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Discovery of a composite reefal terrace of middle and late Pleistocene age in Great Inagua Island, Bahamas. Implications for regional tectonics and sea-level history

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Abstract

We provide here new ^{234}U/^{230}Th ages measured on coral samples collected from a reefal terrace exposed on Great Inagua Island (Bahamas) that was, up to now, wholly attributed to the last interglacial period (Marine Isotope Stage 5e). Our results from the upper part of the terrace confirm the previously reported MIS 5e age, whereas ages obtained from the lower part range between 139,000 and 193,000 years BP, spanning most of MIS 6. Petrographic examination showed that secondary aragonite cement and internal sediment occur in the coral chambers of these samples, indicating they were rejuvenated and likely date from the penultimate interglaciation (MIS 7). The studied terrace is thus a composite build-up and its lower part represents the first coral reef of MIS 7 age ever described in the Bahamas archipelago. Our results further suggest (1) that Great Inagua Island recently underwent a phase of tilting, and (2) that sea level was close present datum during MIS 7.

Keywords: Bahamas; Pleistocene; Coral reef; U-series dating; Tectonics; Sea level

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1. Introduction

The height of the oceans during the penultimate interglacial period (Marine Isotope Stage 7) and the subsidence history of the southeastern Bahamas are controversial topics in Quaternary geology and regional tectonics, respectively. These two themes are interrelated because geological evidence of the former could be found in the latter area. Data from uplifted reefal terraces in Barbados (e.g. Gallup et al., 1994) suggest that MIS 7 sea level was similar to, or even higher than the present one, whereas results from speleothems (Bard et al., 2002) and submerged reefs (Camoin et al., 2001), as well as most deep-sea δ^{18}O records (e.g. Raymo, 1997) indicate that it stood well below modern datum. Many researchers (e.g. Uchupi et al., 1971; White and Curran, 1995) consider the SE Bahamas as a slowly (5 to 10 mm/1000 yr) subsiding area, but other authors (e.g. Mullins et al., 1991) view it as more tectonically active because of its proximity to a tectonic plate boundary. In this

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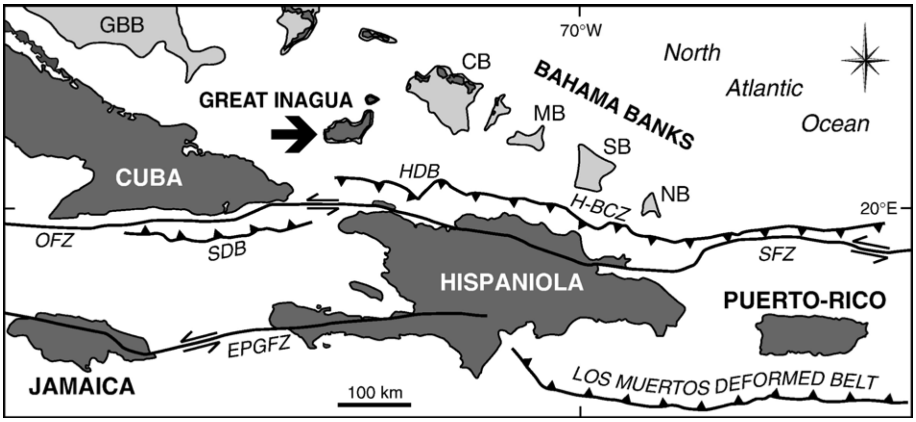

Fig. 1. Geographic and tectonic setting of Great Inagua (after Dolan et al., 1998). The island is located less than 100 km away from the Hispaniola–Bahamas collision zone. GBB = Great Bahama Bank; CB = Caicos Bank; SB = Silver Bank.; MB = Mouchoir Bank, NB = Navidad Bank; OFZ = Oriente fault zone; EPGFZ = Enriquillo–Plantain Garden fault zone; SFZ = Septentrional fault zone; H–BCZ = Hispaniola–Bahamas collision zone; SDB = Santiago deformed belt; HDB = Hispaniola deformed belt.

paper, we present preliminary results from the SW shoreline of Great Inagua Island that address both of these controversial issues.

