Coral Reefs
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REPORT

Last interglacial reef limestones, northeastern St. Croix, US Virgin Islands—evidence of tectonic tilting and subsidence since MIS 5.5

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Abstract Most last interglacial (MIS 5.5) coral reef deposits in the Caribbean are emergent. However, in St. Croix, these are found mainly at depth, underneath Holocene material and confirmed by TIMS U–Th dated corals from eight cores through Holocene reefs. The only emergent MIS 5.5 marine deposit peaks at +1.5 m MSL at the northwestern end of the island. The Late Pleistocene surface decreases at least 9.25 m (based on reef crest elevations) in elevation over 15 km along a 0.62 m/km eastward (alongshore) slope. Neither differential erosion nor a naturally sloping deposit is likely, thus the directional elevation decrease requires the influence of tectonic processes. Platform tilting or differential subsidence increasing in rate to the east probably operated both during and since the last interglacial and created progressively greater accommodation space for increasingly thicker overlying Holocene reefs in an eastward direction. Rates of subsidence since MIS 5.5 increase from west to east, from 0.02 mm/year to 0.1 mm/year, assuming a MIS 5.5 +6-m sea level and +4 m initial reef elevation. St. Croix's association with extensional shelf faulting from the northern part of the Virgin Islands Basin, the Anegada Fault to the east and the Puerto Rico Trench to the north may be significant in terms of identifying mechanisms for, or past events resulting in, directional tilting. Identification of differential elevations of MIS 5.5 reefs adds substantially to the information on Late Quaternary tectonism of the area.

Keywords St. Croix—USVI · MIS 5.5 · Fossil coral reefs · U-Th dating · Platform tilting

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Introduction

Shallow marine deposits of the last interglacial period, Marine Isotope Stage 5.5 (MIS 5.5/marine oxygen-isotope substage 5e) are typically situated above present mean sea level (MSL) throughout the Caribbean region. These are best known in the form of emergent or uplifted fossil coral reefs and associated facies formed at the peak of the last interglacial highstand 125,000 years ago when sea levels were ~6 m above present MSL (e.g., Hoffmeister and Multer 1968; Hoffmeister et al. 1967; Bender et al. 1967; Mesolella et al. 1969; Matthews 1973; Halley et al. 1977; Fairbanks and Matthews 1978; Dodge et al. 1983; Chen et al. 1991; White and Curran 1995; White et al. 1998; Toscano et al. 1999; Vézina et al. 1999; Kindler et al. 2007; Coyne et al. 2007; Blanchon et al. 2009). The range in elevation of Late Pleistocene deposits correlative with MIS 5.5 is wide, from +7-m MSL in the Miami Limestone (dunes in the oolitic facies) along the Atlantic Coastal Ridge in Florida (Hoffmeister et al. 1967; Halley et al. 1977) to −15-m MSL in Belize (Gischler et al. 2000; Macintyre and Toscano 2004). In some areas such as Belize, the Bahamas (e.g., Kindler et al. 2007), and St. Croix (Hubbard et al.

1989, 2005; Macintyre et al. 2008), the MIS 5.5 shallowest marine facies are now found over several meters. For example, MIS 5.5 shallow reef deposits in Belize range (north to south) from +2 to −15 m within a small geographic region. Kindler et al. (2007) invoked tilting of Great Inagua Island (Bahamas) since the last interglacial, resulting in a 2–3 m differential in elevation over 10 km. If the shoreline orientation is used as a reference datum at these locations, it is clear that these elevation changes do not represent onshore–offshore slopes (across which reef facies also form). Neither do they represent shore-parallel wedge-shaped deposits, nor are they indicative of differential post-depositional adjustments to original shallow-water facies elevations alongshore. Clearly, tectonic influences as well as glacio/hydro-isostasy and geomorphologic processes (erosion, karstification) combine to determine the present elevation of these last interglacial highstand deposits.

On St. Croix, the present elevations of MIS 5.5 coral reef deposits are atypically low, indicating different tectonic mechanisms than those of the wider Caribbean region. With the exception of one partially elevated marine deposit peaking at 1.5-m MSL on the northwest coast of St. Croix (Hubbard et al. 1989), MIS 5.5 deposits along the northeast coast have only been found beneath Holocene reefs, following an eastward-deepening (alongshore) trend of 9.25 m over 15 km (Macintyre et al. 2008). St. Croix's tectonic setting (like that of Belize) indicates an exception to the Caribbean-wide elevated reef deposits of the last interglacial highstand. The timing and mechanisms of tectonic activity, and how they affected deposition and elevations of sea-level indicative deposits during MIS 5.5, are currently unknown.

Here, we report the first attempt to quantify the tectonic activity of St. Croix since MIS 5.5. We cored the Pleistocene limestone foundations under Holocene reef systems in transects across Long Reef and Tague Bay Reef (Fig. 1), because no elevated MIS 5.5 reefs are known from the northeast coast of St. Croix. Coral samples from just below the Pleistocene–Holocene unconformity were dated using high-precision thermal ionization mass spectrometric (TIMS) U–Th disequilibrium. When compared with Late Pleistocene ages and elevations from the West End Terrace System (Hubbard et al. 1989) as well as from Late Pleistocene reefs of the wider Caribbean, these new data provide preliminary evidence of tectonic influences affecting fossil reef elevations along the north coast of St. Croix.

