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A sustained +21 m sea-level highstand during MIS 11 (400 ka): Direct fossil and sedimentary evidence from Bermuda

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ABSTRACT

A small, protected karstic feature exposed in a limestone quarry in Bermuda preserved abundant sedimentary and biogenic materials documenting a transgressive phase, still-stand, and regressive phase of a sea-level in excess of 21.3 m above present during Marine Isotope Stage (MIS) 11 (400 ka) as determined by U/Th dating and amino acid racemization. Cobbles and marine sediments deposited during the high-energy transgressive phase exhibit rim cements indicating a subsequent phreatic environment. This was succeeded stratigraphically by a still-stand deposition of fine calcareous lagoonal sediments containing bioclasts of red algae and benthic and planktonic foraminifera that was intensely burrowed by marine invertebrates, probably upogebiid shrimp, that could not be produced under any condition other than sustained marine submergence. Overlying this were pure carbonate beach sands of a low-energy regressive phase containing abundant remains of terrestrial and marine vertebrates and invertebrates. The considerable diversity of this fauna along with taphonomic evidence from seabird remains indicates deposition by high run-up waves over a *minimum* duration of months, if not years. The maximum duration has yet to be determined but probably did not exceed one or two thousand years. The most abundant snails in this fauna are two species indicative of brackish water and high-tide line showing that a Ghyben-Herzberg lens must have existed at > +20 m. The nature of these sediments and fossil accumulation is incompatible with tsunami deposition and, given the absence of evidence for tectonic uplift of the Bermuda pedestal or platform, provide proof that sea-level during MIS 11 exceeded +20 m, a fact that has widespread ramifications for geologists, biogeographers, and human demographics along the world's coastlines.

1. Introduction

Determining the timing and extent of maximum eustatic rise in global sea-level in the Pleistocene is important not only for anticipating the possible effects of future climate change (IPCC, 2007), but is also critical for interpreting the influence that greatly elevated sea-levels may have had on biogeographical patterns and extinctions of organisms on islands and low-lying continental coastal areas. Field and geochronological studies on middle Pleistocene deposits in Bermuda, the Bahamas, and Oahu in the Hawaiian Islands (Hearty et al., 1999; Kindler and Hearty, 2000; Hearty, 2002a; Olson and Hearty, 2003; Hearty and Olson, 2008), indicate that sea-level rose in excess of 20 m above present during MIS 11 about 400 ka ago. Deposits of middle Pleistocene age and of similar height above sea-level were also described by other authors along the North Slope of Alaska (Kaufman and Brigham-Grette, 1993), Curaçao–Netherlands Antilles (Lundberg and McFarlane, 2002), South Africa (Roberts et al., 2007), and the United Kingdom (Bowen, 1999), although in the last case Preece et al. (1990) had noted uncertainties in the ages and generally attributed the elevation to tectonic warping. Perhaps partly because some of these reports have been challenged and for other reasons discussed below (see Section 5.3), the magnitude of this eustatic event, one of the most important of the entire Quaternary, has not yet gained wide acceptance, especially in the stable isotope community (Hodell et al., 2000; McManus et al., 2003) (but see Poore and Dowsett, 2001), despite abundant of tangible geological evidence from several ocean basins. It has also been suggested that the +20 m deposits in Bermuda were the result of a "megatsunami" possibly generated by a volcanic margin collapse in the Canary Islands (McMurtry et al., 2007) that has generated vigorous debate (Hearty and Olson, 2008; McMurtry et al., 2008) of even greater environmental consequence.

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Bermuda has a long history of geological research because the rocks on the island and platform are considered to be a “tide gauge” of Quaternary sea-level fluctuations. The Bermuda carbonate platform is tectonically stable and sits atop a 40 Ma volcanic pedestal. It is most likely slowly subsiding (Vogt and Jung, 2007). The Quaternary stratigraphy of the island has been mapped and described in detail (Vacher et al., 1989, 1995; Hearty et al., 1992; Hearty et al., 2004), and consists of limestone and paleosol couplets correlated with early, middle, and late Pleistocene sea-level cycles (Table 1). Despite this extensive and detailed mapping, no geological deposits of a possible tsunami origin had ever previously been identified. Of particular interest in this investigation are marine deposits associated with middle Pleistocene Lower Town Hill Formation that have been correlated with MIS 11 (Hearty et al., 1992) and are associated with U/Th ages of c 400 ka (Hearty et al., 1999; Olson and Hearty, 2003; Hearty and Olson, 2008). Several sea-level deposits at different elevations reflect changing sea-levels during this interglacial highstand that is recognized as one of the longer and warmer interglacials of the past 1 Ma (Burckle, 1993; Loutre and Berger, 2003; McManus et al., 2003; EPICA, 2004).

In Bermuda, one of the more important sites for establishing this rise is the Government Quarry on Castle Harbour (Fig. 1 upper). First described by Land et al. (1967), marine sand and conglomerate were found between +18 and +22 m as terrace deposits and sediment-filled caverns exposed by quarrying operations in Government Quarry. Hearty et al. (1999) and Kindler and Hearty (2000) described similar fossiliferous marine sand and conglomerate at similar elevations from the “Dead End” cave system (sites UGQ4 and UGQ5) (Fig. 1 lower) situated within a few tens of meters of the original site described by Land et al. (1967); these deposits were destroyed shortly after their discovery in the late 1960s. They were correlated with other high-elevation middle Pleistocene marine deposits in Bermuda and the Bahamas, and an age of c 400 ka was established from U/Th ages associated with the beach deposits. The most convincing physical documentation of the +20 m highstand includes abrasion platforms and morphological terraces, intertidal beach fenestrae, and isopachous rim cements in both cave and terrace deposits indicative of prolonged phreatic conditions at this high-elevation.

Hitherto undocumented in the geological literature are the paleontological excavations of Olson in Government Quarry from 1981 to 1985, which uncovered multiple independent lines of evidence, both geological and biological, for a beach deposit at 21.3 m above present sea-level (designated herein as “+21.3 m”) that was probably part of the same karstic network as the nearby Dead End caves. This small fissure was physiographically and chronologically situated so as to form a perfect time capsule documenting the maximum transgression, still-stand, and regression of the MIS 11 sea-level rise and provides the best evidence yet found that this sea-level exceeded 20 m above present.

2. The Calonectris Quarry deposits

2.1. *Descriptive geology*

The site (Fig. 2) became known as Calonectris Quarry (CQ) from the preponderance of bones of a fossil shearwater of the genus *Calonectris* (Olson, 2008b), and was first detected by D. B. Wingate who collected a small sample of shearwater bones as early as November 1967. Olson was shown the area in 1981 as part of a reconnaissance of fossil bird localities on Bermuda (Olson et al., 2005). In 1981, excavations were carried out in a horizontal crevice exposed in a small quarry face at the NW extreme of Government Quarry, on the western side of Castle Harbour, Hamilton Parish, Bermuda (N32°20′28.3″ W64°42′27.4″).

The deposit formed as a horizontal lenticular body (Fig. 2) at the unconformity between the underlying heavily recrystallized, early Pleistocene Walsingham Formation (Table 1) and the overlying cross-bedded eolianite of the Lower Town Hill Formation (middle Pleistocene, MIS 11; Table 1). A remnant of Walsingham eolianite above the level of the fissure (Fig. 2) indicates a former cliff face against which the younger dunes accumulated, most of which had been quarried away before 1984. The Dead End caves (Fig. 1 lower) are situated on the opposite side of the top of the exposure seen in Fig. 2, ca 15 m straight ahead through the rock as viewed in Fig. 2.

Table 1

Correlation table of nomenclature associated with the stratigraphy of Bermuda and elevated +21 m marine deposits in Calonectris Quarry and Dead End Caves (UGQ 4/5).

