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Sea-level history of past interglacial periods from uranium-series dating of corals, Curaçao, Leeward Antilles islands

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ABSTRACT

Curaçao has reef terraces with the potential to provide sea-level histories of interglacial periods. Ages of the Hato (upper) unit of the “Lower Terrace” indicate that this reef dates to the last interglacial period, Marine Isotope Stage (MIS) 5.5. On Curaçao, this high sea stand lasted at least 8000 yr (~126 to ~118 ka). Elevations and age of this reef show that late Quaternary uplift rates on Curaçao are low, 0.026–0.054 m/ka, consistent with its tectonic setting. Ages of ~200 ka for corals from the older Cortalein unit of the Lower Terrace correlate this reef to MIS 7, with paleo-sea level estimates ranging from −3.3 m to +2.3 m. The estimates are in agreement with those for MIS 7 made from other localities and indicate that the penultimate interglacial period was a time of significant warmth, on a par with the present interglacial period. The ~400 ka (MIS 11) Middle Terrace I on Curaçao, dated by others, may have formed from a paleo-sea level of +8.3 to +10.0 m, or (less likely) +17 m to +20 m. The lower estimates are conservative compared to previous studies, but still require major ice sheet loss from Greenland and Antarctica.

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Introduction

The prospect of a warmer Earth in the near future has increased concern about sea-level rise resulting from melting of large ice sheets in Greenland and Antarctica. One of the most effective means of understanding the magnitude of possible sea-level rise is study of high sea levels during past warm interglacial periods. High sea stands of the past are often preserved in the geologic record as emergent reef terraces with a “staircase” type of geomorphology on tectonically rising coasts, such as those on Barbados or Haiti (Fig. 1a). In contrast, on tectonically stable coasts, or those that are subsiding slowly, such as the Florida Keys or the Cayman Islands, high sea stands are recorded as limestones composed of stacked reef tracts, separated by subaerial exposure surfaces with weathered zones or paleosols (Fig. 1b). In the deep-sea oxygen isotope record, the most recent previous interglacial periods are represented by Marine Isotope Stages (MIS) 5.5 (~125 ka), 7 (~200 ka), 9 (~300 ka), and 11 (~400 ka) (Imbrie et al., 1984; Rohling et al., 2009, 2010). As pointed out in the 2007 IPCC Report, these four interglacial periods differ from one another in their degree of warmth, duration, and timing relative to the Earth's orbital geometry (Jansen et al., 2007).

Of the past warm periods, the last interglacial or MIS 5.5 has received the most attention (see reviews in Kopp et al., 2009 and Muhs et al., 2011). There have been fewer studies of MIS 7 and MIS 9. There has been an increasing interest in MIS 11 (~400 ka) because the Earth's orbital configuration at that time was similar to that of today (Berger and Loutre, 1991, 2002). Indeed, Berger and Loutre (2002) speculate that MIS 11 could have been an exceptionally long and warm interglacial period and a suitable analog for a future climate on Earth. To investigate past interglacial high sea stands, we studied coral reef terraces on the island of Curaçao, Leeward Antilles islands, in the southern Caribbean Sea (Fig. 2).

Geology of Curaçao

The Leeward Antilles islands of Curaçao, Bonaire and Aruba are situated in the southernmost part of the Caribbean Sea (Fig. 2). Nearby, the Caribbean plate underthrusts the South American plate at a shallow angle north of the Leeward Antilles ridge, a major topographic/bathymetric high that includes Aruba, Bonaire and Curaçao (Hippolyte and Mann, 2011). This subduction process has probably been in progress since the Paleogene. However, recent data indicate that the main sense of motion of the Caribbean plate, relative to the South American plate, is east-west, at a rate of ~20 mm/yr (Hippolyte and Mann, 2011).

The geology of Curaçao consists of a core of Cretaceous diabase flanked by Paleogene sedimentary rocks, in turn overlain by the Seroe Domi Formation, a thick sequence of Neogene marine limestones and siliciclastic sandstone (De Buisonjé, 1974). Along the coastal margins of Aruba, Curaçao and Bonaire there are spectacular flights of Quaternary marine terraces (Figs. 3 and 4). Numerous workers in the early part of the 20th century recognized the geologic

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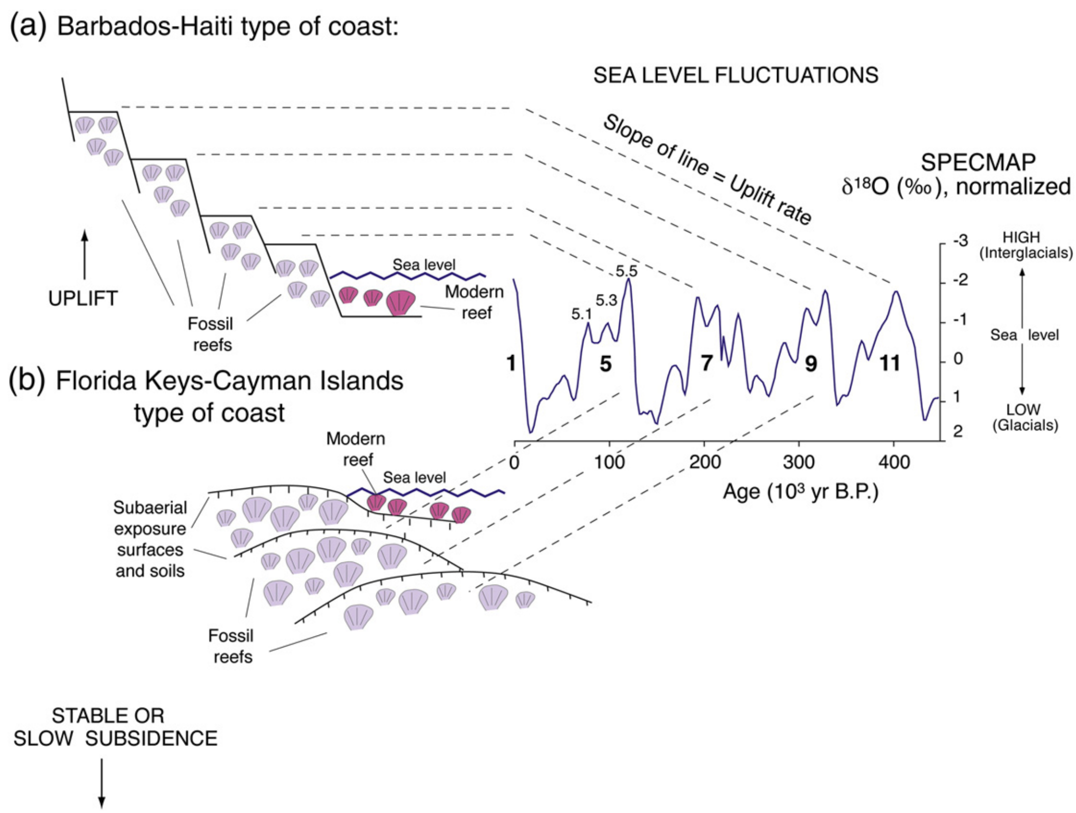

Figure 1. Diagram showing relations of glacial-interglacial sea-level history as recorded in the oxygen isotope record of foraminifera in deep-sea sediments (SPECMAP values and chronology from Imbrie et al., 1984) to interglacial coral reef record on tectonically uplifting coasts [(a) "Barbados-Haiti" type] and tectonically stable or slowly subsiding coasts [(b) "Florida Keys-Cayman Islands" type]. Diagram modified from Muhs et al. (2004).

significance of the marine terraces on Curaçao and De Buisonjé (1974) summarizes these early studies. Alexander (1961) mapped and measured the terraces and was perhaps the first investigator to recognize that the terraces on the islands of the Leeward Antilles were the products of Quaternary interglacial/glacial sea-level fluctuations superimposed on steady tectonic uplift. This fundamental concept is key to our present understanding of marine terrace origins on many coastlines and islands worldwide. Nevertheless, Alexander (1961) interpreted the terraces on Curaçao as erosional landforms. Although De Buisonjé (1974) thought that this interpretation applied to some of the terraces on the leeward (southern) side of the island (where they are cut on the Seroe Domi Formation), he recognized that most of the terraces, particularly on the windward (northern) side, are constructional coral reef terraces, similar to those on the island of Barbados. De Buisonjé (1974) identified three distinct facies in the terraces, seaward to landward: (1) a barrier reef zone, dominated by *Acropora palmata*; (2) a lagoonal or back-reef zone dominated by *Montastraea annularis*; and (3) an innermost lagoonal or back-reef zone dominated by *Siderastrea*. In remapping the Quaternary deposits of Aruba, Curaçao and Bonaire, De Buisonjé (1974) recognized several emergent terraces on Curaçao named, from oldest to youngest: Highest Terrace (~90 up to ~150 m), Higher Terrace (~50 to 85 m), Middle Terrace I (~15 to ~25 m), Middle Terrace II (~25 to ~45 m), and Lower Terrace (~6 to 12 m). De Buisonjé (1974) states that Middle Terrace II deposits overlie Middle Terrace I deposits in places and thus are stratigraphically younger even though they are topographically higher. Herweijer and Focke (1978) report that the Lower Terrace on Curaçao consists of two constructional reef tracts (the lower called the Cortalein, the higher called the Hato) separated by a prominent discontinuity. Pandolfi et al. (1999), Pandolfi (2001), Pandolfi and Jackson (2001) and Meyer et al. (2003) provide details of the coral fauna from the Hato unit.

