the Currimao cores. The depth and lithocolumn of cores are shown in Fig. 4. See Fig. 1 for core locations.

indicate that the Currimao reef flat developed near paleo-sea level that was at 0.3–0.5 m above MSL, and then elevated 3.3 to 3.4 m by tectonics to its present elevation at +3.8 m. The average uplift rate would be about (3.3–3.5)/6.86 or 0.5 m/ky. The depths of the Currimao corals therefore can be corrected by about −0.5 m/ky to compensate for tectonic uplift. If uplift prior to 6.86 ka was episodic, then the correction for samples between 9.85 ka and 6.86 ka could deviate from the average uplift rate. Given the short time span from 9.85 to 6.86 ka, we assume that the mean uplift rate from 6.86 ka to present is valid for the interval from 9.85 to 6.86 ka as well.

The uncertainty in the water depth at which each coral grew is a more significant issue. The fauna of *A. robusta*, *A. digitifera* and *P. eydouxi* typically occur in water depth less than 6 m in Palau, Papua New Guinea and most of Indo-Pacific area (Nakamori et al., 1995; Kayanne et al., 2002; Montaggioni, 2005). If we use 3 ± 3 m for the living depth of our samples, uncertainty in tectonic correction should be less than a ±3 m uncertainty in water depth. We herein only corrected tectonic uplift using an average uplift rate of 0.5 m/ky, bearing in mind that the paleo-sea level might be a few meters higher than the coral depths.

The age versus depth plot of Currimao corals, with the depth of corals corrected for uplift, are presented in Fig. 7. The minimum sea level of Currimao was about 27 m below MSL at 9.86 ka and rose to about 4 m below MSL at 7.3 ka (Fig. 7). $^{230}$Th-dated coral records of Tahiti (Bard, et al., 1996) and Abrolhos Island, offshore from Western Australia (Eisenhauer et al., 1993) are also plotted in Fig. 7 for comparison. The subsidence rate of the Tahiti data was originally considered to be 0.2 m/ky by Bard et al. (1996) but later by Dickinson (2004) be 0.55 m/ky. Both rates were used in constructing Fig. 7 (see caption). The Abrolhos data were not corrected because the area is considered tectonically stable (Eisenhauer et al., 1993). We chose Tahiti and Abrolhos records because they are also coral-based with $^{230}$Th dates, overlap with the Currimao record in ages, and are not contaminated much by tectonic activity. Fig. 7 shows that the minimum sea-level curve in Currimao generally agrees with that of Abrolhos. But there is a significant discrepancy between Currimao and Tahiti during the overlapping period approximately from 9.9 to 8.5 ka. The differences are at least 8 m if using 0.55 m/ky as the subsidence rate (Dickinson, 2004), or even 11 m if using 0.2 m/ky (Bard et al., 1996).

The discrepancy between Currimao and Tahiti could be attributed to the corals dated by Bard et al. (1996), which lived in waters 8–11 m deeper than Currimao corals. However, the fossil assemblage indicated that the dated corals in Tahiti were from reef front or upper reef slope less than 6 m in living depth (Bard et al., 1996; Montaggioni et al., 1997; Cabioch et al., 1999). The dominant corals are *A. robusta*, *A. danai* and *Pocillopora verrucosa*, basically similar environment as corals dated in this study.

Another possible explanation is that the tectonic uplift of Currimao prior to 6.86 ka is underestimated. There could be additional 2 or 3 m uplift for Currimao samples assuming a faster-than-0.5 m/ky uplift rate before 6.86 ka. However, our samples are only distributed in a time span from 9.85 to 6.86 ka, and the uplift of 3.3–3.5 m after 6.86 ka is well constrained. Unless there was much faster uplift from 9.85 to 6.86 ka, it is difficult to attribute the difference between Currimao and Tahiti records totally to tectonics.