Land et al. (1967); (i.e., Gould’s view)	Vacher et al. (1989); Hearty et al. (1992)	Hearty (2002b)	This study	(MIS) correlation
Recent	Recent	Recent	Recent Holocene	1
St. Georges soil?	St. Georges soil?	St. Georges Soil (Last glacial cycle)		2
			St. Georges soil	3
				4
Southampton Fm	Southampton Fm	Southampton Fm	Southampton Fm	5a
Spencer’s point		Pembroke dune (New name: Hungry Bay Fm)	Hungry Bay Fm	5c?
		“Red Harrington” soil	Harrington soil	5d
Pembroke Fm	Pembroke dune	Devonshire marine (max. +6-9 m), including Spencer’s point	Rocky Bay Formation	5e
Harrington soil	Harrington soil			
Devonshire Fm	Devonshire marine/dune	Rocky Bay Formation		
		Mid-5e regression; red colluvium		
		Belmont marine (+2.5 m) (New name: Grape Bay Mb of Rocky Bay Formation)		
Shore Hills soil?	Shore Hills Geosol	Red Geosol (?)	Paleosol	6
Belmont Fm	Belmont marine and dune (+2.5 m)	Harvey Rd Q. eolianite	Eolianite?	7
	Ord Rd. Geosol	Ord Rd. Geosol	Paleosol	8
	U. Town Hill	Upper Town Hill	Upper Town Hill	9
	Harbour Road Geosol	Palaeosol	Paleosol	10
	L. Town Hill	Lower Town Hill	Lower Town Hill; Calonectris	11
	Unnamed?		Quarry; Dead End Caves (UGQ 4/5); +21 m SL	
Shore Hills Soil?	Castle Harbour Geosol – “Big Red Soil” (BRS)			12–22?
Walsingham Fm	Walsingham Fm			23/35?

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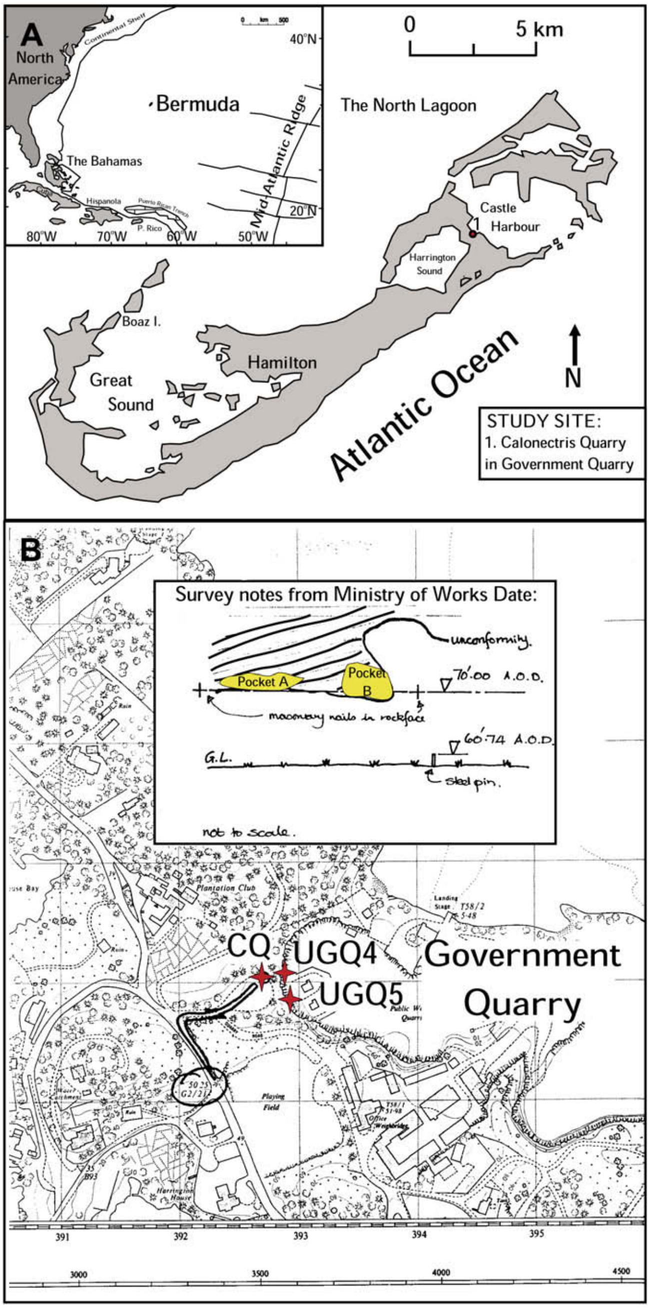

Fig. 1. Upper: Bermuda showing location of Calonectris Quarry (inset A showing general location of Bermuda in the eastern North Atlantic). Lower: topographical map showing relationship of Calonectris Quarry (CQ) to the Dead End Caves (UGQ4, UGQ5) and the nearest survey marker (circled). Inset is surveyor's sketch showing position of pins used to determine elevations. Surveyed by S. G. Johnson, Bermuda Department of Public Works, 14 Aug 1984.

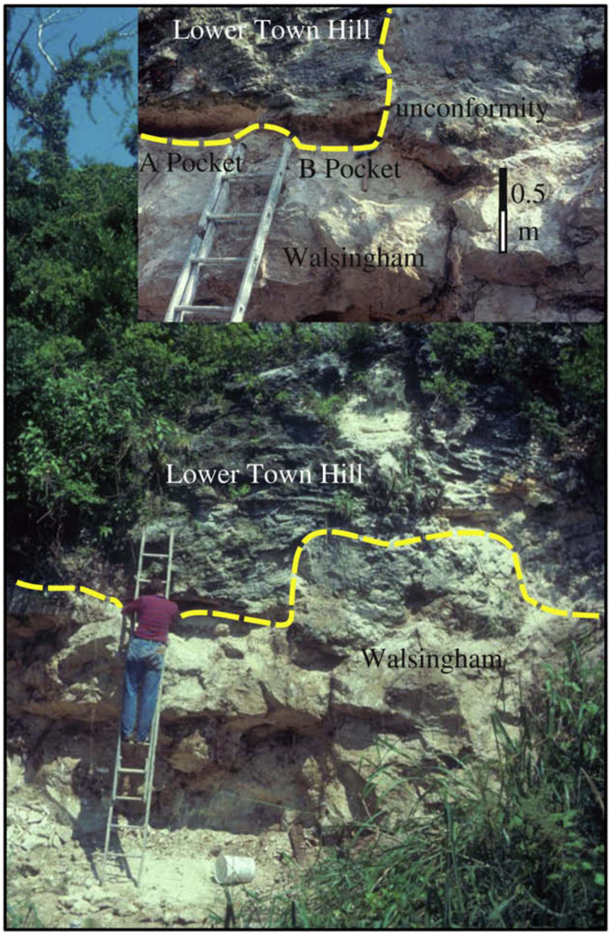

Fig. 2. Calonectris Quarry (horizontal fissure at shoulder level) as it appeared during excavation by Olson et al. in 1981. The dashed line indicates the unconformity between the old, recrystallized rocks of the Walsingham Formation and the overlying Lower Town Hill (LTH) Formation (MIS 11). The projection of Walsingham above the level of CQ is the remains of what was probably a cliff face that was quarried away until operations reached the undesired softer rocks of the LTH. The inset shows an enlarged view of A and B pockets of CQ.

The total width of the exposed CQ fissure was 3 m. The upper portions of the horizontal fissure consisted of two pockets of soft, unindurated sediments. "A pocket" (Figs. 3 and 8) was 1.5 m wide with a maximum height of 13 cm and was excavated to a depth of 40 cm into the cliff [0.08 m^3]. "B pocket" was 70 cm wide with a maximum height of 27 cm and was excavated to a depth of c 50 cm [0.095 m^3]. Thus, all fossils (Appendix A) except possibly the small original sample of *Calonectris* were recovered from a total volume of $<$0.18 m^3. When first discovered in 1981, the bottom of the fissure was observed to be filled with an indurated conglomerate of limestone pebbles with interspersed fragments of speleothems (indicating the proximity of an air filled cave previous to high sea-level), remains of marine invertebrates such as corals and mollusks, usually very worn, and a few fragmentary bones of *Calonectris*. The conglomerate below B pocket was ca 30–35 cm deep at the thickest point (somewhat less under A pocket) and contained a few rounded mud pebbles that were still quite soft. In both A and B pockets, resting on the conglomerate, was an indurated, whitish, sandy-silt layer or "marl" (Fig. 3A, C) several centimeters thick that contained no macrofossils, but that proved on sectioning to be riddled with burrows (Fig. 4).