Most previous age determinations of reef terraces on Curaçao have been on the Lower Terrace. Schubert and Szabo (1978) report alpha-spectrometric U-series ages of ~125 ka, correlating the Hato unit of the Lower Terrace to the peak of the last interglacial period, or MIS 5.5. Hamelin et al. (1991) analyzed two corals from the Hato unit of the Lower Terrace on the leeward side of the island using thermal ionization mass spectrometric (TIMS) U-series dating and report ages similar to those of Schubert and Szabo (1978). Although Schubert and Szabo (1978) concluded that the upper part of the Lower Terrace represents MIS 5.5, they speculated that terraces representing MIS 7 (~250–200 ka) and MIS 9 (~350–300 ka) were missing on Curaçao. In contrast, Herweijer and Focke (1978) hypothesized that the lower, Cortalein unit of the Lower Terrace could date to MIS 7. Schellmann et al. (2004) conducted electron spin resonance (ESR) analyses of corals from both units of the Lower Terrace. They report ages of 140 ka to 101 ka for the Hato unit and 226 ka to 189 ka for the Cortalein unit, in support of Herweijer and Focke's (1978) hypothesis.

There have been a few attempts to date one of the older terraces on Curaçao, all of them on Middle Terrace I and all apparently very close to Boca San Pedro on the windward coast of the island (Fig. 3). McFarlane and Lundberg (2002) report a TIMS U-series age on an unrecrystallized coral from this terrace of ~405 ka. Their sample has a calculated initial $^{234}U/^{238}U$ value that is higher than seawater, indicating that it is probably biased old, but following Gallup et al.'s (1994) model, the coral would fall within the age range of MIS 11. Schellmann et al. (2004) report four ESR ages on coral from Middle Terrace I, with estimates ranging from ~363 ka to ~544 ka. Thus, their data would also permit a correlation of Middle Terrace I with MIS 11, although they caution that the age of this terrace could be >500 ka.

We studied the Lower Terrace on Curaçao, primarily on the windward side of the island (Fig. 3). Our work included measuring terrace elevations, describing terrace stratigraphy, and collecting corals for

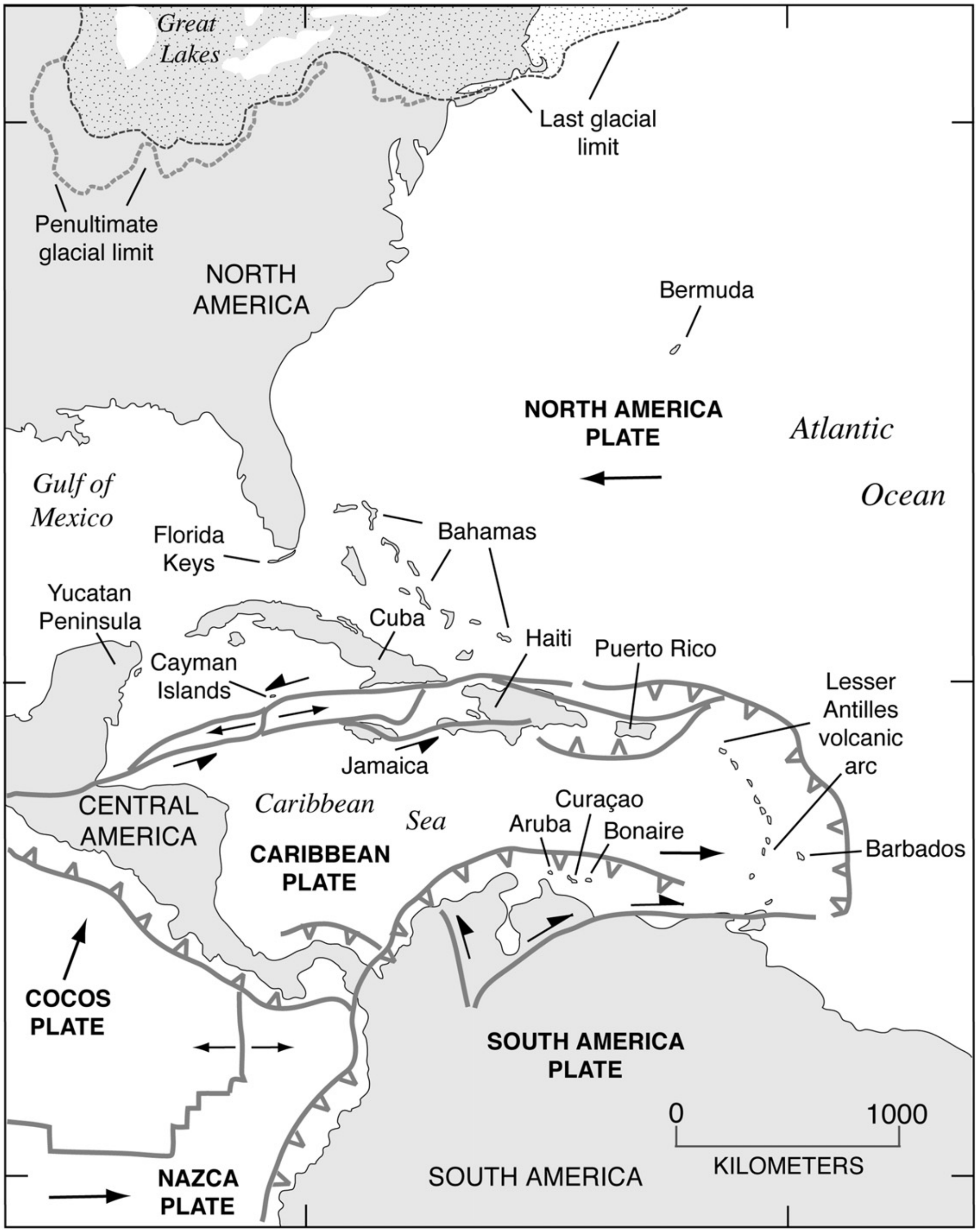

Figure 2. Map of the Caribbean Basin, western Atlantic Ocean, adjacent continents and islands, localities referred to in the text, tectonic features (from Prentice et al., 2010), and southern limits of the Laurentide ice sheet during the past two glacial periods (Flint, 1971; Dyke et al., 2002).

uranium-series dating. Our goals were to determine the ages of the units within the Lower Terrace and to elucidate sea-level history.

Methods

Geomorphology and stratigraphy

There are a number of potential geomorphic indicators of past sea level. In regions where uplifted erosional marine terraces are found, such as California, the shoreline angle (junction of the wave-cut platform with the former sea cliff) is the feature that is closest to the position of sea level (e.g., Muhs et al., 2012). Other methods are used for constructional landforms such as reef terraces. Studies of uplifted reef terraces in the Caribbean region have generally used the elevation of the *Acropora palmata*-dominated reef crest facies as the best paleo-sea-level indicator, following work on Barbados by Mesolella et al. (1969, 1970). These latter studies indicate that the *Acropora palmata*-dominated reef crest facies is typically found at higher elevations than the landward portions of emergent reef terraces, which are characterized by a lower-elevation lagoonal facies.

Around Curaçao at present, *Acropora palmata* lives in water depths of 0–5 m (Bak, 1977; Bruckner and Bruckner, 2006), similar to the modern growth depths for this species around Jamaica (Goreau and Goreau, 1973) and the Florida Keys (Shinn et al., 1989). In contrast, bioerosional notches, analogous to shoreline angles, occur very close to sea level on modern cliffs of the windward side of Curaçao (Focke, 1978) and can

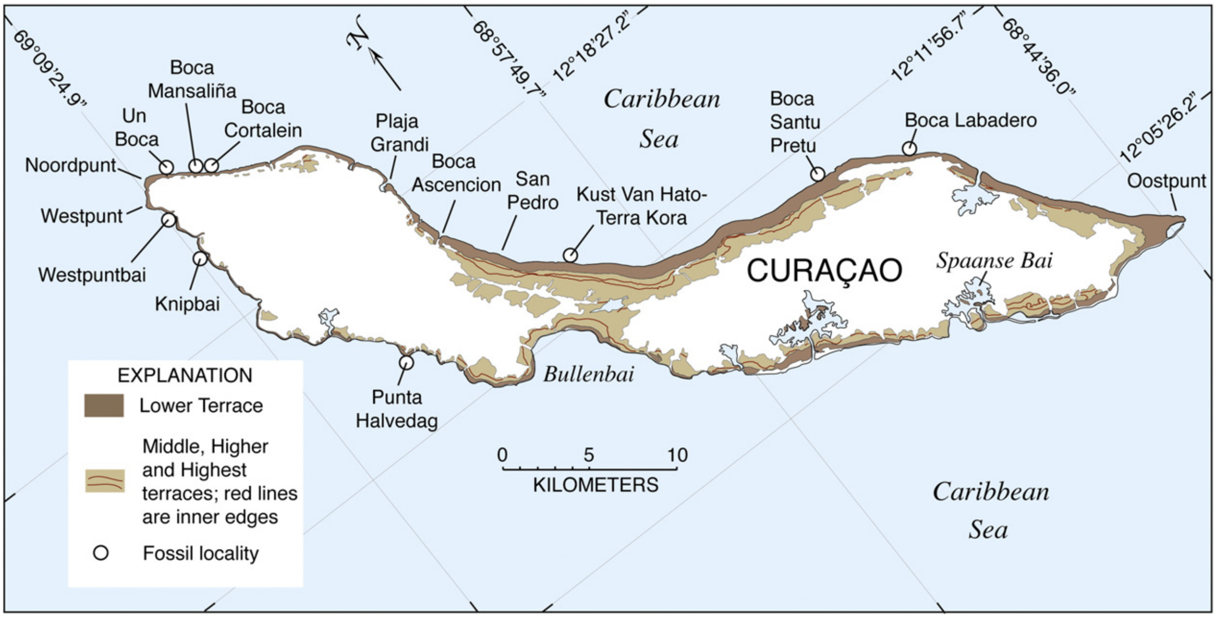

Figure 3. Map showing distribution of the Lower Terrace and all higher terraces on Curaçao (redrawn from De Buisonjé (1974)), fossil sampling localities (Table 1), and other localities referred to in the text.

be observed on the leeward side as well (Figs. 4b, 5a, 5b). Notches are also present as fossil geomorphic features on the landward side of many of the emergent terraces (Alexander, 1961; De Buisonjé, 1974; Focke, 1978; Schellmann et al., 2004), including the Lower Terrace (Fig. 5c). Thus, notches on the landward parts of the Lower Terrace may be more accurate indicators of paleo-sea level.