2. Geological setting

Great Inagua is a relatively large, low-elevation island located in the southeastern Bahamas, less than 100 km away from the oblique convergence zone between the North American and the Caribbean plates (Fig. 1). As mentioned above, the tectonic regime of this area is controversial. Previous geological investigations (White and Curran, 1987; Chen et al., 1991; White and Curran, 1995; White et al., 1998; Wilson et al., 1998) have focused on the SW portion of the island, where an extensive reefal terrace is exposed around Devil's Point (Fig. 2). According to preceding authors, the terrace comprises two units separated by an erosional surface: (1) a coral framework interpreted as a bank-barrier reef, and (2) bioturbated coral rudstones identified as subtidal

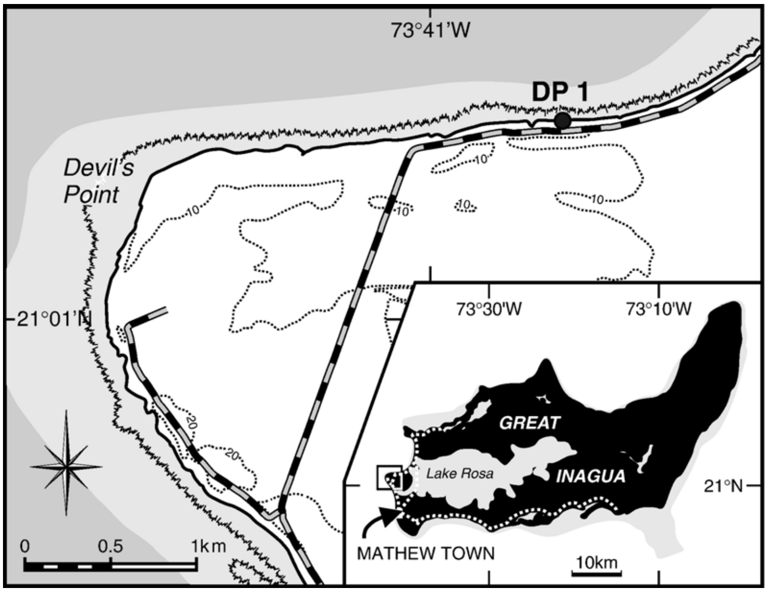

Fig. 2. Location of studied area (inset) and of logged section. Contours (in feet) after the 1:25,000 topographic map of Little and Great Inagua (sheet 11) published by the Lands and Surveys Department of the Bahamas. Corrugated black line represents modern coral reef.

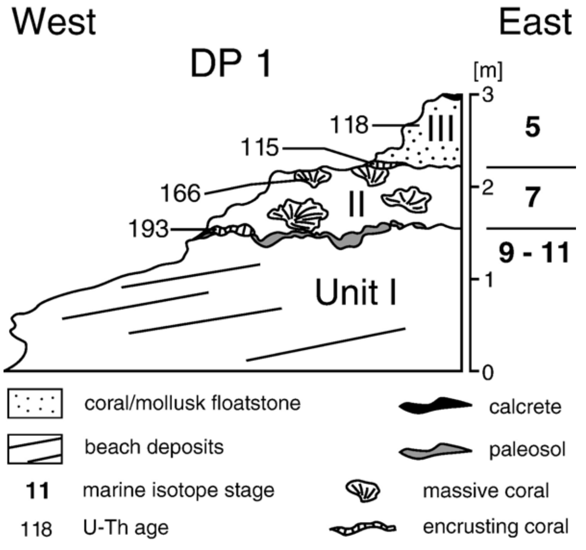

Fig. 3. Stratigraphical and sedimentological section logged at site DP1.