By 1985, quarrying operations revealed that the fissure intersected a vertical sediment-filled pipe ca 40 cm in diameter in the underlying Walsingham Formation that was filled with marine-derived rubble including beach cobbles and clasts of red soil (which probably originally filled the vertical pipe, a feature typically associated with the Big Red Soil development on the Walsingham Fm – see Olson et al., 2005: fig. 3; Hearty and Olson, 2008: fig. 4).

The fine, loose, yellowish-white carbonate marine sand in the upper portions of both pockets (Fig. 3) contained abundant remains of terrestrial and marine vertebrates and invertebrates. All bones were completely disarticulated, mostly encrusted with carbonate, and were generally lying in the horizontal plane. In A Pocket, bones were concentrated at the northern end and no large bones were found in the southern 70 cm of the deposit, suggesting that wave action may have been from south to north (right to left in Figs.

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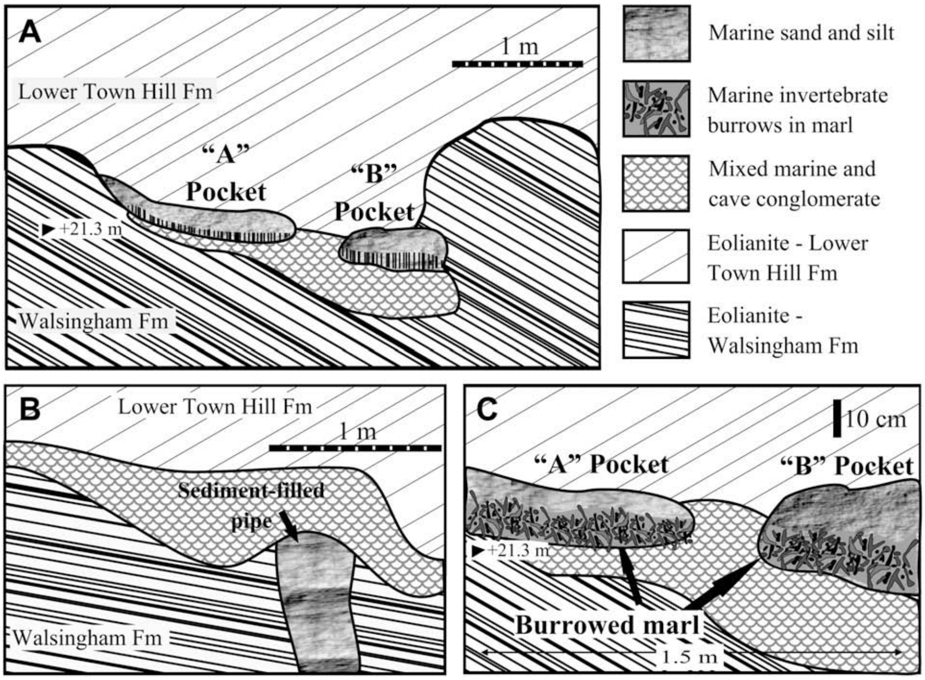

Fig. 3. A, computerized diagram based on Olson's field sketches of Calonectris Quarry in 1981 (C provides detail of A). B, diagram based on Olson's field sketch showing vertical pipe (diameter ca 40 cm) as exposed in Calonectris Quarry in 1984.

2 and 3). In both pockets, bones became decidedly scarcer as the excavation deepened, i.e., farther away from the paleo-cliff in the Walsingham eolianite. Likewise, bones were concentrated in the lower portions of the lenses, just above the pebbly conglomerate, whereas the upper portions were nearly pure sand, suggesting that waves may have stopped reaching the crevice after the bones were laid down and the crevice was then filled with eolian sand.

2.2. Methods: excavation of the site

Excavations were conducted by Olson in 1981, 1984, and 1985. All of the sandy sediments obtained from this deposit were removed and processed elsewhere by wet washing through window screen (1.5 mm mesh) so that specimens as small as bat incisors were recovered. In 1985, portions of the basal conglomerate in the fissure and in the solution pipe were removed with a jackhammer. At some later date the entire section was destroyed by limestone quarrying operations. All fossil specimens and geological samples are housed in the National Museum of Natural History (USNM), Smithsonian Institution, Washington, D.C.

2.3. Elevation of the marine fossiliferous deposits

Olson recognized that CQ was a high-elevation marine deposit and in 1984 arranged for a government surveyor to determine the elevation of the fissure at the level at which the excavations had taken place. This proved to be exactly 70 feet (+21.3 m) above sea-level based on a nearby benchmark (Fig. 1 lower). This survey was in general agreement with the observations from Government Quarry of Land et al. (1967) who described an erosional nip, first estimated to be at +28 m, then later revised to "approximately 70′ [feet]" (Hearty and Olson, 2008). Previous to learning of Olson's excavation at CQ, Hearty et al. (1999) described marine deposits of a similar nature in the two "Dead End" caves in Walsingham rocks which later proved to be situated between Olson's CQ excavation and the approximate location of the fossiliferous marine deposits described by Land et al. (1967). Calonectris Quarry contained beach sand and conglomerate of identical composition and texture to that in the Dead End Caves and to archived samples of Land et al. (1967), along with beach-worn but colored shells of marine mollusks. In summary, the only concrete information on elevation is the surveyed datum of +21.3 m obtained for Olson in 1984. Other estimates that have not been retracted are in basic agreement with that observation (Hearty and Olson, 2008).

3. Dating of the Calonectris Quarry deposits

3.1. Stratigraphic age

Several field and laboratory approaches were taken in order to determine the age of the deposits at CQ and associated deposits collected nearby at UGQ4-5 cave sites (Hearty et al., 1999; Kindler and Hearty, 2000; Olson and Hearty, 2003). The deposits are stratigraphically younger than the largely recrystallized rocks of the Walsingham formation (early Pleistocene) as they are deposited on and within voids in this formation (Table 1). The advanced diagenetic grade of the Walsingham, compared to overlying formations, has long been recognized in Bermuda (Bretz, 1960; Land et al., 1967; Vacher, 1971). In the field, there is little difficulty distinguishing the Walsingham and its capping Big Red Soil (BRS; Hearty, 2002b) from younger formations. The CQ deposits also clearly postdate the BRS, which overlies the Walsingham Fm, as clasts of the BRS, probably eroded as sea-level rose over the soil surface, were contained in the marine deposit. The BRS is interpreted as the result of a prolonged interval of subaerial exposure and weathering, probably due to a series of lower than present highstands that failed to produce carbonate sediments on the island from about 1.0 to 0.5 Ma (Hearty and Vacher, 1994). This estimated age range of the formation of the BRS is consistent with relative ice volume changes indicated from deep-sea isotope records (Lisiecki and Raymo, 2005), and is confirmed by ages of 442 ± 123 and 503 ± 110 ka from flowstone subsamples (Fig. 5; Table 2) overlying the BRS in a small cavern in the Walsingham Formation, Wilkinson's Quarry, Bermuda. Thus, observations of the physical and stratigraphic context and