Critical to our studies is accurate and precise determination of the elevations of past sea-level indicators, whether they are notches or *Acropora palmata*-dominated reef crests. Elevations of all localities we studied in Curaçao were made using either direct measurement by tape or differential Global Positioning System (GPS) measurements. Latitude–longitude data and elevations were determined using a Trimble Pathfinder Pro XH GPS instrument, running Trimble TerraSync software (use of trade names is for descriptive purposes only and does not constitute endorsement or recommendation by the U.S. Government). At each location, data were collected from at least four, and usually six to eight, satellites for at least 500 s to obtain consistent 3-D geometry. The data were post-processed using Trimble Pathfinder Office software, in which GPS field data were differentially corrected against the closest active base stations, which are in Curaçao, Grenada, and Bogota, Colombia. Differentially correcting the GPS elevations generally resulted in horizontal errors of 10 cm or less and vertical errors in the range of 20–80 cm. Our measurements use the CARIB97 high-resolution geoid height model for the Caribbean Sea region (Smith and Small, 1999). Tidal variations on Curaçao are generally less than ~0.3 m, so corrections to these measurements are negligible and we consider the elevations to be accurate to ±0.3 m, relative to mean sea level. Comparison of GPS-derived elevations with spot elevations on 1:25,000-scale topographic maps (Cadastral Department of the Netherlands Antilles) and taped elevations shows good agreement, within the limits of instrumental uncertainty.

Uranium-series dating

Corals used in this study were cleaned mechanically, washed in distilled water and X-rayed for aragonite purity. X-ray diffraction was done using Cu radiation at a scanning speed of 2° per minute; mineralogy was determined by comparison of peak heights for aragonite (26.2°) and calcite (29.4°). All samples are at least 96% aragonite and most are 97–100% aragonite (Table 1). Sample preparation follows methods outlined by Ludwig et al. (1992). Cleaned corals were dissolved in HNO_3, spiked with ^{229}Th, ^{233}U, and ^{236}U (calibrated primarily with a secular equilibrium standard; see Ludwig et al. (1992)) and purified with ion exchange methods. Purified U and Th were loaded with colloidal graphite on separate Re filaments. Isotopic abundances were determined by thermal ionization mass spectrometry (TIMS). Ages were calculated using a half-life for ^{230}Th of 75,690 yr and a half-life for ^{234}U of 245,250 yr (Cheng et al., 2000). Duplicate analyses of individual coral samples generally show good agreement, within limits of analytical uncertainty (Table 1).

Several conditions must be met in order for U-series ages of corals to be considered reliable. These include: (1) little or no evidence of recrystallization to calcite, (2) U concentrations similar to those present in living corals of the same genus, (3) presence of little or no “inherited” ^{230}Th, as indicated by low concentrations of ^{232}Th and high ^{230}Th/^{232}Th values, and (4) a back-calculated initial ^{234}U/^{238}U value in agreement, within analytical uncertainty, with that measured in modern seawater (activity ratio of about 1.141 to 1.155; see Delanghe et al., 2002). In most U-series studies of corals, the usual problem encountered is a calculated initial ^{234}U/^{238}U value that is higher than that measured in modern sea water. Empirical observations from the Bahamas, New Guinea, Australia, Barbados and California (Chen et al., 1991; Stein et al., 1993; Stirling et al., 1995; Edwards et al., 1997; Stirling et al., 1998; Muhs et al., 2012) and modeling studies (Gallup et al., 1994; Thompson et al., 2003; Thompson and Goldstein, 2005) show that higher-than-modern back-calculated initial ^{234}U/^{238}U values tend to bias corals to older apparent ages.

Results

Geomorphology and stratigraphy

The marine terraces on Curaçao are spectacularly exposed, particularly on the windward side of the island, but in places on the southern coast as well (Fig. 4). Along much of the windward coast, but in places on the leeward coast, the Lower Terrace is backed by the outer edge of the Middle Terrace, in turn backed by the Higher Terrace or Highest Terrace, showing a staircase type of marine terrace geomorphology (Fig. 4). Consistent with studies by Herweijer and Focke (1978) and Schellmann et al. (2004), we found that the Lower Terrace is composed of two reef

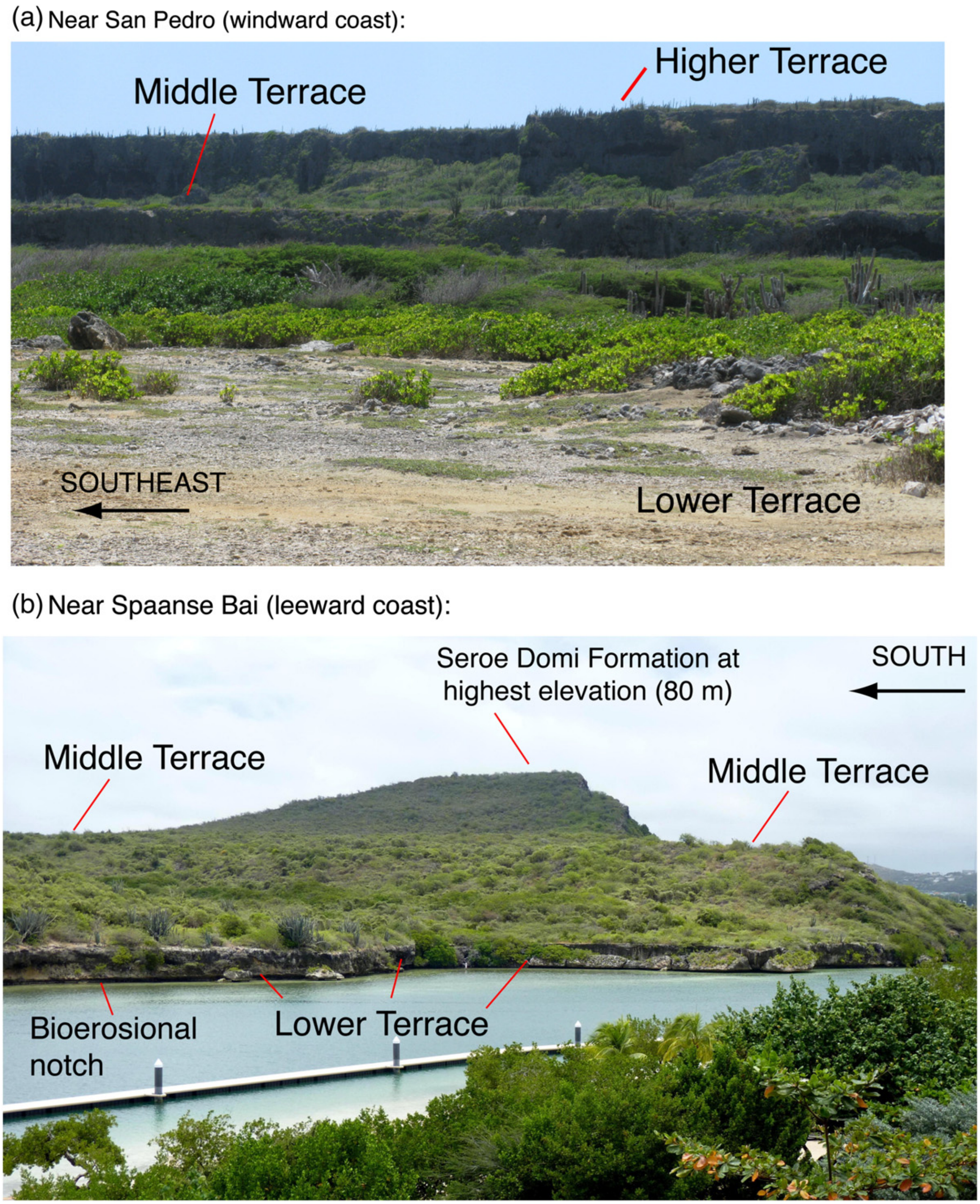

Figure 4. Marine terraces on Curaçao: (a) the Lower, Middle, and Higher terraces in the San Pedro area and (b) the Lower and Middle terraces in the Spaansebai area (see Fig. 3 for locations).

units, Hato (upper) and Cortalein (lower). The contact between these two units is often seen in a topographic break in coastal exposures, where a ledge in the Cortalein unit is apparent (Figs. 5 and 6). Thus, from a geomorphic point of view, the interglacial coral reef record on Curaçao differs from those in other areas, both uplifting coasts and tectonically stable coasts (Fig. 1). Curaçao represents a hybrid of these two types of coasts, with a marine terrace staircase-like geomorphology being present, similar to Barbados and Haiti. Within the Lower Terrace, however, the reef stratigraphic record more closely resembles the stacked limestone sequences found in the Florida Keys and Cayman Islands.