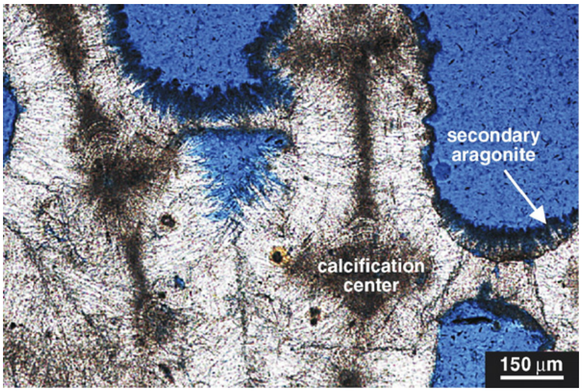

Fig. 5. Thin-section view of sample DP1c1b1 collected near the base of the reef at DP1. Coral (Diploria sp.) skeleton is well preserved, but secondary aragonite cement lines the wall of coral chambers (blue areas = porosity).

deposits. Up to now, this composite build-up was entirely attributed to MIS 5e on the basis of reliable $^{234}U/^{230}Th$ ages (Chen et al., 1991). In the following sections, we report on a previously uninvestigated exposure near Devil's Point.

3. Methods

Detailed sedimentological logging was performed at this new site (DP 1; Fig. 2). Samples were collected for petrographic examination and U-series dating. Ages were measured on selected coral and whole-rock samples using both, the classical α-counting technique (Ku, 1965) and the more recent thermal-ionization mass-spectrometric (TIMS) method (Edwards et al., 1987). A leaching experiment was undertaken on one coral sample (DP1c1b1): the 0.250 to 1 mm fraction of one crushed slab was split into two parts. One part was set aside and the other was further leached in 0.33 N HCl for 1 min to remove all impurities and cement. The three subsamples: bulk, leached fraction, and residue were then separately dated. A spike $^{236}U/^{229}Th$ was added to the residue to control any secondary adsorption of isotopes on the leachate during the leaching step.

Fig. 4. General view of site DP1, looking towards the East. I = beach deposits; II = in-situ coral reef; III = coral/mollusk floatstone (partly dismantled by recent storm activity). White line = karstic surface between Units I and II; black line = marine erosional surface between Units II and III.

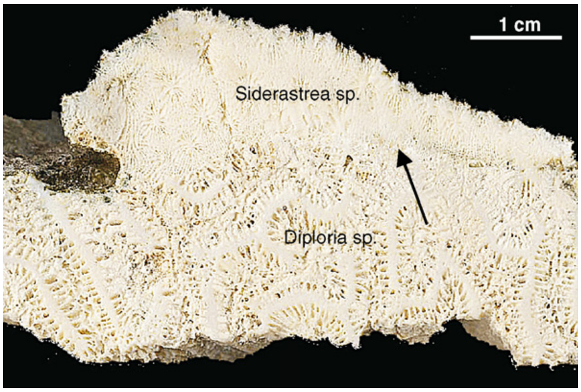

Fig. 6. Sample DP1c8 collected across Units II and III. The lower coral (Diploria sp.) and the upper specimen (Siderastrea sp.) gave α-counting ages of 166 and 115 ka, respectively. Note brownish color of lower coral indicating pedogenic alteration and marine erosional surface (arrow), materialized by truncated septa, separating the two episodes of coral growth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Results

4.1. Stratigraphy, sedimentology and petrography

Located 2.5 km to the E of Devil's Point, site DP 1 exposes three lithologic units (Figs. 3 and 4). The lower one (Unit I) consists of coarse-grained bioclastic calcarenites showing low-angle planar cross-stratification with a seaward dip. Grains are bound by an early generation of isopachous aragonite cement of marine origin. We interpret this unit as a fossil beach. Its upper boundary corresponds to a karst surface and is locally capped by a calcrete and/or a *terra-rossa* paleosol. The second unit (Unit II) is represented by a boundstone predominantly composed of encrusting coral species (*Diploria strigosa*, *D. clivosa*). The chambers of the well-preserved corals are mostly empty, but some of them contain secondary aragonite cement (Fig. 5) and/or marine internal sediment. The unit top is a horizontal surface that likely results from wave abrasion. However, the occurrence of alveolar septal fabric and needle-fiber calcite cement just below this surface suggests that Unit II has been subaerially exposed and pedogenized prior to being eroded by marine processes (Fig. 6). The next unit (Unit III) corresponds to a coral/mollusk floatstone containing large fragments of branching corals (*Acropora palmata, A. cervicornis*) and *Strombus* shells. Small encrusting coral specimens (*Siderastrea* sp.; Fig. 6) are locally anchored on the basal surface of this unit. Tubular burrows (*Ophiomorpha* sp.) are abundant and indicate a shallow subtidal setting. Despite the pervasive pedogenesis affecting Unit III, the internal part of the coral fragments is well preserved. The top of this unit corresponds to the exposed surface and is covered by a calcrete.