This work complements our study on the Holocene reefs overlying most of the MIS 5.5 deposits (Macintyre et al. 2008) and represents a significant addition to the very limited Late Pleistocene age data available for St. Croix. In addition, this study identifies previously unknown Late Quaternary tectonic activity along the northeastern coast of

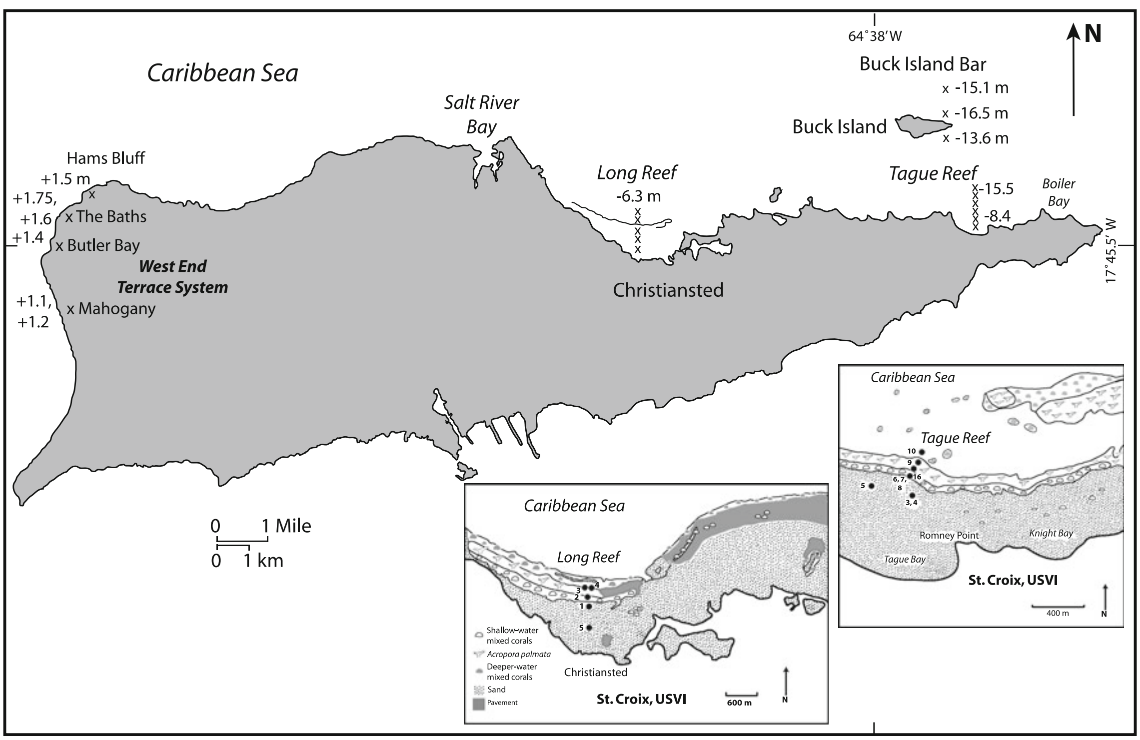

Fig. 1 Location map showing the West End Terrace System sites of Hubbard et al. (1989), the Long Reef and Tague Reef transects of this study, and Buck Island, Buck Island Bar, and Boiler Bay referred to in the text. Numerical data indicate elevations of the Pleistocene surface at each site. Inset maps of Tague and Long Reefs with core locations are from Macintyre et al. (2008)

St. Croix and highlights its potential impact on paleoenvironmental interpretations of fossil reef facies.

Previous work

Emergent fossil reefs and related carbonates of the last interglacial high sea-level stand (MIS 5.5; ~125 to ~135 ka) form major geomorphic coastal features characterizing the tectonically stable and tectonically rising coastlines of the Caribbean, with elevations ranging from +2-m to +10-m MSL (Table 1). Definitive MIS 5.5 reef highstand deposits and related facies are not documented above present mean sea level (MSL) on St. Croix, with the exception of marine nearshore deposits on the northwest coast (Hubbard et al. 1989).

The island of St. Croix is located 56 km to the south of the other (US and British) Virgin Islands and to the east of the Greater Antilles. Because it is predominantly composed of meta-sedimentary and volcaniclastic rocks, St. Croix is geologically more similar to the greater Antillean islands of Puerto Rico, Cuba, and Hispaniola (Dominican Republic/Haiti) than to the volcanic Lesser Antillean islands along the collision zone between the North American and Caribbean plates (Holmes and Kindinger 1985). The island has a complex structural and tectonic geologic history, with units segmented by major fault zones as part of a deformed collisional plate boundary with "initial compression followed by transcurrent tectonics and extension" (Whetten 1966, 1974; Ratte 1974; Holmes and Kindinger 1985; Stanley 1987a, b, 1988, 1989; Nagle and Hubbard 1989; Speed 1989); Case et al. (1984) categorized St. Croix and its platform as one of several moderately to strongly deformed basins of the Anegada Province. Speed and Joyce (1989) reinterpreted the geology of St. Croix as representing a tectonic complex of six fault-bounded, stacked nappes formed in a forearc system with a north-dipping subduction zone during the Late Cretaceous, which later changed to southward subduction in the early Tertiary. Gill et al. (1989) and McLaughlin et al. (1995) documented and interpreted the subsurface and outcropping Neogene geologic history and biostratigraphy of the Kingshill Basin, which runs NE–SW across central St. Croix.