At exposures near the seaward side of the Lower Terrace, we observed that both the Hato and Cortalein units are characterized by an *Acropora palmata*-dominated reef-crest facies, with corals in growth position, similar to that reported by Herweijer and Focke (1978), Pandolfi and Jackson (2001) and Schellmann et al. (2004). Pandolfi et al. (1999), Pandolfi (2001), Pandolfi and Jackson (2001) and Meyer et al. (2003) report that the Hato unit of the Lower Terrace on Curaçao contains 39 species or subspecies of corals. The barrier reef (or reef crest) facies on the windward side of the island is dominated by growth-position *Acropora palmata* but also has lesser numbers of *Montastraea nancyi* (organ-pipe form: see Pandolfi (2007)), *M. annularis*

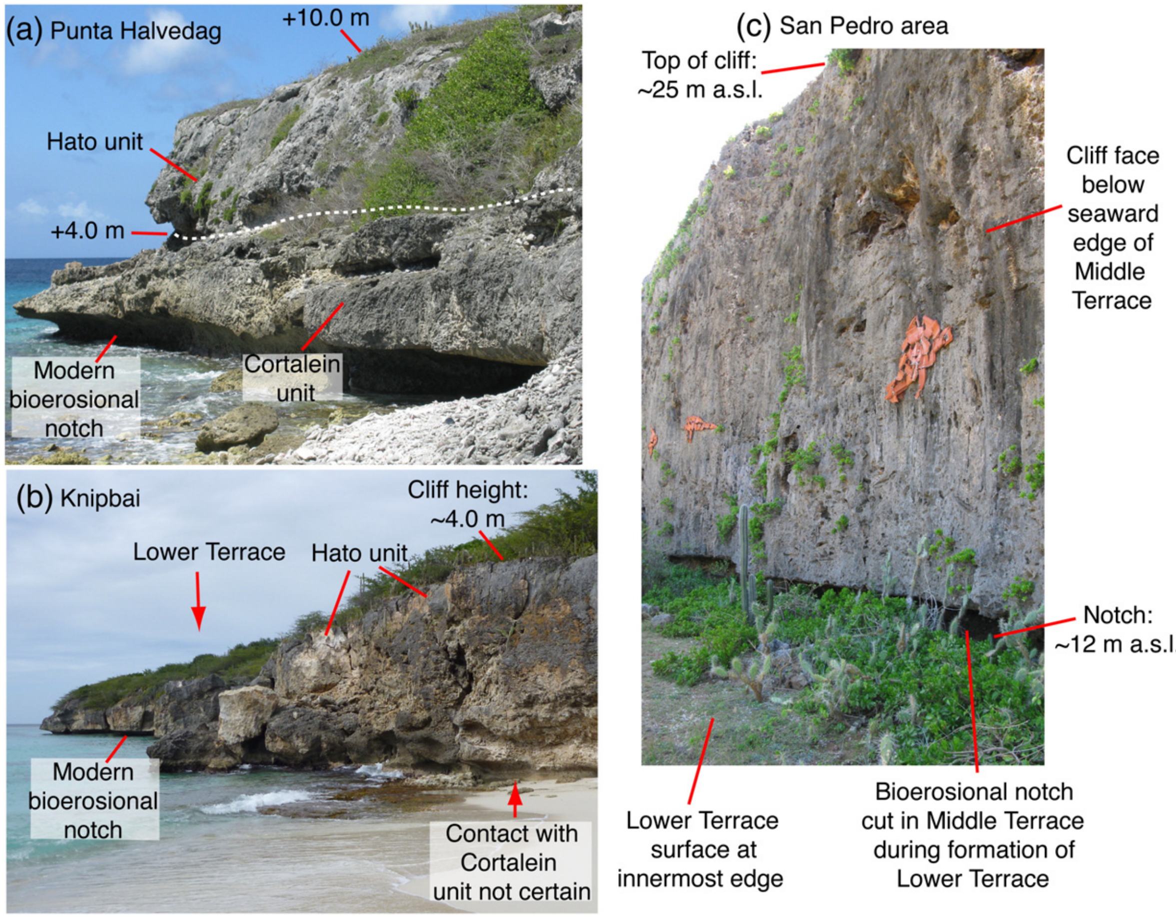

Figure 5. Modern bioerosional notches and stratigraphy of the Lower Terrace exposed at (a) Punta Halvedag and (b) Knipbai. Also shown is a fossil bioerosional notch cut in the cliff of the Middle Terrace, near San Pedro (c).

(sensu stricto), *Diploria strigosa*, *D. clivosa*, and *Pocillopora palmata*. The back-reef or lagoonal facies on the windward side of the island has many more colonies (~50%) of *Montastraea nancyi*, with lesser numbers of *M. annularis*, *M. faveolata*, *Acropora palmata*, *Diploria strigosa*, *D. clivosa*, and *Siderastrea siderea*. The lower, Cortalein unit can be traced without interruption from exposures near the seaward side of the terrace almost the entire shore-normal extent of the terrace. At Boca Cortalein, the most landward part of the Cortalein unit rests on Cretaceous basalt or diabase (Fig. 6b). Here, and in all other exposures we examined, the younger Hato unit extends farther landward, by several tens of meters, than the Cortalein unit. At Boca Cortalein and Boca Mansaliña, the landward part of the Hato unit is thin reef limestone resting on Cretaceous basalt at elevations of +12.4 m and +11.0 m, respectively. On the seaward side, the *Acropora palmata*-dominated reef-crest facies of the Hato units at Boca Cortalein and Boca Mansaliña have elevations of +7.6 m and +6.8 m, respectively (Fig. 6). With a present inner edge at +12.4 m at Boca Cortalein, the reef-crest facies at +7.6 m implies a water depth of about 4–5 m for the *Acropora palmata* corals, in good agreement with modern habitat depths for this species.

Farther southeast, near San Pedro, the Lower Terrace is backed on its landward side by the Middle Terrace. A bioerosional notch, cut into the Middle Terrace, marks the innermost part of the Lower Terrace (Fig. 4b). The elevation of this notch ranges from ~11 m to ~13 m and averages about 12 m (Fig. 7), in agreement with Schellmann et al. (2004). In contrast, the elevation of the outer edge of the Lower Terrace at San Pedro ranges from ~8 m to ~9 m. Thus, in both geomorphic settings (reef lapping onto basalt or reef backed by an older terrace with a bioerosional notch), the most-landward portion of the Lower Terrace has the highest elevation. These two markers (innermost reef on bedrock and bioerosional notch) constitute our points for paleo-sea level elevation measurements.

We conducted only reconnaissance studies of Middle Terrace I on the windward coast of Curaçao, primarily between San Pedro and Boca Santu Pretu (Fig. 3). Cliff exposures of the outer edge of Middle Terrace I between San Pedro and Terra Kora show abundant *Montastraea* and *Diploria*, mostly recrystallized, with rare unaltered specimens. Our GPS measurements show that the outer edge of this terrace decreases in elevation to the southeast, from ~27 m (San Pedro) to ~22 m (Terra Kora) to ~20 m (just east of Boca Santu Pretu). De Buisonjé (1974) did not differentiate Middle Terrace I from Middle Terrace II in the immediate vicinity of San Pedro, although Alexander (1961) did and our observations agree with his. At San Pedro, we measured an inner edge elevation of ~30 m on Middle Terrace I, backed by a cliff forming the outer edge of Middle Terrace II, at an elevation of ~35 m (Fig. 7a).

Uranium-series ages

We collected corals from nine localities on the Lower Terrace of Curaçao (Fig. 3). At four of the localities (Boca Cortalein, Boca Mansaliña, Boca Santu Pretu, and Punta Halvedag), both the younger Hato unit and the older Cortalein unit are exposed, and corals were collected from both units. At Westpuntbai, the contact between the two units is not as apparent as elsewhere, but we collected samples that we hypothesize could be from both units. The Cortalein unit may be exposed at Knipbai as well, but because of uncertainties in identifying a contact here (Fig. 5b), we collected only a coral from the upper part of the section, within what is likely the Hato unit. Near Boca Labadero, we found a sinkhole in what we presume to be the Cortalein unit of the Lower Terrace. A

Table 1
Samples, localities, stratigraphic units, species, aragonite contents, U and Th contents, isotopic activity ratios (AR) and ages of corals from Curaçao.