A third possible explanation is hydro-isostasy. Spatial variations in regional sea levels could mainly result from redistribution of ice meltwater caused by effects of “equatorial ocean siphoning” and/or hydro-isostatic adjustment (Mitrovica and Peltier, 1991; Mitrovica and Milne, 2002). Differences in the response to meltwater loading will create different accommodation space for seawater, and consequently modify the sea level in any particular region. The rheological behavior of crust also plays a significant role in regional sea level in addition to the distance from ice sheets and continents that respond differently than oceanic islands to sea-level rise (Nakada, 1986). Scientists already noted that paleosea-level records after 7 ka revealed two broad patterns (e.g., Camoin, et al., 2004). Continental margins and large islands typically exhibited sea level higher than present during 6–4 ka, while volcanic islands in oceanic basins tended to show a continuously rising sea-level curve or a mild mid- to late Holocene highstand (Nakada and Lambeck, 1989; Grossman et al., 1998; Camoin, et al., 2004). Such a pattern can be explained by different responses of oceanic lithosphere and continental lithosphere to meltwater loading. When an island size exceeds about 10 km, its mantle rheology begins to behave like a mini-continent (Nakada, 1986).

Currimao and Abrolhos are located near island arc or continental lithosphere while Tahiti is located on oceanic lithosphere. As mentioned in Section 2, notches 2.3 to 2.8 m above MSL and $^{14}$C-dated to be 5466 and 5758 cal BP were identified in Palawan (Maeda et al., 2004). The mid-Holocene highstands of the large islands in western Pacific were at most +2.4 to +2.6 m from 5 to 1.5 ka (Grossman et al., 1998; Dickinson, 2001). The Palawan notches are at

**Fig. 4.** Lithocolumn of the Currimao cores. See Fig. 1 for their locations. $^{230}$Th ages of fossil corals are also shown at depth where the coral was recovered. Depths were below the ground surface. The elevation of CRM-1 is 1.2 m above MSL. CRM-2 and CRM-3 are near MSL while CRM-2C is 3.8 m above mean sea level. Only ages printed in bold are plotted in Fig. 7.

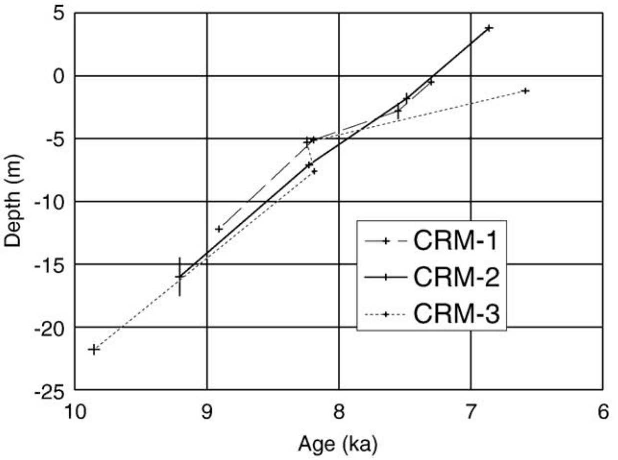


**Fig. 6.** Depth-age plots of fossil corals in the Currimao cores. Depths are not corrected for tectonics. Errors in ages and depths are indicated by length of crossbar.