Masson and Scanlon (1991) citing Holcombe et al. (1989) reported Late Miocene to Early Pliocene faults to the west

Table 1 Summary of locations and elevations of MIS 5.5 reef limestones in the wider Caribbean

Locality	Late Pleistocene MIS 5.5 reef formations	Maximum elevation M MSL	Reference studies
Florida	Key Largo Limestone (Unit Q5/Q5e)	+5.5 m	Sanford (1909), Broecker and Thurber (1965), Osmond et al. (1965), Stanley (1966), Hoffmeister and Multer (1968), Mitterer (1975), Perkins (1977), Coniglio and Harrison (1983), Fruijter et al. (2000), Multer et al. (2002)
Bahamas	Cockburntown Reef (San Salvador)	+2 m	Chen et al. (1991), White and Curran (1995), Carew and Mylroie (1995), White et al. (1998), Kindler et al. (2007)
	Devil's Point Reef (Great Inagua)		
Cuba	Jaimanitas Fm	+2 to +3 m	Toscano et al. (1999)
Haiti	Nicholas Terrace	Uplifted to +52 m	Woodring (1925), Dodge et al. (1983), Dumas et al. (2006)
Dominican Republic	Pleistocene Terrace Reefs	3–6 m Terrace	Klaus and Budd (2003, citing Geister 1982)
Cayman Islands	Ironshore Fm, unit D	+2 m	Woodroffe et al. (1983), Jones and Hunter (1990), Hunter and Jones (1996), Vézina et al. (1999), Coyne et al. (2007)
Jamaica	Hope Gate Fm	+2 to +3 m	Burne and Cant (1972), Cant (1972), Land (1973), Larson (1985), Boss and Liddell (1987), Precht and Hoyt (1991)
	Falmouth Fm		
	Terrace I		
Puerto Rico/Mona	Pleistocene reef tracts	+5 m	Frank et al. (1998), Taggart (1993)
Yucatan Peninsula	Upper Pleistocene reef limestones	+2 to +5 m	Szabo et al. (1978), Blanchon et al. (2009)
Barbados	First High Cliff/	Variably uplifted: +37±2 m (Christ Church) 61± 2 m (Clermont Nose)	Mesolella et al. (1969), Matthews (1973), Fairbanks and Matthews (1978), Bender et al. (1979); Ku et al. (1990), Schellmann and Radtke (2004)
	Barbados III/		
	Rendezvous Hill		
Curaçao, Netherlands Antilles	Hato/Cortalein Units, Lower Terrace; Last Interglacial Limestone Terrace	+2 to +8 m; +10 to +12 m Maximum	Pandolfi et al. (1999), Meyer et al. (2003), Schellmann et al. (2004)

of St. Croix that are likely still seismically active today. These include NE trending, post-Oligocene extensional faults on the VI shelf and northern St. Croix (Whetten 1966; Donnelly 1966; Masson and Scanlon 1991).

Ongoing faulting will obviously also affect the elevations of Pleistocene carbonate deposits over time. A subaerial coastal terrace system and shallow offshore pavement along the west coast of St. Croix consist of elevated (up to +1.5-m MSL) beach and coral-rich limestones deposited either during a highstand or uplifted, or both (Hubbard et al. 1989). Measured sections of this subaerial West End Terrace System and evidence from cores indicate that these limestone deposits extend to depths of over 4 meters below sea level. At the top of the lowermost (coral-bearing) unit C at the "Baths" (Fig. 1), one potassium–argon (K–Ar) date of 125,000 years (no 2σ error given) from a conch shell indicates a MIS 5.5 age. In the top unit "A" (cross-bedded grainstone, possibly a beach facies), one radiocarbon-dead age from a mollusk, and one minimum age of 29,600 ± 550 ybp from a sample of *Acropora palmata* (contaminated with modern marine cements) suggest that this facies also might have formed during MIS 5.5 (Hubbard et al. 1989). These are the only published Late Pleistocene dates from St. Croix. An important observation from this work is that the contact between the coral-bearing facies and the beach facies slopes to the south at a rate of 1.24 m per 5 km (Hubbard et al. 1989), implying to those authors that tectonic tilting in a southerly direction (opposite to an onshore–offshore depositional slope) may have been ongoing at least since the MIS 5.5 deposits formed.

Despite this observation, and considering the atypical absence of extensive emergent MIS 5.5 fossil reefs in St. Croix, no comprehensive age dating or mapping of the top of the Pleistocene surface along the north coast of St. Croix has been attempted in any further studies since Hubbard et al. (1989). This study is therefore the first that maps the eastern extension of the top of the Pleistocene section, identifies MIS 5.5 reef occurrences, and provides the first reliable radiometric dates to determine a preliminary scenario of reef development under proposed tectonic influences over the past 125,000 years.

Methods

A diver-operated hydraulic drill (Macintyre 1975) was used to collect 54 mm diameter cores in reef deposits. A ten core transect across Tague Reef (Fig. 2; eight were used in this study) extended from the West Indies Laboratory pier, across the back-reef lagoon, and the Tague Bay bank-barrier reef to the bottom of the outer slope at a depth of 14.9 m (Burke et al. 1989; Macintyre et al. 2008).