Sample	Locality	Stratigraphic unit and elevation*	Species	Aragonite	U	+/−	^{232}Th	^{234}U/^{238}U	+/−	^{230}Th/^{238}U	+/−	^{230}Th/^{232}Th	^{230}Th/^{238}U	+/−	^{234}U/^{238}U	+/−
				(%)	ppm		ppm	AR		AR	AR	Age (ka)**	initial AR			
New analyses of samples previously studied by Schubert and Szabo (1978)																
Cur-13-d	Kust Van Hato	Hato, ~8 m (?)	*Acropora palmata*	100	3.49	0.11	0.0001	1.1101	0.0017	0.7717	0.0025	85,797	124.9	0.8	1.1567	0.0022
Cur-22-d	Boca Santu Pretu?	Hato, ~7 m (?)	*Diploria* sp.	98	2.37	0.11	0.0004	1.1083	0.0016	0.7461	0.0041	11,969	118.0	1.2	1.1511	0.0021
Cur-32-d	Un Boca	Hato, 7–8 m (?)	*Diploria* sp.	98	2.70	0.11	0.0018	1.1104	0.0017	0.7960	0.0022	3,651	132.3	0.8	1.1604	0.0022
Cur-33-d	Un Boca	Hato, 7–8 m (?)	*Acropora palmata*	>99	3.34	0.12	0.0001	1.1054	0.0019	0.7443	0.0025	62,467	118.1	0.8	1.1471	0.0025
Analyses of newly collected samples in the present study																
Cur-Dat-4	Boca Mansalina	Hato, 6–7 m	*Siderastraea siderea*	100	2.83	0.12	0.0009	1.1086	0.0020	0.7730	0.0015	7,303	125.7	0.7	1.1549	0.0026
Cur-Dat-4 dup	Boca Mansalina	Hato, 6–7 m	*Siderastraea siderea*	100	2.83	0.12	0.0010	1.1073	0.0022	0.7730	0.0021	6,821	126.0	0.8	1.1532	0.0029
Cur-Dat-1	Boca Cortalein	Hato, 7–8 m	*Acropora palmata*	96	2.93	0.11	0.0008	1.1138	0.0030	0.7826	0.0019	8,334	127.3	0.9	1.1630	0.0040
Cur-Dat-1-A	Boca Cortalein	Hato, 7–8 m	*Acropora palmata*	>99	2.97	0.10	0.0010	1.1136	0.0017	0.7824	0.0037	7,107	127.3	1.2	1.1629	0.0023
Cur-Dat-5	Knipbai	Hato, 2–4 m	*Acropora palmata*	>99	4.69	0.12	0.0032	1.1431	0.0017	0.7920	0.0015	3,519	123.3	0.6	1.2028	0.0022
Cur-Dat-5-P	Knipbai	Hato, 2–4 m	*Acropora palmata*	>99	4.57	0.12	0.0015	1.1480	0.0015	0.8064	0.0020	7,411	126.2	0.7	1.2115	0.0020
Cur-Dat-10	Boca Santu Pretu	Hato, ~5.5 m	*Acropora palmata*	98	3.38	0.11	0.0010	1.1514	0.0022	0.9657	0.0027	9,667	182.4	1.6	1.2536	0.0031
Cur-Dat-10 dup	Boca Santu Pretu	Hato, ~5.5 m	*Acropora palmata*	98	3.38	0.12	0.0011	1.1499	0.0017	0.9624	0.0022	9,332	181.5	1.3	1.2503	0.0024
Cur-Dat-12	Boca Santu Pretu	Hato, ~4.5 m	*Acropora palmata*	>99	3.57	0.13	0.0011	1.1454	0.0017	0.8640	0.0028	8,532	144.7	1.1	1.2188	0.0023
Cur-Dat-13	Boca Santu Pretu	Hato, ~4.5 m	*Acropora palmata*	98	3.15	0.11	0.0012	1.1255	0.0019	0.9466	0.0022	7,577	185.6	1.4	1.2121	0.0027
Cur-Dat-16	Punta Halvedag	Hato, 4.5–5.5 m	*Acropora palmata*	98	3.64	0.12	0.0021	1.1200	0.0020	0.7766	0.0020	4,137	124.1	0.7	1.1704	0.0027
Cur-Dat-17	Punta Halvedag	Hato, ~6 m	*Porites astreoides*	100	3.03	0.10	0.0024	1.1110	0.0014	0.7857	0.0018	2,972	128.9	0.7	1.1598	0.0019
Cur-Dat-17-A	Punta Halvedag	Hato, ~6 m	*Porites astreoides*	100	3.04	0.11	0.0086	1.1133	0.0010	0.8008	0.0019	861	133.0	0.6	1.1650	0.0014
Cur-Dat-17-A dup	Punta Halvedag	Hato, ~6 m	*Porites astreoides*	100	3.04	0.13	0.0026	1.1187	0.0031	0.7976	0.0021	2,873	130.7	1.0	1.1717	0.0042
Cur-Dat-9	Boca Labadero	In sinkhole, 2.5 m	*Acropora palmata*	100	3.20	0.11	0.0008	1.1193	0.0013	0.7946	0.0016	9,974	129.6	0.6	1.1721	0.0018
Cur-Dat-3	Boca Mansalina	Cortalein, ~4 m	*Acropora palmata*	100	3.05	0.11	0.0006	1.1019	0.0020	0.9723	0.0022	16,013	213.9	2.0	1.1865	0.0030
Cur-Dat-3 dup	Boca Mansalina	Cortalein, ~4 m	*Acropora palmata*	100	3.05	0.11	0.0031	1.1032	0.0021	0.9740	0.0025	2,911	214.1	2.2	1.1890	0.0032
Cur-Dat-2	Boca Cortalein	Cortalein, ~4 m	*Acropora palmata*	>99	3.08	0.12	0.0008	1.0999	0.0018	1.0448	0.0025	11,787	277.2	3.7	1.2187	0.0029
Cur-Dat-2-A	Boca Cortalein	Cortalein, ~4 m	*Acropora palmata*	98	3.01	0.11	0.0008	1.1088	0.0022	1.0633	0.0024	11,541	286.3	4.4	1.2443	0.0034
Cur-Dat-2-P	Boca Cortalein	Cortalein, ~4 m	*Acropora palmata*	>99	2.96	0.24	0.0018	1.1097	0.0087	1.0887	0.0041	5,348	319.8	18.7	1.2708	0.0095
Cur-Dat-8	Westpuntbai	Cortalein(?), ~4 m	*Acropora palmata*	96	3.56	0.12	0.0021	1.1808	0.0017	1.0147	0.0021	5,156	191.5	1.3	1.3106	0.0023
Cur-Dat-8-P	Westpuntbai	Cortalein(?), ~4 m	*Acropora palmata*	96	3.52	0.11	0.0032	1.1844	0.0013	1.0154	0.0023	3,431	190.1	1.2	1.3155	0.0019
Cur-Dat-11	Boca Santu Pretu	Cortalein, ~2.25 m	*Acropora palmata*	98	3.68	0.12	0.0007	1.2007	0.0023	1.0400	0.0020	16,577	193.8	1.5	1.3471	0.0030
Cur-Dat-14	Punta Halvedag	Cortalein, ~3 m	*Acropora palmata*	100	3.88	0.11	0.0017	1.2035	0.0022	1.1556	0.0036	8,221	264.8	3.8	1.4302	0.0042
Cur-Dat-14 dup	Punta Halvedag	Cortalein, ~3 m	*Acropora palmata*	100	3.87	0.12	0.0016	1.2043	0.0020	1.1488	0.0035	8,423	258.4	3.4	1.4241	0.0039

* Elevations of samples themselves. Elevations for samples of Schubert and Szabo (1978) are estimated from spot elevations on 1:25,000-scale topographic maps.
** Calculated using a half-life of 75,690 yr for ^{230}Th and a half-life of 245,250 yr for ^{234}U (Cheng et al., 2000).

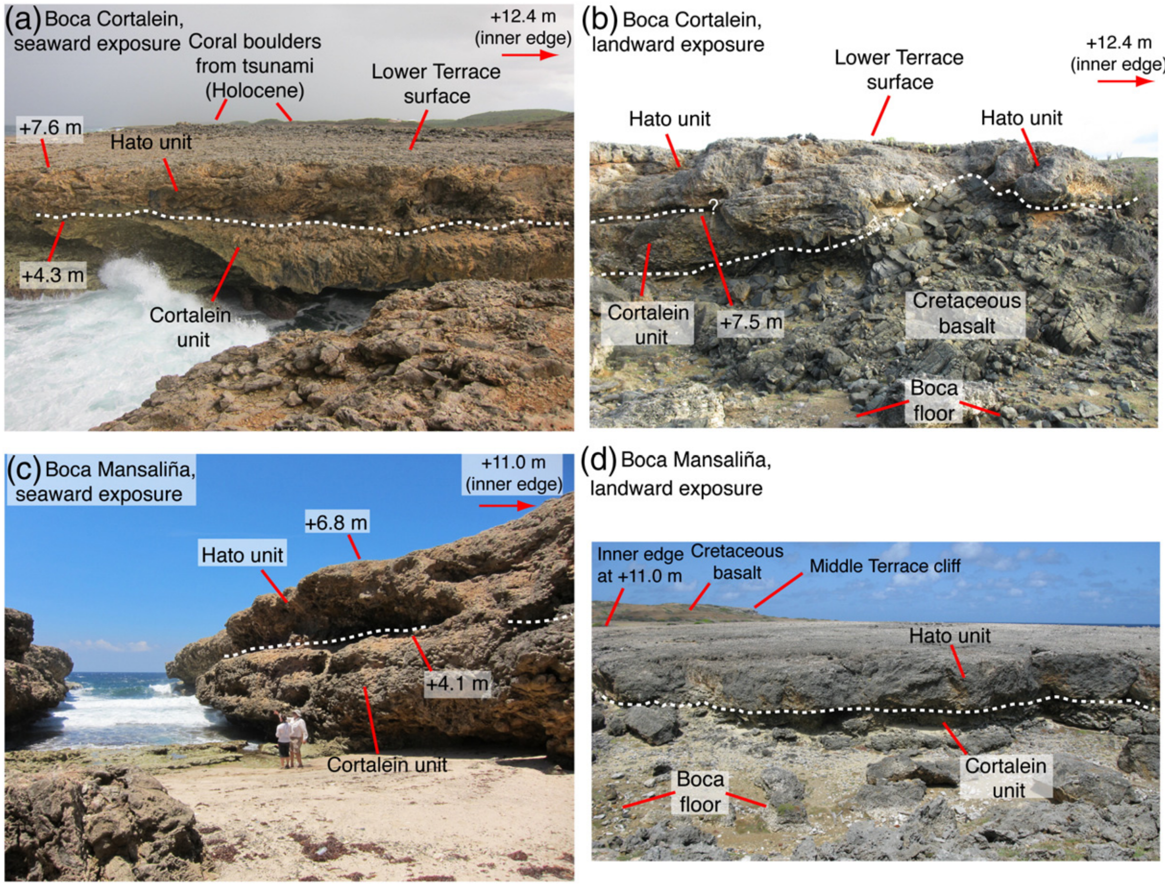

Figure 6. Exposures of the Hato and Cortalein units (contact shown as a dashed white line) of the Lower Terrace at Boca Cortalein [(a) and (b)] and Boca Mansaliña [(c) and (d)]. Also shown are measured elevations. Holocene tsunami deposits shown were dated by Radtke et al. (2003).

detrital specimen of *Acropora palmata* was collected from this sinkhole, although it was not apparent in the field if the coral was derived from the Hato unit or Cortalein unit.