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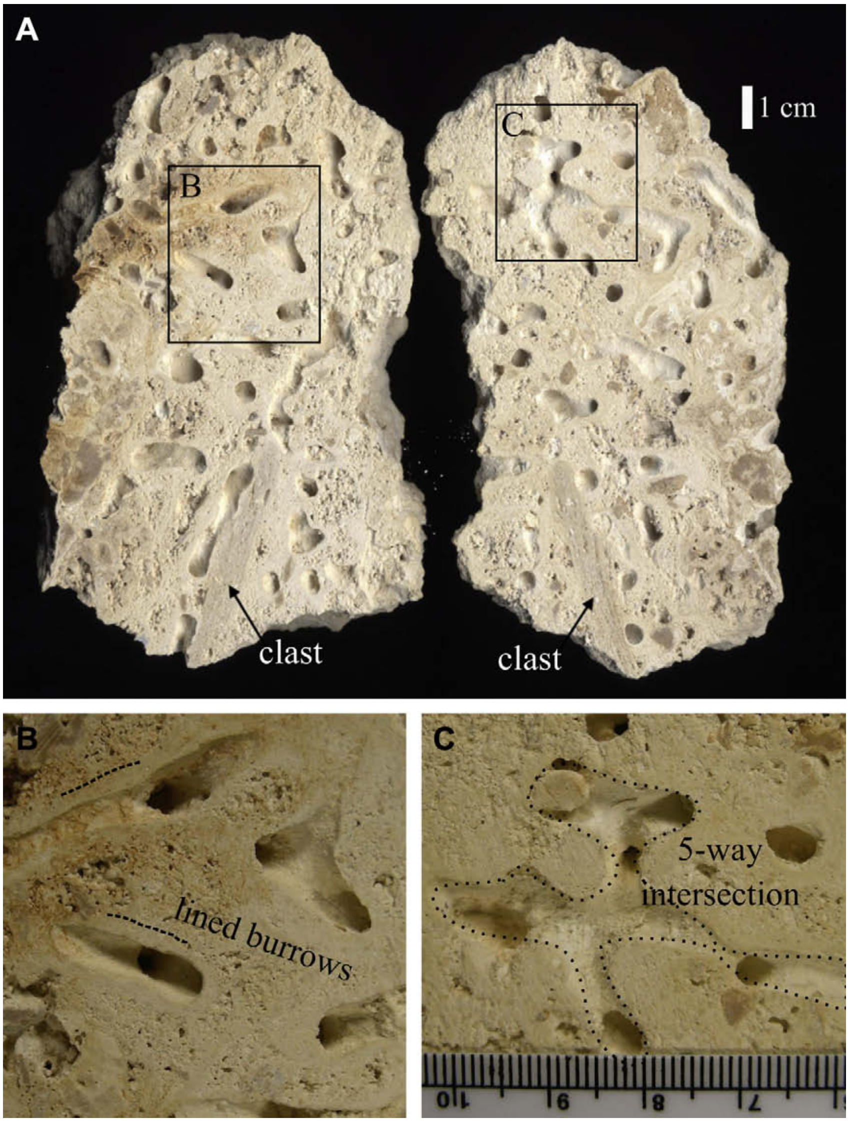

Fig. 4. A, cut surfaces of hand sample of lagoonal marl from B Pocket showing abundant burrows of marine invertebrates similar to those made by upogebiid shrimp ("type 5" burrows of Griffis and Suchanek, 1991). The long, thin clast of harder limestone (arrows) was not penetrated, indicating that the burrows were made in soft matrix. B, closeup showing indurated layer of walls of the burrows. C, closeup showing Y-shaped branching burrows.

diagenetic characteristics constrain the age of the CQ deposits to between the penultimate interglacial (MIS 7) and a mid Brunhes interglacial post-dating the BRS (i.e., younger than 500 ka). Replicate U/Th ages of 525 ± 50 and 530 ± 50 ka (Hearty et al., 1999) from a well-worn *Montastraea* sp. coral cobble about 5 cm in diameter from CQ appear to confirm a mid Brunhes correlation of the deposit.

Eolianites overlying the fossiliferous marine conglomerate and marl above +21 m are tentatively correlated with the Lower Town Hill Formation (Table 1) based partly on their position directly on the Walsingham Formation exposed in Government Quarry (Figs. 2 and 3). However, unlike the Walsingham, the CQ sediments are generally not recrystallized, in agreement with most other outcrops of middle Pleistocene sediments of Town Hill age (Hearty et al., 1992; Vacher et al., 1995). Their superior state of preservation (retention of original color, etc.) is partly due to protection offered by the cave environment, but also due to their relative youth; contrasting with the Walsingham Fm (>1.0 Ma versus <0.5 Ma) in which most carbonate organics are recrystallized. In contrast, the Lower Town Hill limestone is diagenetically more altered than widespread MIS 5e (<0.125 Ma) deposits around Bermuda (Hearty, 2002b).

3.2. Amino acid racemization (AAR) geochronology

A large database of AAR analysis of whole-rock (WR), the land snail *Poecilozonites*, and the marine bivalve *Glycymeris* provides a basis for age comparisons with CQ. WR samples were milled and sieved, split into two equal samples, and each prepared and analyzed on an ion exchange column (Miller and Brigham-Grette, 1989) to assess the analytical uncertainty within samples. The D-alloisoleucine/L-isoleucine, or A/I value is a measure of the extent of epimerization of the common amino acid isoleucine. A/I data (Table 3) are thus reported as 0.65 ± 0.03 (4) indicating the mean, 1σ standard deviation, and number of samples (e.g., "(4)" is the average of 8 preparations from 4 field collections; single preparations in the case of shells). Additional details of the WR sample preparation procedures and protocols are available elsewhere (Hearty et al., 1992; Hearty and Kaufman, 2000).

In living organisms, the A/I value after preparation is initially near zero (~0.015) and increases with age to a ratio of ~1.30. Several A/I modal classes or "aminozones" from the three different sample materials were calibrated with numerical ages by U/Th ages published in previous studies. Shells of *Poecilozonites* and

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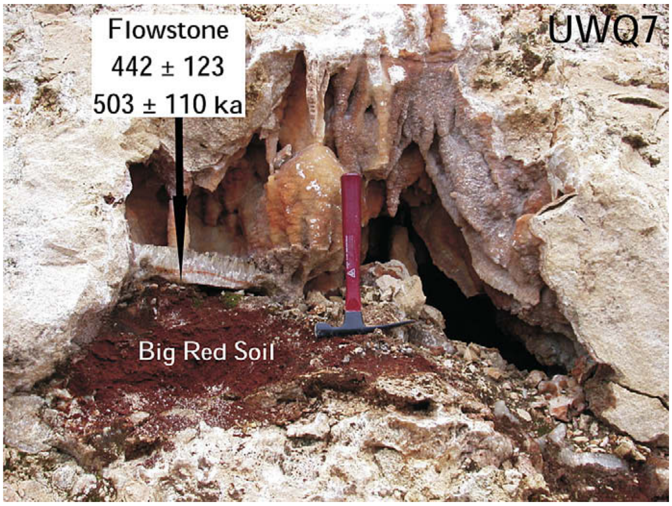

Fig. 5. A small cavern in the Walsingham Fm, Wilkinson Quarry, Bermuda, containing a pocket of Big Red Soil (BRS) overlain by flowstone yielding ICPMS U/Th ages of 442 ± 123 and >503 ± 110 ka. The ages support the finding that the BRS represents a long interval of non-deposition of carbonate on the Bermuda platform between 0.5 and 1.0 Ma, in agreement with relative ice volume changes inferred from deep-sea oxygen isotope records (Lisiecki and Raymo, 2005).

Glycymeris from CQ were analyzed and averaged (Table 3). In all cases, the shells were routinely sub-sampled from the aperture of *Poecilozonites* and the inner layers at the apex of *Glycymeris* (as in Hearty et al., 1992; Hearty et al., 2004). Each of these terrestrial and marine taxa from deposits on Bermuda demonstrates very consistent AAR results over several hundred thousand years. All AAR analyses were performed at the Amino Acid Laboratory of Northern Arizona University (D. Kaufman, Director) following the standard protocols of Miller and Brigham-Grette (1989).