A five core transect drilled across the northwestern limit of the shelf-edge reef system at Long Reef (Macintyre et al. 2008; Fig. 3) extended from the back-reef lagoon (Core 5)

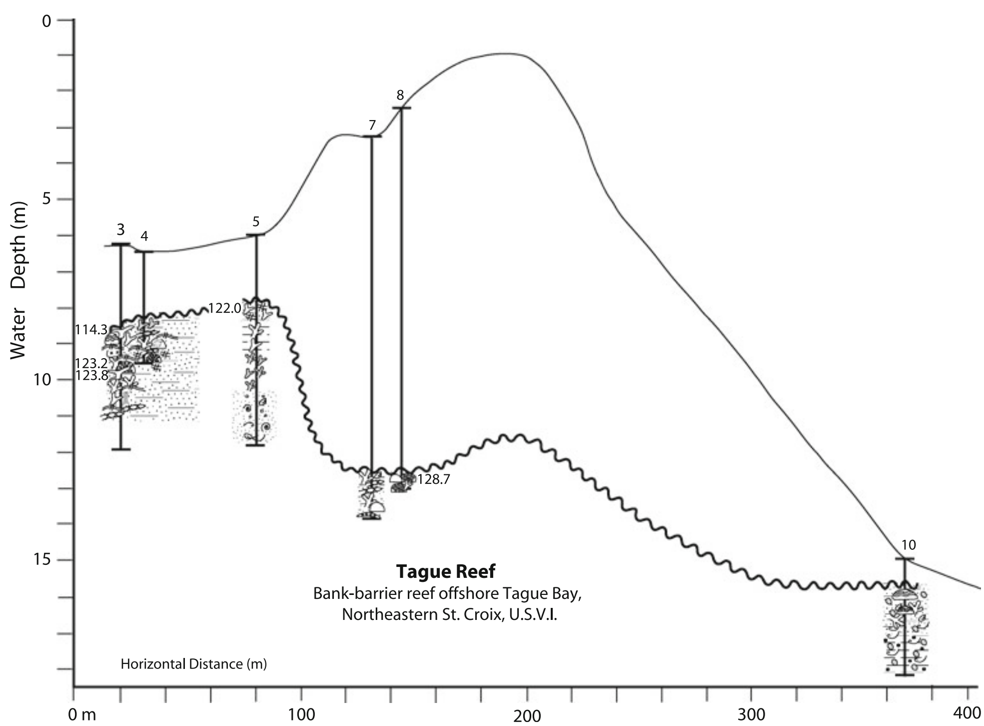

Fig. 2 Tague Reef transect showing the Pleistocene section and radiometric dates. The present reef profile is from Macintyre et al. (2008). Holocene stratigraphy and data for this transect may be found in Macintyre et al. (2008)

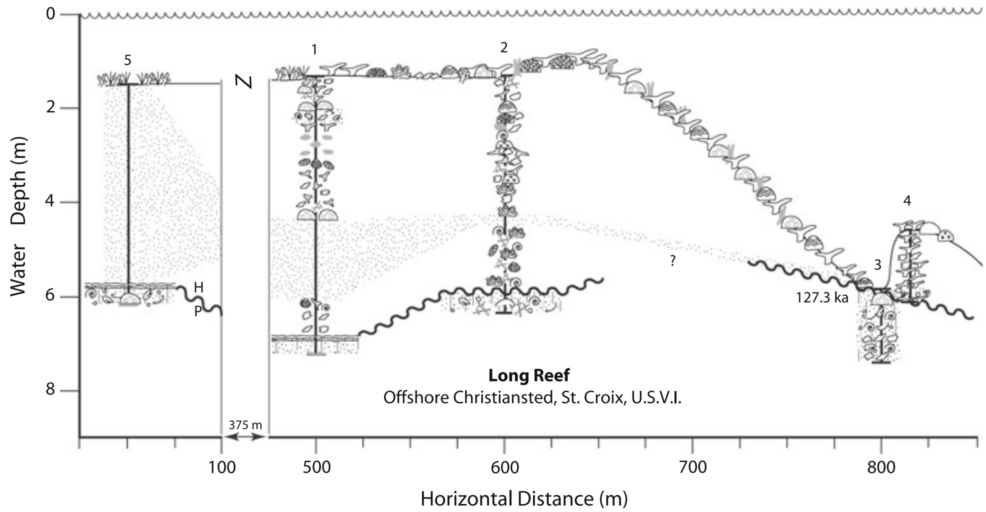

Fig. 3 Long Reef transect showing the limited recovery of the uppermost Pleistocene reef deposits below a caliche horizon signifying subaerial exposure. The present reef profile is from Macintyre et al. (2008). Holocene stratigraphy and data for this transect may be found in Macintyre et al. (2008)

across the reef crest (Cores 1 and 2) to two cores drilled adjacent to each other on a slight spur (Core 4) and groove (Core 3).

Cores were split with a wet saw, measured, and described in hand specimens and thin sections. Corelogs and transects were drawn using present elevations of coral specimens in relation to the elevation of the seabed, the local water depth and tidal cycle (in relation to present mean sea level (MSL)). Coral samples intended for radiometric dating were analyzed for mineralogic content via X-ray diffraction using the SCINTAG system at SI. Only samples displaying aragonitic texture and consisting of 100% aragonite (0% calcite) were selected for U-Th analysis. Thermal ionization mass spectrometric (TIMS) U–Th dating was completed in the Isotope Geochemistry and Geochronology Research Facility, Carleton University, Ottawa, Ontario, following standard techniques (e.g., Ivanovich et al. 1992). Samples were ultrasonically cleaned, ignited for 5 h at 875°C to remove organics, dissolved in HNO_3, and spiked with ^{233}U-^{236}U-^{229}Th tracer. U and Th were co-precipitated with iron hydroxide and purified twice on anion exchange columns (Dowex AG1-X 200-400 mesh). Measurement of U and Th isotopic ratios was done on the Triton TIMS, in peak-jumping mode using secondary electron multiplier with retarding quadrupole filter. Ages were calculated using half lives from Cheng et al. (2000). In view of the potential of corals for open-system behavior (e.g., see Thompson et al. 2003; Sholtz and Mangini 2007), the ages were also re-calculated assuming open-system behavior following Thompson et al. (2003) and assuming an initial sea-water $^{234}U/^{238}U$ activity ratio of 1.145 (Stirling et al. 1995). Multiple dating of each sample, as recommended by Sholtz and Mangini (2007), was not possible in this case because of limited sample material.