With the exception of two localities, all corals we sampled from the Hato unit of the Lower Terrace are *Acropora palmata*, in growth position. At Boca Mansaliña and Punta Halvedag, the corals sampled from the Hato unit are *Siderastrea siderea* and *Porites astreoides*, respectively. In addition to corals we collected, we re-analyzed four of the corals studied by Schubert and Szabo (1978) that were archived at the U.S. Geological Survey by B.J. Szabo (Table 1). Using the sample nomenclature of Schubert and Szabo (1978), these included CUR-13, an *Acropora palmata* from the Kust Van Hato/Terra Kora area, CUR-22, a *Diploria* from Boca Santoe Pretoe, and CUR-32 and CUR-33, both from Un Boca (Fig. 3). CUR-32 is a specimen of *Diploria*; Schubert and Szabo (1978) report CUR-33 as *Montastraea*, but we identify it as *Acropora palmata*. All of Schubert and Szabo's (1978) samples were collected from specimens in growth position.

Our U-series results from Curaçao confirm previous results that the Hato unit of the Lower Terrace records the last interglacial period or MIS 5.5 (Table 1 and Fig. 8). Samples of *Acropora palmata* from Kust Van Hato and Un Boca, *Diploria* from Boca Santu Pretu and *Siderastrea siderea* from Boca Mansaliña meet all our criteria for closed-system histories with respect to U-series isotopes. These corals have ages ranging from 126.0 ± 0.9 ka to 118.0 ± 1.2 ka. Three other samples, *Diploria* (Un Boca), *Acropora palmata* (Boca Cortalein) and *Porites astreoides* (Punta Halvedag), have no evidence of U loss or gain or indications of inherited ^{230}Th, but have initial $^{234}U/^{238}U$ values slightly higher than the range for modern seawater. These corals likely have ages that are biased old by ~2.5–3.5 ka, following the criteria of Gallup et al. (1994). If so, these slightly biased corals may have true ages of ~129–124 ka. All other corals from the Hato unit of the Lower Terrace have initial $^{234}U/^{238}U$ values of 1.17–1.25, indicating potential bias to older apparent ages by ~5 ka to ~26 ka. Corals falling into this category plot well above a theoretical isotopic evolution pathway on a $^{230}Th/^{238}U$ vs. $^{234}U/^{238}U$ graph (Fig. 9). In addition, the *Acropora palmata* specimen from Knipbai shows evidence of U gain, which would tend to bias the sample to a younger apparent age.

Results of U-series analyses of corals from the older Cortalein unit of the Lower Terrace support a previous hypothesis (Herweijer and Focke, 1978) and ESR age estimates (Schellmann et al., 2004) for a penultimate interglacial age (MIS 7). All samples we collected from the Cortalein unit are *Acropora palmata* and none shows evidence of U gain or loss or inherited ^{230}Th. Unfortunately, all show calculated initial $^{234}U/^{238}U$ values of 1.18–1.43, indicating probable bias to older ages (Table 1 and Fig. 9). The least biased sample is Cur-Dat-3 from Boca Mansaliña, where the true age of the coral is likely ~205 ka. The most biased sample is Cur-Dat-14 from Punta Halvedag, but the true age of this coral is likely ~195–190 ka, in broad agreement with the age of Cur-Dat-3 from Boca Mansaliña. Corals from both these localities plot close to a trend line (shown as a thin dashed line in Fig. 9), derived from studies of corals on Barbados (Gallup et al., 1994), that extrapolate to a closed-system age of ~200 ka. *Acropora palmata* specimens analyzed from the Cortalein unit at Boca Cortalein have ages that also are probably biased old, based on their initial $^{234}U/^{238}U$ values, but when corrected using the Gallup et al. (1994) model, indicate significantly older possible ages of ~260 ka. In theory, then, the coral from this locality could correlate with an earlier high sea stand of MIS 7. Nevertheless, Boca Cortalein is only ~800 m to the southeast of Boca Mansaliña. Our examination of the exposures in both bocas does not indicate any significant difference in the stratigraphy, facies, or fauna that would imply an older age for the Cortalein unit in Boca Cortalein. The simplest explanation

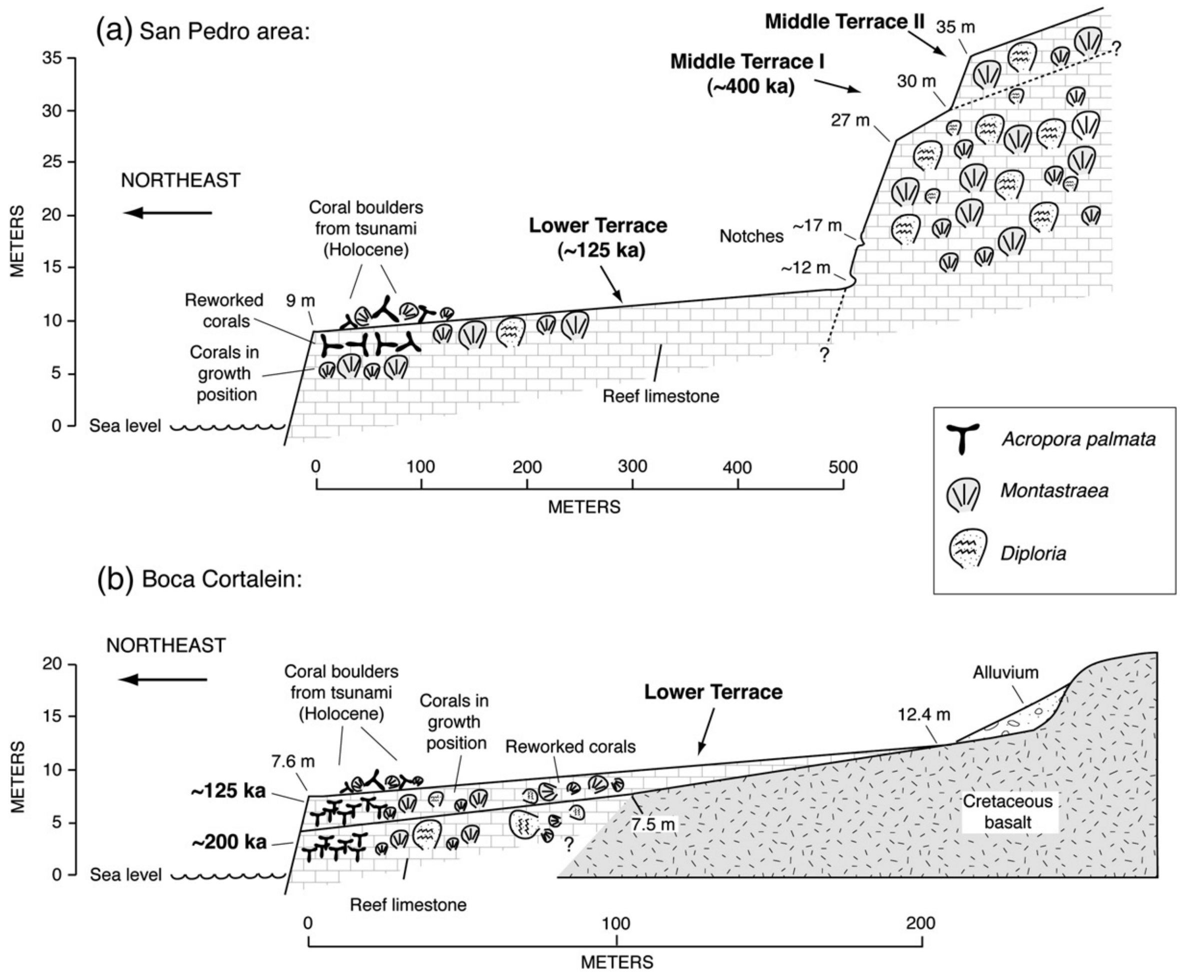

Figure 7. Cross sections showing terrace geomorphology, stratigraphy and measured elevations at San Pedro (a) and Boca Cortalein (b).

is that the corals in the Cortalein unit at Boca Cortalein have experienced a more complex open-system history with respect to U and Th isotopes compared to other corals from this unit. Thus, we interpret the coral from the Cortalein unit at Boca Cortalein to be about the same age as that from nearby Boca Mansaliña, with a more open-system history. On the other hand, specimens from the hypothesized Cortalein unit at Westpuntbai (Cur-Dat-8) and Boca Santu Pretu (Cur-Dat-11), when corrected, show possible ages of ~150 ka and ~144 ka, significantly younger than all other corals analyzed from the Cortalein unit, but much older than all corals from the Hato unit. We are uncertain how to interpret these younger apparent ages.