3.2.1. AAR correlation and estimated age of marine sediments

Whole-rock bioclastic sand samples were collected from the surface of rounded cobbles, coarse and fine marine sands from A and B Pockets including the marine invertebrate burrows, and from within those burrows. The sediment from the cobbles produced A/I values of 0.89 ± 0.04 (2) and low concentrations indicative of largely reworked Walsingham sediment. A single coarse sand sample from the bottom of B Pocket produced a mean of 0.77 (1), possibly also reflecting the reworking of a substantial amount of older sediment. The remaining coarse and fine marine sediments from A and B Pockets yield a solid average of 0.65 ± 0.01 (4), slightly lower, but in total agreement with an island-wide, core MIS 11, Lower Town Hill value of 0.69 ± 0.01 (9) (Hearty et al., 1992), and a mean of 0.67 ± 0.05 (3) more recently obtained from Dead End caves (Hearty et al., 1999) (Table 3). Two samples from sediment filling the marine invertebrate burrows produced a mean of 0.58 ± 0.01 (2), reflecting a somewhat younger age corresponding with late Lower Town Hill values. To summarize, the WR A/I reinforce and replicate the physical stratigraphic relationships and succession, in the appropriate order of deposition/formation, and correlate the sand pockets with other dated marine deposits at c +20 ± 2 m, and published island-wide core MIS 11 values.

The CQ marine sediments produce whole-rock A/I ratios that are unambiguously correlated with structured and complex Lower Town Hill eolian and shoreline deposits at type section and various locations around Bermuda (Hearty et al., 1992; Hearty et al., 1999). Four TIMS U/Th ages on flowstone directly overlying (at millimetric scale) beach deposits at +21 m in Dead End Caves yield a weighted mean of 399 ± 11 ka (Hearty and Olson, 2008), confirming a correlation with MIS 11.

3.2.2. AAR of land snails and marine shells

Terrestrial pulmonate gastropods *Poecilozonites* cf. *cupula* from the CQ deposits yielded a mean A/I of 0.96 ± 0.04 (4) (Olson and Hearty, 2003). *Poecilozonites. cupula* from Lower Town Hill deposits on Bermuda produce a statistically similar mean of 0.91 ± 0.03 (9) (Table 3). The marine shell *Glycymeris pectinata* from the CQ deposits produce a mean of 0.99 ± 0.02 (2) (Olson and Hearty, 2003). *Poecilozonites* and *Glycymeris* are known to epimerize at similar rates, and the *Glycymeris* age model in Hearty et al. (1992) predicts a MIS 11 age estimate of 380 ± ~30 ka of the CQ beach deposit as calculated from the A/I from the marine shells, thus confirming a correlation with the Lower Town Hill Formation.

These relatively precise correlations among three different sample materials (marine pelycepods, terrestrial gastropods, and skeletal marine sediment) from CQ with the type locality at Bierman's Quarry (on "Town Hill") and other well known Lower Town Hill sections around the island are highly improbable if a tsunami formed the deposits, as they would consist of an admixture of marine and terrestrial debris of various ages scooped up from the Bermuda shelf and island. Even more implausible if formed by tsunami is the fact that MIS 5e/11 amino acid and numerical age relationships agree between Bermuda, Bahamas, and Hawaii as explained in Hearty (2002a). Hearty and Olson (2008) further strengthened the correlation between widespread locations in multiple ocean basins.

4. Paleobiology

4.1. Marine invertebrate burrows

A fine-grained, chalky limestone or "marl" was collected from the base of both A and B pockets (Figs. 3 and 4), which contains partly sediment-filled, smooth-sided, meandering and branching burrows with a consistent width of about 5 mm (Fig. 4). Segments of individual burrows extend for lengths of at least a few cm. Y-shaped branching or even more complex branching intersections are characteristic (Fig. 4B and C). Walls of these burrows are lined with a thin (<1 mm), hardened layer of micrite (Fig. 4B), making the burrows sufficiently strong that they were later partially infilled by soft matrix rather than collapsing. These burrows appear to be

Table 2
U/Th data and ages from 2 subsamples of a flowstone directly overlying the Big Red Soil in a small cave in Wilkinson Quarry, Bermuda.

Sample	U (ppm)	^{230}Th (ppt)	^{232}Th (ppb)	δ^{234}U[a]	^{230}Th/^{238}U[b]	[^{230}Th/^{232}Th]	Age (ka)[c]	Initial δ^{234}U[d]
UWQ7c1	0.05127	0.84307	0.48890	24.34 ± 5.36	1.0159 ± 0.0139	323.54	442 ± 123	85 ± 30
UWQ7c2	0.03643	0.60363	0.07046	24.19 ± 8.63	1.0237 ± 0.0145	1608.0	503 ± 110	101 ± ?

[a] $\delta^{234}U = \{[(^{234}U/^{238}U)/(^{234}U/^{238}U)_{eq}] - 1\} \times 10^3$. $(^{234}U/^{238}U)_{eq}$ is the atomic ratio at secular equilibrium and is equal to $\lambda_{238}/\lambda_{234} = 5.4891 \times 10^{-5}$, where λ_{238} and λ_{234} are the decay constants for ^{238}U and ^{234}U, respectively, adopting half-lives of Cheng et al. (2000).

[b] $[^{230}Th/^{238}U]_{act} = (^{230}Th/^{238}U)/(\lambda^{238}/\lambda^{230})$.

[c] U/Th; ages are calculated iteratively using: $1 - [^{230}Th/^{238}U]_{act} = \exp^{-\lambda_{230}T} - (\delta^{234}U(0)/1000)\,(\lambda_{230}/(\lambda_{230} - \lambda_{234}))\,(1 - \exp(^{\lambda_{234}}{}^{-\lambda_{230}T}))$ where T is the age in years and λ_{230} is the decay constant for ^{230}Th. $\lambda_{238} = 1.551 \times 10^{-10}\ y^{-1}$; $\lambda_{234} = 2.826 \times 10^{-6}\ y^{-1}$; $\lambda_{230} = 9.158 \times 10^{-6}\ y^{-1}$.

[d] The initial value is given by $\delta^{234}U_i = \delta^{234}U(0)\exp(\lambda_{234}{}^{T})$, where T is the age in years.

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Table 3
Results of amino acid analyses of whole-rock (WR), *Poecilozonites*, and *Glycymeris* shells from Calonectris Quarry. WR is compared to mean values for the Lower Town Hill Fm, Bermuda (Hearty et al., 1992, 1999).

AAL #	Material	Mean	±1σ	CV	N = samples[a]	Comments
Calonectris whole-rock samples						
6237 B	WR	0.57	0.03	5.7	1	Late 11 or 9
6239 B	WR	0.59	0.01	1.3	1	Late 11 or 9
6240 B	WR	0.63	0.01	1.4	1	Core MIS 11
6238 B	WR	0.66	0.01	2.0	1	Core MIS 11
6241 B	WR	0.65	0.00	0.5	1	Core MIS 11
6243 B	WR	0.65	0.01	1.3	1	Core MIS 11
6244 B	WR	0.77	0.03	4.3	1	Core MIS 11 + RW Wals
6236 B	WR	0.86	0.03	3.0	(1)	Wals sand? Low concentration
6242 B	WR	0.92	0.04	4.2	(1)	Wals sand? Low concentration
Comparison of WR means						
Lower Town Hill	Mean	0.69	0.01		6	Hearty et al., 1992
UGQ4-5	Mean	0.67	0.05		3	Hearty et al., 1999
CQ above	Mean	0.65	0.06	9.6	7	This study
Poecilozonites CQ						
3168	*P. cupula*	0.95	0.01	1.1	1	
3169	*P. cupula*	1.03	0.03	2.5	1	
3170	*P. cupula*	0.94	0.01	1.3	1	
3171	*P. cupula*	0.94	0.02	2.2	1	
Mean		0.96	0.04	4.6	4	Olson and Hearty, 2003
Lower Town Hill	*P. cupula*	0.91	0.03		9	Hearty et al., 1992
Glycymeris CQ						
2684	*G. pectinata*	0.98	0.00		1	
2684	*G. pectinata*	1.01	0.01		1	
Mean		0.99	0.01	1.1	2	Olson and Hearty, 2003

[a] Each WR sample consists of duplicate preparations and analyses, averaged to yield analytical uncertainty. Samples in parentheses are not included in the mean.

closely similar to those of thalassinidian shrimp making the "type 5" burrows of Griffis and Suchanek's (1991) classification. Burrows did not penetrate larger indurated intraclasts (Fig. 4A) indicating that the matrix was soft when burrowed. The burrows were partially filled by medium-grained bioclastic carbonate sand that likely entered after their abandonment.