Results

Radiometric dating

Reliability of U-Th data is assessed with respect to the inherent quality of each individual sample and the analytical indicators determined during the analysis. Stirling et al. (1998) set up five fundamental criteria for reliability in coral dating (aragonitic texture, <1% calcite, $^{234}U/^{238}U_{init}$ of 149 ± 4‰, U concentration of "about 3 ppm" and low ^{232}Th concentrations (<1 ppb)). Additionally, according to Muhs et al. (2011), "we consider samples with calculated initial $^{234}U/^{238}U$ values ranging from 1.147 to 1.158 to have accurate ages or at least to be minimally biased."

We report six new TIMS U–Th dates in Long Reef Core 3 and Tague Reef Cores 3, 5 and 8 (Table 2), all of which were dated from 100% aragonitic material as discussed above. Our U ppm values also match those samples judged by Stirling et al. (1998) as "strictly reliable." Stirling et al. (1998) do not specify the range of U contents that would fulfill the "about 3 ppm" criterion, but the mean of our samples is 2.86 ± 0.65. Th concentrations are at, or less than, 1 ppb, with a mean of 0.621 ppb.

Apart from one sample (LR C3), the calculated initial $^{234}U/^{238}U$ activity ratios are within error of the modern ratio (1.145, Thompson et al. 2003), suggesting that the samples remained as closed systems since deposition. The single TIMS U–Th date of 138.9 ± 0.4 ka (LR C3; Table 2) on *Montastraea annularis* is erroneously old due

Table 2 TIMS U–Th dates from Long Reef Core 3 and Tague Reef Cores 3, 5 and 8

Sample (laboratory code)	Elev (m MSL)	Coral	Conventional age (ka)	Open-system age (ka)[a]	ppm U	$^{230}Th/^{234}U$	$^{234}U/^{238}U$	$^{234}U/^{238}U$ initial
TR3.1-1 (ET311)	−8.50	*A. palmata*	114.9 ± 0.3	114.3 ± 0.7	3.37	0.6601 ± 0.0010	1.1059 ± 0.0008	1.1465 ± 0.0008
TR3.1-6 (JT316)	−9.25	*P. astreoides*	124.4 ± 0.3	123.2 ± 0.6	2.93	0.6900 ± 0.0007	1.1040 ± 0.0007	1.1478 ± 0.0007
TR3.1-9 (FT319)	−9.75	*A. palmata*	123.2 ± 0.3	123.8 ± 0.8	2.71	0.6865 ± 0.0009	1.1031 ± 0.0010	1.1461 ± 0.0010
TR5.1-4 (GT514)	−7.80	*P. porites*	125.5 ± 0.3	122.0 ± 0.6	3.03	0.6937 ± 0.0008	1.1077 ± 0.0008	1.1535 ± 0.0008
TR8.5-4 (AT854)	−12.50	*P. astreoides*	129.2 ± 0.3	128.7 ± 0.9	2.66	0.7042 ± 0.0009	1.1015 ± 0.0011	1.1462 ± 0.0011
LR C3 (KC311)	−5.80	*M. annularis*	138.9 ± 0.4	127.3 ± 0.9	2.44	0.7331 ± 0.0009	1.1168 ± 0.0010	1.1730 ± 0.0010

[a] Calculated using Thompson et al. 2003 method for open-system correction and assuming an initial $^{234}U/^{238}U$ activity ratio of 1.145

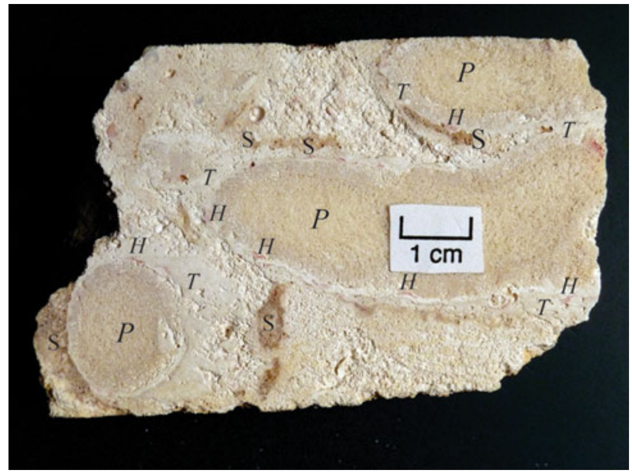

Fig. 4 Core photograph of a section of the *P. porites* unit from Tague Reef (H3 C3). P—*P. porites*; H—*H. rubrum*; T—*T. prototypum*; S—Spionid worm tube

to open-system behavior indicated by its elevated initial $^{234}U/^{238}U$ ratio, but the open-system correction brings it to 127.3 ± 0.9 ka, within MIS 5.5. The ages of all six samples, when corrected for the possibility of open-system behavior according to the Thompson et al. (2003) model (Table 2), fall within the MIS 5.5 (∼130–114 kyr) age range. This indicates deposition during the peak of the last interglacial period, when extensive reef systems were developing above present MSL throughout the Caribbean and Florida under a high (+6 m) sea-level scenario. In contrast, the elevations of these new samples range from −5.8 m MSL to −12.5 m MSL (Table 2). The only previously published Pleistocene date from St. Croix consists of the K–Ar date of ∼125 ka (no 2σ error given) on a conch (at ∼+0.75 m MSL) from the elevated West End Terrace System (Hubbard et al. 1989).