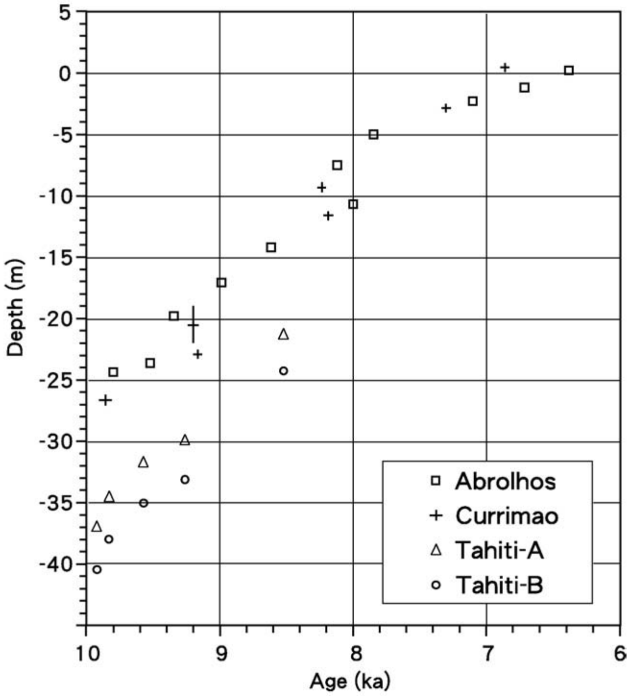


**Fig. 7.** Comparison of sea-level records of Currimao, Abrolhos Island (Eisenhauer et al., 1993) and Tahiti (Bard et al., 1996). Currimao data were corrected tectonic uplift by 0.5 m/ky, and CRM-1 corrected for wellhead elevation. Errors in ages and depths of Currimao data are indicated by length of crossbar. Tahiti data were corrected using subsidence rate of 0.55 m/ky (Taihiti-A) after Dickinson (2004) and 0.2 m/ky (Taihiti-B) after Bard et al. (1996) respectively.

comparable elevations and ages, hence probably represent mid-Holocene highstands in the Philippines. On the other hand, Tahiti sea level reached only +0.35 during the same time span (Grossman et al., 1998), but the leeward Society Islands recorded mid-Holocene highstands at 0.9–1.1 m (Dickinson, 2003), which may be a better sea-level record for the region because the leeward Society Islands are not affected by the load of Mehetia Volcano (Dickinson, 2003). Therefore, the hydro-isostatic effect seems to be responsible for only 1.2–2.4 m difference between western Pacific and Tahiti for the mid-Holocene, apparently not enough to explain the difference between Luzon/Australia and Taihiti sea levels (Fig. 7). However, when extrapolated to early Holocene, Nakada and Lambeck (1989) demonstrated that spatial variations in mantle rheology between Australia and Tahiti could caused sea-level differences to be as much as about 10 m given certain assumptions (Fig. 14 of Nakada and Lambeck, 1989). Thus, the differences between Albrolhos and Tahiti records can be explained by hydro-isostasy and mantle rheology. Given the size of Luzon and its island-arc setting, it is anticipated that the sea-level records of Luzon will be similar to those of continental margins rather than oceanic islands. Therefore, the discrepancy between Currimao and Tahiti records can also be attributed to difference in hydro-isostatic adjustment between Luzon and Tahiti using Nakada's model (Nakada, 1986; Nakada and Lambeck, 1989).

## 7. Conclusions

1. Holocene reefs of Currimao in northwestern Luzon, Philippines developed in an overall aggradation mode from 9.86 ka to 6.59 ka during deglacial sea-level rise. During 9.2–8.2 ka, the accretion rate of Currimao reefs was as high as 10–13 m/ky as revealed by 3 cores.
2. Shortly after 7.48 ka, the reef crest shifted landward by about 40 m, from CRM-3 site to Terrace 2, accompanying facies change and low accretion rate at CRM-3 from robust branching corals to domal corals after about 8.18–8.23 ka.
3. The reef reached the paleo-sea level of about 0.5 m above MSL about 6.86 ka after that continued to be uplifted by about 3.3–3.5 m by tectonic activity. The coral reef pro-graded and continued to grow till about 6.59 ka.
4. The minimum sea-level curve of Currimao, as indicated by the ages and depth of very shallow-water coral species, is similar to that of Abrolhos, offshore Western Australia. The minimum sea level was likely about 27 m below the MSL at 9.86 ka and rose to about 4 m below the MSL at 7.3 ka. The Currimao sea-level record is at least 8–11 m higher than that of Tahiti between 9.9 and 8.5 ka.

## Acknowledgements

This study was supported by NSC grant 96-2116-M-178-003. $^{230}$Th dating at the HISPEC was supported by the NSC grants 94-2116-M-002-012, 95&96-2752-M002-012-PAE, and 97-2745-M-002-009 to CCS. Authors thank the municipal government of Currimao, Ilocos Norte for granting the permit for the drilling operation. The authors thank Dr. Yasuo Maeda for valuable discussions, and Peter Zamora for administrative and field help. Gratitude is given to Dr. William R. Dickinson and an anonymous reviewer for their help in improving an early version of the manuscript.

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