Uplift rate and estimated sea-level history during MIS 7

It is possible to calculate a late Quaternary uplift rate for the island of Curaçao using the age and elevation of the Hato unit of the Lower Terrace, with a correction for paleo-sea level at the time of terrace formation. Kopp et al. (2009) conducted a global assessment of last interglacial sea level, accounting for glacial isostatic adjustment effects. They suggest that there was a 95% probability that last interglacial sea level was at least 6.6 m higher than present and a 67% probability that it was higher than 8.0 m, but thought it was unlikely to have exceeded 9.4 m. We use values of +6 m and +9 m to bracket the range of probable last interglacial paleo-sea levels based on this study. Our U-series data indicate that the last interglacial high stand on Curaçao could have lasted from ~129 ka to ~118 ka, so we use this range of ages. Finally, we use the highest inner edge elevation (+12.4 m) of the Hato reef at Boca Cortalein to calculate a range of possible uplift rates using the paleo-sea level and age ranges. Results indicate late Quaternary uplift rates ranging from 0.026 to 0.054 m/ka (Table 2). For the ~200 ka Cortalein unit, we use the innermost reef elevation (+7.5 m) found in Boca Cortalein. This elevation, along with an assumption of a constant uplift rate back to ~200 ka, yields a range of possible paleo-sea levels on Curaçao during late MIS 7 from −3.3 m to +2.3 m, relative to present.

Uplift rate and estimated paleo-sea level during MIS 11

Using the same late Quaternary uplift rate, we also estimate paleo-sea level at the time of formation of Middle Terrace I (Fig. 7), but this requires careful interpretation of existing data. Lundberg and McFarlane (2002), McFarlane and Lundberg (2002) and Schellmann et al. (2004) suggest that Middle Terrace I could represent a high sea stand during MIS 11 at ~400 ka. De Buisonjé (1974) infers that deposits of Middle Terrace I underlie deposits of Middle Terrace II. Above Middle Terrace II, there is a notch cut in the cliff face of the outer edge of the Higher Terrace that Lundberg and McFarlane (2002) and McFarlane and Lundberg (2002) infer to have formed during MIS 11. Because the notch is undated, it could be older than MIS 11, as pointed out by Bowen (2010). There is no direct evidence that Middle Terrace II is of MIS 11 age either, although Lundberg and McFarlane (2002) and McFarlane and Lundberg (2002) infer that it dates to this time period. We take a conservative view that the maximum elevation recorded by a high stand in MIS 11 at ~400 ka is the highest elevation (~30 m) of the inner edge of Middle Terrace I that we measured at San Pedro (Fig. 7a). For San Pedro, we use the same late Quaternary uplift rate that we calculated

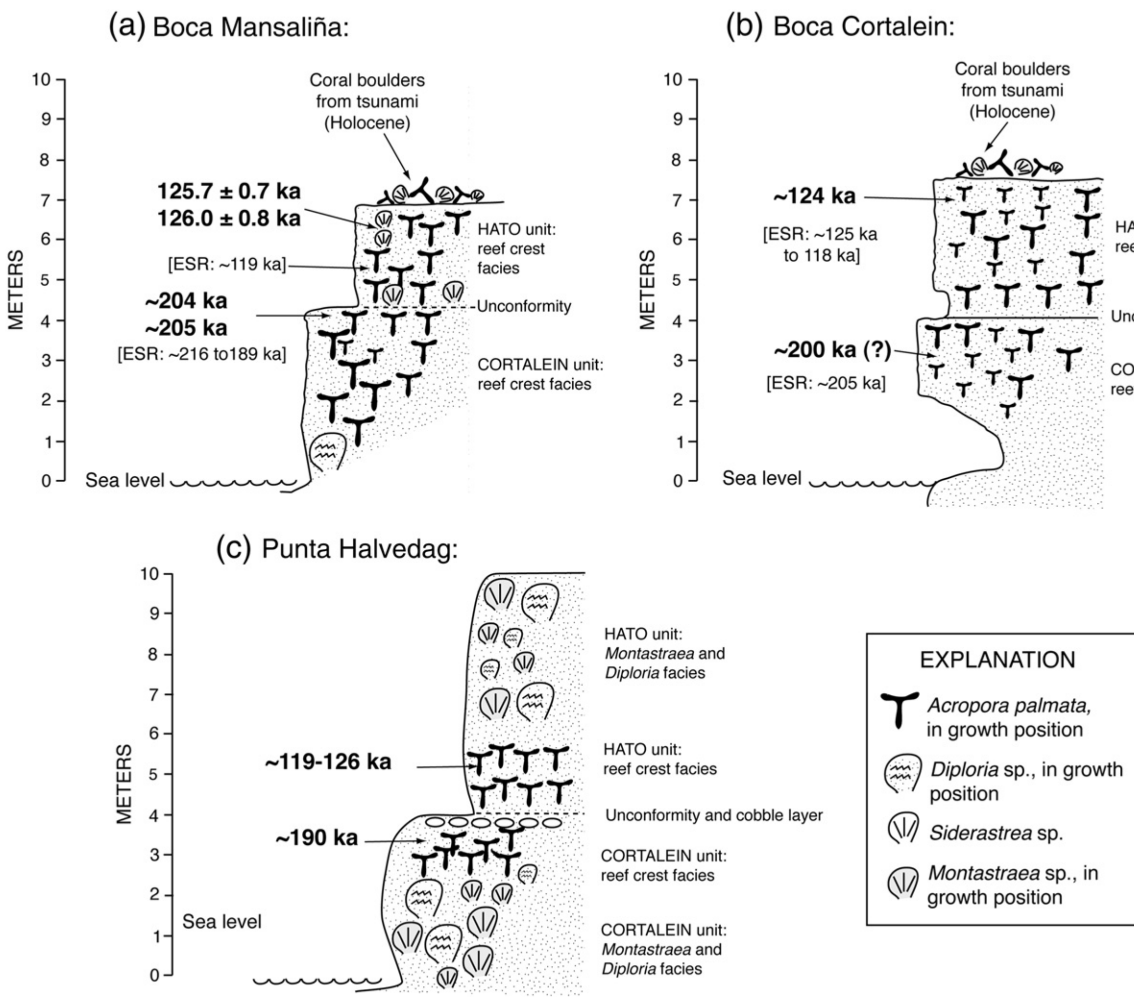

Figure 8. Stratigraphy of cliff exposures of Hato and Cortalein units at Boca Mansaliña, Boca Cortalein and Punta Halvedag showing dominant coral taxa, U-series ages in bold type (this study), and ESR ages (from Schellmann et al. (2004)). Stratigraphy of sections at Boca Mansaliña and Boca Cortalein are from this study, but are similar to those figured in Schellmann et al. (2004).

for the Boca Cortalein/Boca Mansaliña area. Our GPS elevations of the notch at the inner edge of the Lower Terrace at San Pedro were hindered by poor satellite geometry because of the high (~27 m) cliff of the outer edge of Middle Terrace I. Nevertheless, we measured notch elevations here of 11.1–13.1 m, which bracket the inner edge elevation of 12.4 m at Boca Cortalein. Thus, we use the same uplift rate for San Pedro as we use for Boca Cortalein (Table 2). Results indicate that with a conservative estimate of last interglacial paleo-sea level (+6 m), MIS 11 sea level on Curaçao could have been +8.4 to +10 m, relative to present. Using a higher last interglacial sea level of +9 m yields much higher MIS 11 sea level estimates, from +17.4 m to +19.6 m (Table 2).

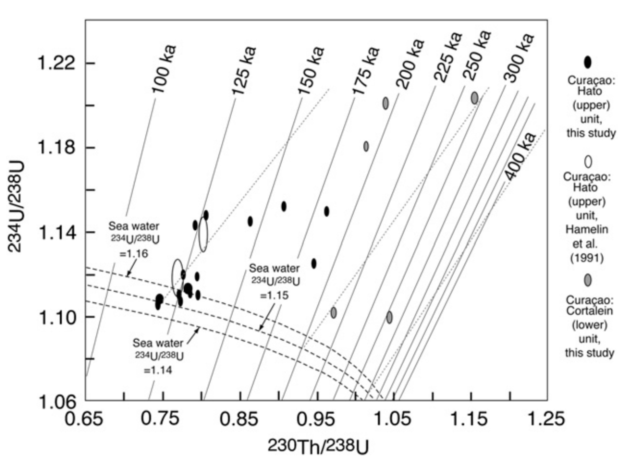

Figure 9. Isotopic evolution diagram (drawn using software in Ludwig, 2001) of corals from the Hato and Cortalein units of the Lower Terrace from this study (solid black and gray ellipses) and two samples from Hamelin et al. (1991) (open ellipses). Ellipses define 2-sigma uncertainties in isotope ratios. Bold dashed lines define hypothetical isotopic evolution pathways for corals with initial $^{234}U/^{238}U$ values of 1.14, 1.15, and 1.16. Dashed gray lines show open-system trends for corals on Barbados (from Gallup et al., 1994).

Discussion

The last interglacial period (MIS 5.5)

Corals showing mostly closed-system histories from the Hato unit of the Lower Terrace have U-series ages ranging from ~126 ka (Boca Mansaliña, Boca Cortalein, Punta Halvedag) to ~118 ka (Un Boca and Boca Santu Pretu). If the corrected age of ~129 ka at Un Boca is accepted, then the high stand could have started even earlier. These ages indicate that the last interglacial period on Curaçao had a duration of at least 8,000 yr, and possibly ~11,000 yr, similar to what has been reported for tectonically stable coasts elsewhere (Chen et al., 1991; Stirling et al., 1995, 1998; Muhs et al., 2002, 2011). The Curaçao fossil reefs are dominated by the rapidly growing *Acropora palmata*, and thus may be examples of "keep-up" reefs that respond quickly to a rising sea level (Neumann and MacIntyre, 1985). Sea level was

Table 2
Late Quaternary uplift rates and paleo-sea level estimates for older deposits on Curaçao.