Tague Bay transect

Six cores drilled across the Holocene modern bank-barrier (inner-shelf) reef at Tague Bay penetrated the well-lithified Pleistocene limestone beneath the Holocene reef section (Macintyre et al. 2008). Pleistocene core sections (Electronic Supplemental Material, ESM Appendix) recovered shallow reef, reef flat and back-reef corals, and carbonate sediments of MIS 5.5. Recovery ranged from 0.77 m (Core 7), 1.19 m (Core 10), 1.55 m (Core 8), 1.6 m (Core 4), 3.52 m (Core 3) to 4.05 m (Core 5). One distinctive unit in the cores consists of a coarse-grained shallow marine carbonate sedimentary matrix in which numerous branches of *Porites porites* (S. D. Cairns, pers. comm.) are embedded. While *P. porites* is well known to occur on the fore reef from 5 m up to 20 m, its optimal range (overlapping that of *P. furcata and P. divaricata*; Cairns 1982; Suchanek 1989; Shinn et al. 1989) is 1–3 m.

The fairly regular coating of encrusters around the *P. porites* fragments (diameter 2 cm; Fig. 4) indicates these fragments were subject to a period of constant wave agitation prior to the infilling by sediments. Encrusters indicating a shallow-water setting include the crustose coralline alga *Titanoderma prototypum* Foslie (Littler and Littler, pers, comm.; type locality St. Croix, U.S.V.I.; Woelkerling et al. 1985) found in depths less than 5 m (Littler and Littler 2000); the family of worm tubes Spionidae that thrive in shallow water (Fauchald 2011, personal communication) and the encrusting foraminifera *Homotrema rubrum* that is very abundant in shallow water (growing attached to lower surfaces of shells, corals, and reef debris; Mackenzie et al. 1965; Elliott et al. 1996; Pilarczyk and Reinhardt 2011) but which can be found on deeper slopes (Buzas 2011, personal communication). In this case, the sum of all observations indicates a shallow-water paleoenvironment (<5 m MSL) such as a reef flat and/or back-reef setting with sufficient wave action to maintain a state of constant agitation.

This facies from Tague Reef is also found in the uppermost Pleistocene of Buck Island Bar (Hubbard 1991) where it was described as "packstones and wackestones" with *Diploria* sp. and "numerous smaller fragments of *A. cervicornis* and/or *P. porites*" as well as "molluscan grainstone to packstone with a few fragments of *A. cervicornis* and/or *P. porites*."

The best samples for TIMS U–Th dating came from Cores 3 (3 dated samples), 5 and 8 (Table 2). The elevation of the Pleistocene (MIS 4, 3, 2 last glacial, subaerially eroded) surface ranged from 7.75 to 8.4 m among the landward Cores 3–5, and from −12.2 to −15.5 m in the seaward Cores 7, 8 and 10 (Fig. 2; Macintyre et al. 2008).

Long Reef transect

The outer shelf-edge reef system reaches its western terminus at Long Reef, which was initiated on a pre-Holocene (MIS 4, 3, 2; last glacial) subaerially exposed surface ranging from −5.8 to −7 m MSL (Fig. 3; Macintyre et al. 2008). Despite the higher elevation of the Pleistocene surface in this area, five cores penetrated only the top 0.11–0.85 m of the well-lithified MIS 5.5 limestone beneath the Holocene reef section. One TIMS date was obtained in this transect (LR C3; Table 2). The elevations of the top of the Pleistocene section at Long Reef provide a midpoint along the northeastern coast for determining the slope of the tilted surface.

Slope of Late Pleistocene (MIS 5.5) surface

A distance of 9.41 km from West End Terrace System sites (Hubbard et al. 1989) to the Long Reef transect represents an elevation change of 7.3 m (from the beach facies at 1.5 m MSL to a maximum elevation of −5.8 m MSL), resulting in a slope of 0.78 m/km. If the top of West End Unit C (at ~1 m) is used instead of the beach facies, the elevation change of 6.8 m results in a slope of 0.72 m/km. Extending eastward 14.9 km from the West End to the Tague Reef section, the maximum Pleistocene surface elevation of −7.8 m MSL gives a slope of 0.62 m/km. If the top of Unit C is used, the slope from the West End to Tague Reef is 0.59 m/km.

Calculated subsidence rates

Assuming that St. Croix experienced a similar MIS 5.5 high sea-level stand of ~5–6 m MSL and that the marine facies (Unit C) encountered in outcrop on the West End and beneath Holocene reefs on the northeast coast initially formed in shallow water of ~2 m depth, the amount and rates of subsidence over the past 125 kyrs can be estimated for each location. At the West End, the beach facies mapped at +1.5 m MSL (±0.5 m tide range) is estimated (based on data in Hubbard et al. 1989) to have formed during a ~+5 m MSL highstand (consistent with the widely accepted +5 to +6 m sea-level elevation for the last interglacial highstand throughout the Caribbean region), resulting in a possible 3.5 m of subsidence or a rate of 0.03 mm/year. At Long Reef, where the MIS 5.5 reef attains elevations up to −5.8 m MSL (Fig. 3), estimated initial reef elevations of +3 m MSL (under 2 m water depth) are indicative of a minimum of 8.8 m of subsidence at a rate of 0.07 mm/year. At Tague Reef, the MIS 5.5 reef surface at −7.75 m on the landward side results in subsidence, assuming an initial reef elevation of +2 m MSL (under 3 m water depth), or ~9.75 m subsidence at a rate of ~0.08 mm/year. The increasing rate of subsidence over 15 km from west to east is apparent from the progression of 0.03 mm/year at the West End to 0.07 mm/year at Long Reef and 0.08 mm/year at Tague Reef.