Table 1
^{230}Th ages measured on coral samples from the composite reefal terrace in Great Inagua Island

Field #	TS #		Elev.	Calcite	^{238}U	^{230}Th/^{234}U	(^{234}U/^{238}U)	(^{234}U/^{238}U)	^{230}Th age (ka)			^{230}Th/^{232}Th
	INA		(m)	(%)	(ppm)		measured	initial		–	+	
Unit III												
Coral fragments in subtidal deposits												
DP1d2		M	3	1.5	2.637±0.051	0.672±0.02	1.096±0.012	1.133±0.017	118	6	6	*
Encrusting corals												
DP1c8′	30	S	2.2	0.2	3.197±0.075	0.666±0.01	1.15±0.02	1.206±0.028	115	4	4	*
Unit II												
DP1c8	30	D	2.2	<2	2.878±0.053	0.799±0.008	1.106±0.014	1.170±0.023	166	5	5	*
DP1c2b		D	2	0.6	3.407±0.042	0.778±0.014	1.1±0.014	1.155±0.022	157	6	6	*
DP1c2a		D	2	0.8	3.777±0.034	0.738±0.009	1.107±0.009	1.158±0.013	141	3	3	*
DP1c6	22	D	1.5	0.1	2.86±0.06	0.74±0.02	1.09±0.01	1.14±0.02	142	7	7	*
DP1c4b	20	D	1.5	0.1	3.085±0.68	0.753±0.02	1.137±0.023	1.205±0.034	145	7	8	*
DP1c4a	20	D	1.5	0.2	2.80±0.06	0.74±0.02	1.09±0.02	1.14±0.03	142	7	8	*
DP1c3	*19*	D	*1.5*	*0.2*	*3.154±0.005*	*0.734±0.06*	*1.105±0.06*	*1.156±0.01*	*139.3*	*1.6*	*1.6*	*3733±38*
DP1c3	19	D	1.5	0.2	3.267±0.055	0.748±0.017	1.094±0.017	1.141±0.026	145	6	7	*
DP1c1b3	Y	D	1.5	<1	3.189±0.045	0.805±0.028	1.105±0.013	1.168±0.021	169	12	14	*
DP1c1b2	Y	D	1.5	<1	3.080±0.026	0.798±0.012	1.105±0.008	1.168±0.012	166	6	6	*
DP1c1b1	*Y*	*D*	*1.5*	*<1*	*3.124±0.002*	*0.798±0.002*	*1.114±0.002*	*1.183±0.004*	*165.6*	*0.9*	*0.9*	*1 300±6*$^{\perp}$
DP1c1a	Y	D	1.5	0.2	3.159±0.062	0.847±0.023	1.099±0.011	1.160±0.02	193	13	15	*
Unit I												
DP1a3	32		0.5	50	2.110±0.030	0.990±0.020	1.160±0.020	1.370±0.04	316	25	32	*
Leaching experiment on DP1c1b1												
Bulk	Y	D	1.5	<1	3.080±0.026	0.798±0.012	1.105±0.008	1.168±0.012	166	6	6	*
Leachate					2.778±0.047	0.690±0.018	1.116±0.023	1.164±0.032	123	6	6	*
Residue					3.177±0.042	0.833±0.014	1.085±0.016	1.142±0.027	185	8	8	*

TMS data are in italics with a 2σ error, while α-spectrometric data are given with a error. Samples name DP1c8 and DP1C8' refer to the two subsamples of DP1c8 as displayed in Fig 6. TS=thin-section number; third column refers to coral species: D=Diploria sp.; A=*Acropora palmata*; P=*Porites porites*; S=*Siderastrea* sp.; M=*Monstastrea* sp; Elev.=elevation at which sample was collected.