Locality	Assumed age of last interglacial reef (ka)	Paleo-sea level estimate for last interglacial reef (m) (Kopp et al., 2009)	Present elevation of inner edge of last interglacial reef (m)	Uplift rate (m/ka)	Older reef name	Assumed age of older reef (ka)	Present elevation of inner edge of older reef (m)	Amount of uplift (m)	Paleo-sea level, relative to present (m)
Boca Cortalein	118	6	12.4	0.054	Cortalein unit	200	7.5	10.8	−3.3
Boca Cortalein	129	6	12.4	0.05	Cortalein unit	200	7.5	10	−2.5
Boca Cortalein	118	9	12.4	0.029	Cortalein unit	200	7.5	5.8	1.7
Boca Cortalein	129	9	12.4	0.026	Cortalein unit	200	7.5	5.2	2.3
San Pedro	118	6	12.4	0.054	Middle Terrace I	400	30	21.6	8.4
San Pedro	129	6	12.4	0.05	Middle Terrace I	400	30	20	10
San Pedro	118	9	12.4	0.029	Middle Terrace I	400	30	11.6	17.4
San Pedro	129	9	12.4	0.026	Middle Terrace I	400	30	10.4	19.6

probably already high, at or above modern sea level, by ~129–126 ka, when summer insolation at high latitudes in the Northern Hemisphere was peaking (Berger and Loutre, 1991). This contrasts with the present interglacial, wherein the peak of sea level lagged the Northern Hemisphere summer insolation high by several thousand years.

The penultimate interglacial period (MIS 7)

The penultimate interglacial period, MIS 7, was a complex consisting of three high-sea stands, based on the Red Sea oxygen isotope record (Fig. 10). In the Mediterranean region, speleothem records also show evidence of three relatively high sea stands, with the oldest (about 249–231 ka) and youngest (about 201–190 ka) stands being higher than the intermediate-aged (about 217–206 ka) stand (Dutton et al., 2009), consistent with the Red Sea record. At least three MIS 7 terraces may be present on Barbados (Bender et al., 1979; Schellmann and Radtke, 2004). The youngest of these (~200 ka) is estimated to have been a high stand above present (Gallup et al., 1994, 2002; Schellmann and Radtke, 2004). On tectonically stable Bermuda, the Florida Keys, and Grand Cayman Island, an MIS 7 sea level dated to ~200 ka is estimated to be near present (Harmon et al., 1983; Vénzina et al., 1999; Muhs et al., 2002, 2011). Chappell (1974) estimated paleo-sea levels for emergent MIS 7 reefs very close to present on the rapidly rising coast of New Guinea. In contrast, on the very slowly uplifting island of Oahu, Hawaii and on the slowly subsiding island of Mururoa in the South Pacific, MIS 7 sea levels are estimated to be well below present (Sherman et al., 1999; Camoin et al., 2001; Fletcher et al., 2008).

Some of the differences in estimates of MIS 7 sea levels could be due to glacial isostatic adjustment (GIA) processes (Nakada and Lambeck, 1989; Mitrovica and Peltier, 1991; Milne and Mitrovica, 2008; Raymo and Mitrovica, 2012). Potter and Lambeck (2003) and Lambeck et al. (2012) show that because of the proximity of Bermuda to the Laurentide ice sheet (Fig. 2), GIA processes have likely affected this island's sea-level record, at least during the last interglacial complex. In contrast, Curaçao, like Barbados, is distant from the Laurentide ice sheets of the past two glacial periods (Fig. 1) and thus can be considered a far field location with respect to GIA effects. If so, apparent paleo-sea levels on Curaçao may be close to those of eustatic sea levels. Nevertheless, our estimates of sea level close to present for Curaçao are similar to those estimated for Bermuda, which should have been affected by GIA processes.

The high stand at ~400 ka (MIS 11)

Studies of the magnitude of the MIS 11 high sea stand at ~400 ka have generated highly divergent estimates, from ~22 m above present (Hearty et al., 1999; Lundberg and McFarlane, 2002) to a high sea stand near present (Bowen, 2010). The high MIS 11 sea level proposed by Hearty et al. (1999) is based on data from both Bermuda and the Bahamas, and there have been challenges to this interpretation of the record for both islands (McMurtry et al., 2007; Mylroie, 2008). As discussed above, GIA effects could have had a strong imprint on the sea-level record for Bermuda. Recent modeling by Raymo and Mitrovica (2012) indicate that at least 10 m of the alleged MIS 11 high stand on Bermuda can be accounted for by GIA effects. These workers estimate the eustatic component of sea level rise during MIS 11 to be on the order of +6 m to +13 m. Our most conservative estimates of the MIS 11 high stand on Curaçao indicate it could have been as high as +10 m or as low as +8.4 m, in broad agreement with Raymo and Mitrovica (2012) These conservative estimates are still higher than those from the Red Sea oxygen isotope record (Fig. 10). Even with the most cautious approach, our paleo-sea level estimate for MIS 11 at ~400 ka would still imply a very warm interglacial, requiring loss of most or all of the present Greenland and West Antarctic ice sheets (see discussion in Muhs et al., 2011). We stress, however, that better geochronology is needed for Middle Terrace I before firm conclusions can be drawn about sea-level history during this period.

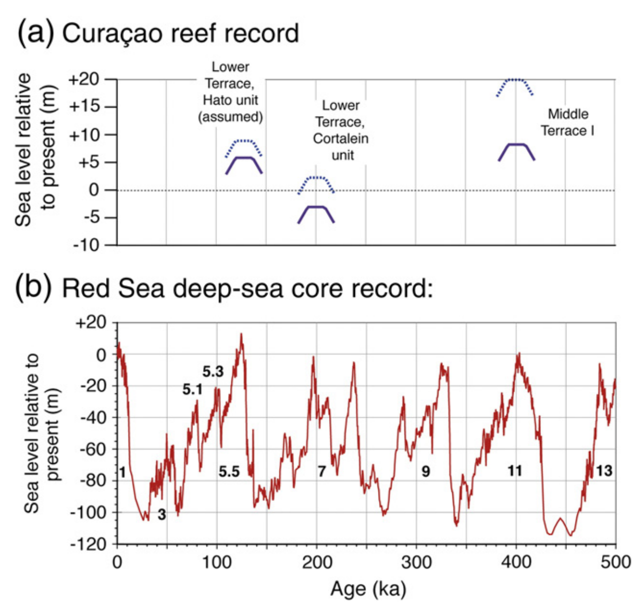

Figure 10. (a) Paleo-sea level estimates for marine deposits on Curaçao at ~129-118 ka (assumed, from estimates of Kopp et al. (2009)), ~200 ka, and ~400 ka. Solid lines indicate lower estimates based on late Quaternary uplift rates using +6 m for a paleo-sea level at ~129-118 ka; dashed lines indicate upper estimates based on late Quaternary uplift rates using +9 m for a paleo-sea level at ~129-118 ka. Shown for comparison in (b) is the Red Sea record of sea-level fluctuations for the past 500 ka, taken from data in Rohling et al. (2009, 2010).

Conclusions

(1) We confirm the last interglacial (MIS 5.5) age of the Hato unit of the Lower Terrace on Curaçao. The last interglacial period on Curaçao had a duration of at least 8000 yr (~126 ka to ~118 ka) or possibly 11,000 yr (~129 ka to ~118 ka). A relatively early record of high sea level on Curaçao confirms earlier studies that indicate *Acropora palmata*-dominated reefs respond quickly to sea-level rise as interglacial periods begin. Also, this early age indicates that the last interglacial period differed from the Holocene, with an MIS 5.5 sea level near present coinciding with, or even preceding the time of maximum summer insolation in the Northern Hemisphere.

(2) Elevations and age of the Lower Terrace indicate that late Quaternary uplift rates on Curaçao are low, on the order of 0.026–0.054 m/ka. Low uplift rates are consistent with the recently studied structural and tectonic setting of the island.

(3) Because of the low uplift rate, Curaçao's terrace geomorphology is a hybrid of that of uplifting coasts ("staircase" geomorphology) and stable coasts (stacked reef limestones with little relief).

(4) Uranium-series ages indicate that the Cortalein unit of the Lower Terrace represents the youngest high-sea stand of the penultimate interglacial period, or MIS 7. Although all corals from this unit show open-system histories, two localities have corrected, open-system age estimates of ~200 ka, in agreement with other coastal records.

(5) Paleo-sea level estimates for the Cortalein unit of the Lower Terrace range from as high as +2.3 m to as low as −3.3 m, depending on which assumptions about MIS 5.5 age, sea level and uplift rate are made. Despite this range, the estimates are in broad agreement with those for MIS 7 from other localities and indicate that the penultimate interglacial period was a major period of warmth, on a par with the present interglacial period.

(6) Using the late Quaternary uplift rate derived here and age and elevation data for the Middle Terrace I on Curaçao, we estimate paleo-sea levels during MIS 11 at ~400 ka to have been somewhere between 8.4–10.0 m and 17–20 m above present. These estimates are lower than some reported by other workers. Nevertheless, even our most conservative estimates imply loss of most or all of the West Antarctic and Greenland ice sheets during what must have been a very warm interglacial.

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