Discussion

In the Long Reef transect (Fig. 3), we obtained 0.11 m to 0.85 m recovery of MIS 5.5 shallow reef deposits below an exposure/erosional surface varying over only a 1.2 m elevation range (−5.8 to −7 m MSL; Macintyre et al. 2008). Deposits consist of caliche crust at the surface, indicating prolonged subaerial exposure, underlain predominantly by rubble, calcarenite, mollusk and other coral fragments. The lack of sufficient MIS 5.5 section in these cores precludes definitive facies interpretations along this transect. The single TIMS U–Th date corrected to 127.3 ± 0.9 ka (Table 2) on *M. annularis* serves to confirm that the material is from MIS 5.5.

Within the Tague Reef transect, however, cores encountered the Late Pleistocene surface from −7.75 to −15.5 m in a stepped profile (Fig. 2), with cored sections ranging from 0.77 to 4.05 m thick. Recovery of *A. palmata* reef crest was limited in both transects. Instead, the dominant recovery of a facies containing numerous *P. porites* fragments encrusted by shallow-water indicators and in a matrix of biogenic sands (Fig. 4; ESM Appendix) at the base of Tague Reef, and *Acropora cervicornis* below Long Reef, strongly suggest that the uppermost last interglacial reef limestones cored in this study resemble shallow back-reef or reef flat facies, or a lagoonal reef setting similar to the branching *Porites* communities dominating modern shallow carbonate lagoons such as Bahia Almirante, Panama (Guzman Guevara and Guzman Guevara 1998; Aronson et al. 2005) and the *Acropora cervicornis* communities that flourish in the central shelf lagoon of Belize (Aronson et al. 2002). This is not an assemblage that could have formed on the outer reef due to the fragmentation of the *Porites* branches, the collective shallow-water assemblage and matrix present (Fig. 4), the coatings of crustose coralline algae and spionid worm tubes, and encrusting *Homotrema*. Jaap (1984) discusses Florida's shallower reef habitats (shallow patch reefs, reef flats) in terms of their dynamic nature (storms relocating coral populations, fragmentation, scattering). Branching species were specified as being most affected, including *A. palmata*, *A. cervicornis*, and *P. porites*. Adey et al. (1977) offer another modern analog for the cored *P. porites* facies in Boiler Bay just to the east of Tague Reef (Fig. 1), in the form of extensive pavement areas at depths of 1–2 m between individual lobes (boilers) of the algal ridge. The pavement areas support algal growth (*Sargassum* spp.; *Dictyota*), scattered *P. porites* and *Siderastrea* sp. Adey et al. (1977) describe the pavement as being a one-half to one meter thick "sediment filled and cemented framework of either *P. porites* or *Acropora cervicornis*…." Hubbard et al. (1989) describe a similar facies within the West End sequence.

Recent (2010 and 2011) field observations (MAT) in both Panama (Caribbean side, Bahia Almirante at Isla Solarte; e.g., Aronson et al. 2005; Guzman Guevara and Guzman Guevara 1998) and the Belize Barrier Reef (Carrie Bow Cay) confirm that these shallowest reef facies and shallow back-reef lagoonal areas are dominated by *A. palmata*, *P. porites*, *P. furcata*, *P. astreoides*, *A. cervicornis* and *A. diffusa* (hybrid), *Agaricia* sp., *Halimeda* sp. and other calcareous green algae, coralline red algae, *Homotrema*, and numerous head corals (*M. annularis*, *Diploria* sp., *Siderastrea* sp., and others) in less than 1.5 m water depths.

The TIMS U–Th dates from beneath the Holocene section at Tague Reef confirm that this pre-Holocene reef limestone formed during the last interglacial (MIS 5.5) high sea-level stand ~125,000 years ago (114.3 ± 0.7, 123.2 ± 0.6, 123.8 ± 0.8, 122.0 ± 0.6, and 128.7 ± 0.9; Table 2) when significant reefs developed throughout the Caribbean. The Late Pleistocene reef below the present Long Reef (127.3 ± 0.9 ka; Table 2; Fig. 3) was also emplaced during MIS 5.5.

The major implication of this research derives from the elevation data on the top of the Pleistocene section. If a tectonically stable platform is assumed, these depths suggest that the Pleistocene section at Tague Reef reached only ~−8 m MSL and only up to −6 m MSL at Long Reef, despite the timing of their deposition during a +6 m high sea-level stand. Although the species present do also exist in deeper water, it must be noted that abundant *P. porites* and *A. palmata* do not form reef framework at depths greater than −5 m MSL. Given this framework-forming range limitation, the deep depths of the Pleistocene reef cross sections presented herein, if interpreted as not having subsided/tilted, are inconsistent with typical shallow reef and lagoonal coral facies development in the Caribbean. The only other dated MIS 5.5 material from St. Croix, the beach and reef limestones on the West End (K/Ar dated to 125 ka), occurs at an elevation range from −4 to +1.5 m MSL (*Strombus* dated at +0.75 m; Hubbard et al. 1989). In contrast, MIS 5.5 reefs in other parts of the Caribbean were deposited at much higher elevations (+2 to +7 m MSL; Table 1) than any at St. Croix. Differential erosion of formerly elevated Pleistocene reef facies since MIS 5.5 is unlikely given the consistent ages of the deposits at both ends of the elevation gradient.