After microscopic examination (by P. Kindler, U. Geneva), the "marl" was classified as wackestone with ∼80% micritic matrix. It contains bioclasts of red algae, benthic foraminifers (miliolids, rotaliids), mollusk shell fragments (some very thin), and rare planktonic foraminifera (Fig. 6B) suggesting the proximity of open ocean circulation. Lithoclasts include rounded bioclastic grainstone (some over 5 mm in diameter), angular and rounded mud clasts some containing planktonic foraminifera (Fig. 6), and a variety of fine-grained allogenic minerals (possibly quartz, apatite, and iron oxides, Fig. 6C, D) almost certainly derived from the volcanic basement.

The occurrence of silt-sized carbonate grains and mud clasts with planktonic foraminifera clearly suggests a low-energy marine depositional environment, which is further corroborated by the abundance of thin-shelled molluscs (Fig. 6B). The marine shells, benthic foraminifers, red algae, and burrowing marine invertebrates indicate a generally tranquil coastal marine environment, possibly a protected lagoon situated platformward adjacent to a deep-ocean margin, much like the current setting on the South Shore of Bermuda. Catastrophic, high-energy, or persistent wave impact would certainly have destroyed the burrows unless well protected. The burrowed wackestone shows that sea-level was at or above the position of the A and B pockets (+21.3 m), and remained there for a duration sufficient to accumulate the biogenic sediments, be colonized and burrowed by marine invertebrates, and to become hardened subsequently so as to preserve the marine fossil traces. Evidence for this shallow subtidal environment of deposition is bolstered by isopachous "rim" cements (Fig. 6D) similar to those described from nearby UGQ 4/5, exposed terrace deposits at +20 m in the Bahamas (Hearty et al., 1999; Kindler and Hearty, 2000), and +28 m in Hawaii (Hearty and Olson, 2008). However, in this particular case, the rims are composed of calcite relatively low in Sr (P. Kindler, personal communication, March 2008). This suggests either the original marine aragonite has reverted to calcite and Sr lost, or possibly the cements may have formed under fresh water phreatic conditions. Because the caves under discussion were situated near the morphological crest of a dune and the old limestone in the area is profusely perforated with solution conduits, a perched water table would have been highly unlikely, and no such elevated features of any size are known from the island today. A prolonged submergence by fresh and/or salt water (at least tens to hundreds of years as evidenced by rates of cementation in beachrock) is required to produce the well-developed rim cements observed in CQ deposits (Fig. 6D). Because a sustained perched groundwater table is not likely, and given the abundance and diversity of supporting data, we surmise that both a shoreline and a Ghyben-Herzberg freshwater lens were present for some duration above +20 m, and were responsible for the formation of isopachous rims throughout these marine sediments.

4.2. Biodiversity of the Calonectris Quarry deposits

For a very small volume of deposit (<0.18 m^2), the diversity of fossil organisms recovered is remarkable (Appendix A). The Calonectris Quarry deposit is a classical example of a Concentration Lagerstätte (Seilacher et al., 1985) and is perhaps the oldest known for any small oceanic island, as opposed to the youngest claimed for Mauritius (Rijsdijk, 2008). The fossils occurring here include (minimum number of *species* in parentheses): a coral (1), sea urchins (2), bivalves (13), aquatic snails (23), terrestrial snails (3), crabs (7), fish (9), a lizard (1), seabirds (4), land birds (3), and a bat (1). The circumstances of deposition must have been truly extraordinary as we know of no other instance on Bermuda or other oceanic islands where such diversity of organisms has been found in such a small volume of sediment.

It would be difficult to hazard a guess at how long such an assemblage might take to accumulate under modern conditions, but one might expect that for 7 individuals of 3 species of land birds and a vagrant bat to die and be transported into a crevice 3 m wide a period of months or even years would be required. As discussed under taphonomy, the accumulation of seabirds probably had to take place over a period of a minimum of months but more likely much longer. Likewise, such a diversity of fish and marine invertebrates would be unlikely to wash up on a beach in only a few days or to be cast out of the sea during a "megatsunami" (McMurtry et al., 2007) and then deposited into a void in the rocks of only 0.18 m^3. The catastrophic process of tsunami is particularly important as it relates to the large number of bird remains, as they may exercise the option of flying away from danger.

On the other hand, if sea-level was at or above +20 m, the terrestrial biota of Bermuda would have been concentrated on several very small islets (Olson and Hearty, 2003). Consequently, all land organisms of necessity would be living and dying close to the shoreline. Potential seabird nesting sites would have been greatly reduced and long-lived petrels and albatrosses may have stayed around the islands in vain attempts to nest until they died and washed ashore.

Depending on the angle at which the waves struck the beach, carcasses may have been carried along the cliff face by longshore drift for some distance before arriving at the fissure, so that the area of catchment was probably greater than the width of beach immediately in front of the fissure. Nevertheless, this area would still have been relatively small, so that it is hardly possible that such

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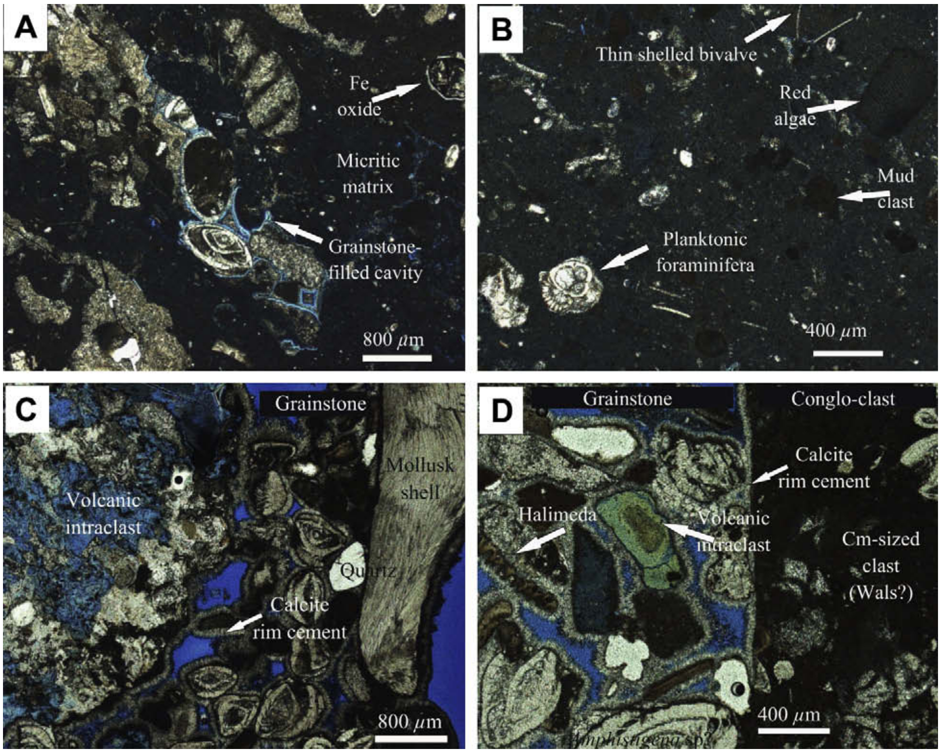

Fig. 6. A, grainstone-filled cavity in micritic sediment matrix in burrowed marl, B, planktonic foraminifera and thin-shelled bivalves in muddy matrix of burrowed marl. C, shells and volcanic clasts among bioclastic grains bound by an isopachous rim cement. D, contact between worn cobble of Walsingham eolianite and marine bioclastic sand, with volcanic grains all cemented by rim cements.

a diverse assemblage of organisms could be deposited in a single tsunami event that took place geologically instantaneously.

Perhaps one of the most telling indications of sea-level is the abundance of two species of snails that today are restricted to brackish or marshy situations. Hydrobiids in Bermuda, represented in CQ by ca 200 individuals, occur only in fresh or brackish water. Another ca 200 individuals of the ellobiid snail *Myosotella* would have lived just above the high-water mark and today are found in marshes or mangroves. The presence of such significant numbers of fresh or brackish water snails is consistent with a Ghyben-Herzberg lens existing in the rocks adjacent to a quiet marine lagoon at an elevation above +20 m.