* the ^{230}Th/^{232}Th activity ratio was below the detection limit for alpha-spectrometry, that is >1000.

$^{\perp}$ an age of 149,900 +/− 2400 years BP was obtained by running our isotopic date through the open-system model of Thompson et al. (2003).

4.2. U-series dating

Details and error margins of our geochronological data are listed in Table 1. One whole-rock sample from Unit I gave an α-counting age of about 316 ka, close to the limits of the method, whereas values measured on in-situ coral specimens from Unit II range between 193 and 141 ka. TIMS ages of 165.6 and 139.3 ka were obtained from the same unit. When run through the open-system model of Thompson et al. (2003), the former sample yielded an age of 149.9 ka. Applying this model to coral data from Barbados, Thompson et al. (2003) and Thompson and Goldstein (2005) demonstrated that open-system ages from a single stratigraphic level are in much better agreement than conventional U-series ages calculated from the same isotope ratios. The bulk fraction, the residue and the leached fraction of one crushed slab from sample DP1c1b1 gave ages of 166, 185 and 123 ka, respectively. Finally, one small in-situ coral at the base of Unit III and one coral fragment included in this unit provided ages of 115 and 118 ka, respectively.

5. Discussion

5.1. Reliability of U–Th ages

Except for the whole-rock specimen collected from Unit I, our samples are composed of almost pure aragonite and do not show evidence of recrystallization. The U content and the initial $^{234}U/^{238}U$ ratio of our samples are somehow elevated, but do not differ markedly from those measured by other authors on corals from the last or the previous interglacial (Bard et al., 1991; Chen et al., 1991). Finally, no contamination by detrital Th has been detected and obtained ages are in stratigraphic order. Our radiometric data thus appear to be reliable, however the secondary aragonite and/or the internal sediment found in some corallites could have driven ages towards younger values.

5.2. Correlation with marine isotope stages

With some caution (Carew and Mylroie, 1991), interstratified terra-rossa paleosols can be used in conjunction with U–Th ages to correlate Bahamian limestone units with marine isotope stages because carbonates essentially accumulate during interglacials, whereas soils primarily form during glacial periods. At DP1, all units are covered by a pedogenic layer, although that capping Unit II (coral boundstone) has been almost totally removed by marine erosion. The lowermost beach deposits (Unit I) occur below three paleosols and could consequently correlate with MIS 9 (301–334 ka BP; Bassinot et al., 1994), which is in agreement with the U–Th age (316 ka) obtained from this unit. The truncated boundstone (Unit II) appears below two paleosols and could thus be correlated with MIS 7. One of the obtained age (193 ka) corresponds indeed to MIS 7, but the remaining data fall within MIS 6 (133–186 ka BP; Bassinot et al., 1994). These values are atypical because MIS 6 corresponds to a glacial period when sea level was several tens of meters below its present stand (Rohling et al., 1998; Thompson and Goldstein, 2005). Thus, during this stage, no corals could have possibly grown at the location of the observed reef, more than 2 m above modern sea level. Therefore, the obtained isotopic data have most likely been biased by diagenetic processes of unusual magnitude. We argue that the precipitation of aragonite cement and the infiltration of internal sediment in the corallites have driven ages towards younger values, which could have occurred when the reef was submerged during the last interglacial highstand. This viewpoint is supported by radiometric ages obtained from the bulk slab, residue and leached fraction of sample DP1c1b1, which can be assigned to MIS 6 (bulk), MIS 7 (residue) and MIS 5e (leached fraction), respectively. Thus, the Devil's Point boundstone represents a composite structure containing coral specimens of both MIS 7 (at DP1) and MIS 5e age (at the sites studied by Chen et al., 1991). Similar composite coral terraces have been described in active tectonic settings (e.g. Pirazzoli et al., 1993). Finally, the subtidal sediments (Unit III) capping the coral boundstone occur below one paleosol, suggesting they accumulated during MIS 5e, which is corroborated by both our U-series data and that of Chen et al. (1991).