It has been suggested to us in one review (citing Pandolfi 1996; Speed and Cheng 2004) that this deposit represents an over-thickened, keep-up unit deposited under a tectonically stable setting such as seen in MIS 5.5 reefs elsewhere, where units thicken toward the reef crest. However, the LIG deposits along the north coast of St. Croix do not exhibit thickening along strike (i.e., the shoreline) even if one assumes that the higher West End deposits represent the keep-up end or the reef crest. If the West End was interpreted as the over-thickened keep-up reef crest, the entire deposit would have to be oriented perpendicular to the shoreline and hence to the direction of sea-level change. Instead as we have also documented, the contact of uppermost Pleistocene shallow reef facies deepens along strike to the east. A keep-up unit under a 5–6 m highstand would have thickened parallel to, and along, the full length of the shoreline to elevations well above those reported for this locality. Neither do the LIG deposits thicken seaward within the study area, nor do the surface maintains its slope and depth under Buck Island and Buck Island Bar.

The most likely explanation for this locality requires a differential tectonic influence. The contact between the coral-bearing and the beach facies at the West End slopes to the south at a rate of 1.24 m per 5 km (Hubbard et al. 1989). Hubbard et al.'s (1989) sections and cores are confined to the northwestern corner of St. Croix, thus any continuity of this tilting in an easterly direction is determined by comparing the elevation of the top of the Pleistocene section in their northernmost site (Hams Bluff; Fig. 1) with the same in our Long Reef and Tague Bay sites (Fig. 1).Using the elevation of the Pleistocene surface of −5.8 m MSL at Long Reef compared with the highest elevation from the West End Terrace System at the Hams Bluff site of +1.5 m, we calculate a 7.3 m lower surface. Continuing eastward, this surface measured at −7.8 m at Tague Bay indicates a deepening Pleistocene contact and implies directional tectonic tilting or differential subsidence of at least 7.5 m from the West End to Tague Bay. The fact that the MIS 5.5 reefs of northeastern St. Croix are now at these low, eastward-deepening elevations implies that tectonic tilting has been ongoing, at least since the MIS 5.5 deposit formed ~125,000 years ago. If we assume that the tilting has not been episodic in nature, then we can calculate a rate of subsidence (assuming +6 m sea level and +4 m MSL initial facies elevations) of 0.02 mm/year (West End) to 0.09 mm/year (Tague Reef). Increasing rates of subsidence or platform tilting allowed for greater accommodation space in an eastward direction, as indicated by the progressively thicker overlying Holocene reefs from Long to Tague Reefs (Figs. 2, 3; Macintyre et al. 2008).

In previous studies of the Virgin Islands region, St. Croix, which lies about 56 km to the south of the Antillean Virgin Islands, has largely been unrepresented. Holmes and Kindinger's (1985) study of the Virgin Islands platform around St. Thomas and St. John indicated that tectonic fragmentation of the area controlled carbonate sedimentation and shelf processes, but the study did not address St. Croix. Masson and Scanlon (1991; see also Whetten 1966; Donnelly 1966) provide useful indications of local post-Oligocene extensional shelf faulting (associated with the northern margin of the extensional Virgin Islands Basin and continuing northeast through the Anegada Passage) that is active to the present day; however, they do not discuss mechanisms for tectonic tilting or how the movements may be controlling (or have controlled) deposition and erosion in the recent geologic past. Dolan et al. (1998, and similar studies) likewise do not address St. Croix but focus on the area of the northern Hispaniola slope and northwestern Puerto Rico. Our findings thus constitute the first quantitative estimates of Late Pleistocene tectonism of the St. Croix area.

While the majority of important MIS 5.5 fossil reef localities (e.g., Florida, Bahamas, and Barbados; Table 1) have emergent deposits formed at a higher-than-present stand of sea level, MIS 5.5 reef facies at deeper elevations are known from other parts of the Caribbean. For example, deep Pleistocene reef-related deposits have been cored at −15 m MSL along the Belize Barrier Reef (Macintyre et al. 1995; Gischler et al. 2000; Macintyre and Toscano 2004) despite the occurrence of elevated (+2 to +5 m MSL) MIS 5.5 deposits to the north and west (Yucatan Peninsula, e.g., Szabo et al. 1978; Blanchon et al. 2009). This elevation change from +2 to +5 m and to −15 m within a small geographic region requires a directional tilt (Choi and Ginsburg 1982; Choi and Holmes 1982; Lara 1993) of even greater magnitude than that required to explain the St. Croix data. Tilting has also been suggested in other areas with emergent Late Pleistocene reef facies. Kindler et al. (2007) suggested 2–3 m of tilting over 10 km of MIS 5.5 deposits on Great Inagua Island, Bahamas. In Jamaica, Cant (1972) indicated that the Pleistocene reefs, which are elevated along the north coast, occur at lower elevations toward the south coast, suggestive of tilting to the south during the Pleistocene. Schellmann et al. (2004) offered titling as a possible explanation for decreasing elevations [from (+10 to +12 m) MSL to (+2 to +7 m) MSL] from NW to SE of the emergent MIS 5.5 Lower Terrace around Curaçao.

Although the mechanisms and rates of tilting or differential subsidence required to lower last interglacial highstand reef deposits at St. Croix to their present elevations are not known, these data from the northeast coast of St. Croix greatly increase knowledge of geologically recent tectonic activity in this region and its affect on the relationships of present paleo reef elevations to their original paleo sea levels.

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