4.3. Taphonomy of avian fossils

The state of preservation of the seabirds, particularly the *Calonectris* shearwaters, is informative. In the small space of A and B pockets, a minimum of 26 individuals of *Calonectris* were collected, including 2 pre-fledging juveniles at different stages of development that had to have hatched on Bermuda, presumably near the site of deposition. The composition of skeletal elements of the adults is entirely consistent with individuals having died at sea and that underwent varying periods of decomposition before being washed ashore. Schäfer (1972: 46) noted that after 27 days the carcass of a gull (*Larus argentatus*) was "still afloat, the head hangs into the water and is well-preserved, even skin and feathers. The legs, however, have dropped away; the sternum, too, has separated from the skeleton and has sunk to the sea floor… Many carcasses of birds which have died on the open sea reach the beaches before sinking because the bodies drift for weeks." The minimum number of 24 adults is based on humeri, whereas apparently fewer than half of those were washed into the deposit with the legs still attached as only 10 individuals are indicated by tarsometatarsi. Likewise, there were only 14 sternal manubria. Heads are also underrepresented at 15, based on the number of rostral hooks, suggesting that there may have been some loss of elements through tumbling in the surf, so that some carcasses that entered the deposit were reduced to the wings and pectoral girdle, which are held together by strong ligaments. Yet others must have been interred relatively intact as some delicate skulls with the rostrum still attached were included (Fig. 7). It is hardly likely that these birds that died and partially decomposed at sea would have their remains, some in an excellent state of preservation, be concentrated in a deposit at +21.3 m unless sea-level was near that elevation at the time of deposition.

Mass mortality ("wrecks") of seabirds can produce large numbers of carcasses in a short period, but the apparent differences in degree of decomposition of carcasses of *Calonectris* indicates that they must have died at different distances from land and were in the water for different amounts of time, so it is highly unlikely that all came ashore in a single period between high waves reaching the fissure. Furthermore, at least 4 and perhaps 5 individuals of seabirds were pre-fledging and would not have been part of any pelagic "wreck." The two juveniles of *Calonectris* are at such different stages of development that they would have to have died weeks apart, given the normal degree of breeding synchronization of most procellariiform birds. The taphonomic evidence, including a variety of seabirds of various ages and in various stages of decomposition indicates accumulation over a considerable period of time and is contrary to instantaneous deposition by tsunami.

5. Discussion

5.1. General interpretation of the depositional environment

We can interpret the Calonectris Quarry deposits only in light of sea-level having been at or near the same height as the deposits themselves for an extended period of time during MIS 11. Deposition took place in a small niche at the base of a cliff or escarpment of old

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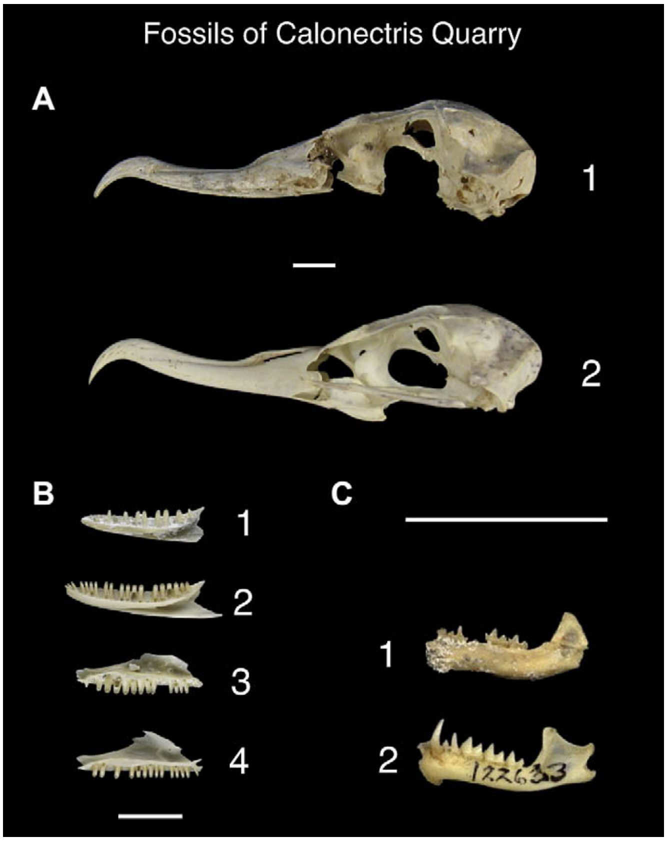

Fig. 7. Selected vertebrate fossils from Calonectris Quarry to show delicate preservation. A, (1) skull of the extinct endemic Bermuda shearwater *Calonectris wingatei,* (2) modern *Calonectris d. diomedea*. B, (1, 3) fossil dentary and maxilla of the Bermuda skink *Eumeces longirostris* compared with modern individual (2, 4). C, (1) fossil mandible of vagrant red bat *Lasiurus borealis* compared with modern specimens of the same (2).

Walsingham limestone that intersected karstic features such as a solution pipe. It is not clear whether this niche was at the back of a shallow cave or not but Walsingham rock does not extend over the top of the fossiliferous pockets at the excavation.

Coarse, angular rubble with numerous marine and some terrigenous inclusions were washed into the niche, filling the solution pipe and flooring the void. The rubble was cemented to conglomerate by isopachous rim cements, which are generally interpreted as having formed during prolonged inundation. The mix of clasts included in the conglomerate probably represents a combination of surface and cave colluvium and fresh marine material, which probably accumulated in the void early in the transgressive phase of the MIS 11 sea-level rise. The angularity of some of the colluvial clasts was preserved because once the voids were packed with sediments, they were stabilized and could no longer be worked by the sea. The partial colluvial composition and probable reworking of the surface sand and conglomerate is further supported by high A/I values and very low amino acid concentration as would be typical of reworked Walsingham-age sediments.

Subsequent to emplacement of the conglomerate, sea-level rose above the crevice and a quiet lagoon formed that became floored with a mixture of fine soft carbonate silt and sand that was heavily burrowed by marine invertebrates, which can only be explained by sustained marine inundation. The burrowed wackestone may well have nearly filled the crevice and later partially eroded away by wave action when sea-level receded.

During the regressive phase, a sloping beach of carbonate sand formed in front of the fissure. These marine sands produced numerous whole-rock A/I ratios that are virtually identical to those of Lower Town Hill marine and eolian successions around Bermuda (Hearty et al., 1992), as well as marine sediment (also with rim cements) from the nearby caves (Hearty et al., 1999; Kindler and Hearty, 2000).

We postulate that most of the fossils in the sandy sediments of Calonectris Quarry were deposited at a point when sea-level was such that only the highest waves, perhaps of spring tides, reached the base of the cliff. Longshore drift along an adjacent sandy beach would carry carcasses of vertebrates up to the cliff face, where they washed into the fissure where the fossils were concentrated.

5.2. *Analysis of possible alternative explanations*

Emplacement of elevated marine deposits, such as Calonectris Quarry and Dead End Caves on Bermuda, can theoretically be explained by more than one geological process. In a tectonically stable environment, eustatic sea-level rise to the elevation of the deposit, such as we propose, would be one means. Another would be through a violent and random geological event such as a tsunami that carried marine sediments from a lower elevation up to the level at which the deposit occurred (McMurtry et al., 2007), or their accumulation as storm deposits high above sea-level by wave splash, as Mylroie (2008) has suggested for correlative +20 m deposits in Eleuthera, Bahamas. Finally, it may be postulated that the land itself has not been stable, that the marine deposits formed at a lower elevation and were later carried to a higher position through tectonic uplift.