5.3. Relative sea-level indicators

Relative sea-level (RSL) datum during deposition of the studied units can be deduced from their present-day elevation and paleo-depositional setting. RSL was thus at about +1 m during the formation of the lowermost beach deposits that could be coeval with, or older than MIS 9. This datum is consistent with the eustatic record derived from the study of coastal deposits in the NW Bahamas (Hearty and Kindler, 1995; Hearty et al., 1999). A RSL near +5 m can be calculated for the MIS 7 coral boundstone by adding up the elevation of the surface truncating the reef (+2 m), the thickness of the reef that has been removed by erosion (possibly 1 m, based on the diameter of massive coral remnants), and the inferred paleo-depth (>2m). This value clearly conflicts with eustatic sea-level estimates found in most previous coral-terrace studies and oxygen-isotope records (e.g. Raymo, 1997) concerned with the penultimate interglacial. Finally, adding up the elevation of the uppermost exposure of Unit III subtidal sediments (+4 m) and their minimum depth of occurrence (4 m) leads to a conservative estimate of +8 m for MIS 5e RSL, which is a bit higher than the value commonly admitted for the eustatic highstand during the last interglacial (5 to 7 m; Selivanov, 1992). Note that near Mathew Town, 10 km to the S of Devil's Point, MIS 5e beach deposits occur less than 1 m above modern datum.

5.4. Southern Bahamian tectonics and MIS 7 sea level

In this section, we try to reconcile three seemingly conflicting observations: (1) the southward decrease in elevation of MIS 5e marine sediments from Devil's Point to Mathew Town; (2) the unusual RSL estimate derived from MIS 5e subtidal sediments (Unit III; >8 m); and (3) the absence, along the SW shoreline of Inagua, of deposits equivalent to Unit II (coral boundstone) that would further confirm a higher than present RSL during MIS 7. To resolve the first point, we propose that the island has been tilted since the last interglacial, resulting in a 2 to 3 m subsidence in the Mathew Town area, and an equivalent uplift near Devil's Point. This hypothesis clarifies also the other two conflicting points, i.e. the anomalously elevated MIS 5e RSL derived from Unit III, and the absence, due to subsidence, of a MIS 7 reef in the SW corner of the island. This explanation is further is consistent with the transpressive regime near Great Inagua (Hine, A.C., personal communication, 2004). Future investigation will show whether the SW portion of Inagua is an independent fault block, or if the entire island has been tilted towards the South. If verified, our hypothesis would further suggest that sea level was close to modern datum during the penultimate interglacial. Indeed, subtracting the minimal amount of uplift deduced from the elevation of Unit III (2 to 3 m) from the RSL value estimated from the MIS 7 reef (5 m), we obtain a eustatic datum of about +2 m (with an error margin of a few meters mainly due to uncertainties in paleodepths) for the penultimate interglacial period. This estimate is substantially higher than that proposed in isotopic and most previous coral-terrace studies.

6. Conclusions

Our new data suggest that the Devil's Point reef on the SW shoreline of Inagua has a polycyclic origin: an early construction phase occurred during MIS 7, but the main growth phase took place during MIS 5e. Our results indicate also that sea level was close to modern datum during the penultimate interglaciation (MIS 7), which contrasts with most coral-terrace studies and oxygen-isotope records concerned with this time interval. In addition, our observations imply that part of Great Inagua has experienced tectonic uplift and tilting during the past 100,000 years. This is not surprising considering the proximity of the island to an active plate margin, and supports the views of previous authors who consider the SW Bahamas as more tectonically active than their north-western counterparts. Finally, ^{234}U/^{230}Th ages obtained from coral samples collected in other areas that range between 135 and 180 ka should now be re-examined keeping in mind that they could represent rejuvenated MIS 7 material rather than diagenetically aged MIS 5e samples.

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