5.2.1. *Emplacement by tsunami?*

McMurtry et al. (2007) proposed that the marine deposits found at the adjacent UGQ 4/5 cave sites did not result from a maximal eustatic rise to +20 m but were instead emplaced catastrophically by a "megatsunami" generated by various known and hypothesized undersea events. We rebutted this idea (Hearty and Olson, 2008) and McMurtry et al. (2008) responded in turn. The issues appearing to favor their tsunami hypothesis (italics) and our brief response to them (refer to the Section 5-reply articles for details) are as follows:

(1) *That the elevation of the deposits occurs across a wider elevation between +18 to +28 m. Such a range, extending to a maximum of +28 m, favors a tsunami origin*. The original reference to the deposits under consideration extending to +28 m by Land et al. (1967) was an estimate. The only precisely surveyed elevation of the deposits of "70.00 ± 0.08 feet" (+21.3 m) was conducted by the Bermuda Ministry of Works at the request Olson in 1984. We therefore believe that the upper limit of these deposits is no more than +22 m.

(2) *That the sedimentology of the deposits suggests tsunami deposition as opposed to that associated with a long-lived highstand*. First, McMurtry et al. (2007, 2008) have yet to demonstrate what deposits from *known* tsunami events look like in comparable depositional settings. Their reference to megatsunami deposits in Kohala, Hawaii (McMurtry et al., 2008, Fig. 1a on p. 314), emphasizes this point because those Pleistocene deposits were not necessarily emplaced by a *known* "megatsunami" as one may be led to believe. Indeed, from a sedimentological perspective, we suspect that they are deposits typical of a rocky shoreline. Alternative hypotheses such as sea-level highstands are not considered by McMurtry et al., 2007, 2008). Secondly, a tsunami wave moving at speeds of up to 800 km/h (Noson et al., 1988) and overflooding the entire Bermuda platform, presumably with blue water, would be unlikely to emplace *anything* in a closed-pipe system such as the Dead End Caves rather than evacuating the contents of the caves in a series of violent explosions of compressed air, rock, and water (Hearty and Olson, 2008). Thirdly, why are such deposits not widespread on Bermuda and the East Coast of North America and the

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Caribbean? A tsunami wave with a height of 20 m *at sea* as postulated by McMurtry et al. (2007) would have built up to enormous height and destructive power upon piling up on the extensive shallows of eastern North America, yet where is the evidence for such a cataclysmic event in the geological record of that continent?

(3) *That isopachous "rim cements" were formed in sandstone on a distant lower shoreline, then transported by a megatsunami into the caves at +21 m where successive generations of cements were formed.* We disagree with this argument, suggesting instead that in order to for rim cements to form in several deposits at and around +20 m, sea-level and an associated freshwater lens must have been present at the same elevation for a protracted period of time.

(4) *That the microfauna represent an odd mixture of coastal environments collected and deposited by "an energetic event (the putative tsunami)".* The ancient caves, filled with marine deposits and microfauna, were located in close proximity to diverse coastal environments and were mixed by normal longshore processes, as we have documented here.

(5) *That U/Th dating from flowstone overlying marine deposits at around +20 m in Government Quarry reflects a wider range in ages than* Hearty and Olson's (2008) *weighted mean of 389 ± 26 ka* ($n = 5$). Our field observations show that the surface of the beach deposits on which the flowstone was deposited is irregular, and thus flowstone would first pond in the lowest areas, then progressively fill and cover broader areas. Even the most precise microsampling may not collect the very first flowstone to form on this irregular surface. However, five U/Th ages of this flowstone at its lowest levels provide a weighted average of 389 ± 26 ka and thus reasonably associate the underlying marine event and sea-level of +20 ± 2 m with MIS 11. Although there are "likely candidates" (McMurtry et al., 2008, p. 317), neither flank margin collapse events nor megatsunami emanating from them have been dated during MIS 8, 9, 10, or 11 (Masson, 1996; Masson et al., 2002), and are thus purely conjectural. Therefore, neither the cause nor the geologic effects of these hypothetical events are clearly demonstrated.

(6) *That a 20 m tsunami wave generated the deposits observed.* McMurtry et al. (2007) suggest that a tsunami wave that rose over 20 m *at sea* is an alternative hypothesis for the deposits under consideration, citing the modeling work of Ward and Day (2001). Tsunami waves at sea, however, are typically less than a meter high and only build up higher upon piling up in shallow water (Heliker, 1990). A tsunami arriving at Bermuda from the east would not encounter any shallow water and would break directly on the Bermuda pedestal, thus necessitating a highly anomalous (implausible?) 20 m high wave in order to reach the elevation of the Dead End Caves. Such a complete washover would have likely exterminated all terrestrial animals on Bermuda, yet as we document here, at least one species of lizard, two species of small land birds, and several lineages of land snails survived through MIS 11 and lived on into the late Holocene.

Our present study provides unique documentation through biological and ecological observations from CQ that cannot be explained by a single catastrophic washover of Bermuda by a "megatsunami." Perhaps the two most important of these are:

(1) The presence of fine lagoonal silts containing abundant, well-preserved burrows of marine invertebrates (most likely thalassinidian shrimp) indicating sustained low-energy sedimentation in ocean water that was over +21.3 m elevation.

(2) The presence of abundant snails at +21.3 m that only occur either in fresh (hydrobiids) or brackish water (ellobiids) just above the tide line.

5.2.2. Uplift of the Bermuda platform?

The Bermuda platform rests upon an ancient volcanic pile last active during the Oligocene (Reynolds and Aumento, 1974). The volcanic seamount is several thousand meters thick, has a pillow-basalt density equivalent to the densest lithosphere of >2.5–3.0 gm/cm^3, is over a hundred km in circumference, and situated in the abyssal plain of the western North Atlantic on relatively thin oceanic lithosphere far away from any active plate margins (Vogt and Jung, 2007). Unless gravity fails or loci of plate tectonics shift, the seamount and its platform have been sinking, are sinking, and will continue to sink. All subaerial volcanics have been removed either by erosion or subsidence, or both, but still exist as little as 26 m below present sea-level (Vogt and Jung, 2007).

By all who have studied the surficial geology, the exposed rocks have been considered to be no older than early Pleistocene (Hearty et al., 1992; Vacher et al., 1995). Bermuda is considered a "tide gauge" for Quaternary highstands (Harmon et al., 1983) based on its diagnosis as tectonically stable (Land et al., 1967). The traditional view is that the maximum rise of sea-level in the Pleistocene was about +6 m during MIS 5e (Harmon et al., 1983), but Hearty (2002b) offered detailed evidence of early stability at +2.5 m, and late fluctuations of sea-level at and over +6 m at the close of MIS 5e.

From a global perspective, the sea-level positions in Bermuda during MIS 5e are in precise agreement with most sites from demonstrably stable coastlines and carbonate platforms, including Oahu with a minor 3 m correction for uplift since the Last Interglaciation (Hearty et al., 2007a). Thus, any argument suggesting that Bermuda has been uplifted contradict the sea-level record, as well as the physical, crustal, and mantle rheology of the North Atlantic abyssal plain. Furthermore, there is no evidence of any such dynamic tectonic forces acting anywhere in the western North Atlantic at the latitude of Bermuda (Vogt and Jung, 2007).

For the Calonectris Quarry deposits to have been raised tectonically to the elevation of 21 m above present sea-level would require >14 m of uplift in only 400 ka. Had this been the case, the evidence would be obvious and overwhelming. An uplift of 14 m would not involve the just the area of Government Quarry but the entire Bermuda platform so that Bermuda would now be exposed as an island of about 650 km^2 surrounded by steep cliffs of volcanic rock with a carbonate cap that would lack evidence of a significant portion of later Pleistocene interglacials. Because this is clearly not the case, uplift is not a viable explanation for the elevation of the Calonectris Quarry deposits.

5.2.3. Evidence for +20 m deposits in MIS 11 outside of Bermuda

Field studies on middle Pleistocene deposits in the Bahamas (Hearty et al., 1999; Kindler and Hearty, 2000), Oahu, Hawaiian Islands (Hearty, 2002a), the North Slope of Alaska (Kaufman and Brigham-Grette, 1993), the United Kingdom (Bowen, 1999) (but see Preece et al., 1990), Curaçao–Netherlands Antilles (Lundberg and McFarlane, 2002), and South Africa (Roberts et al., 2007) have also been interpreted as indicating that sea-level rose in excess of 20 m above present during MIS 11 about 400 ka ago. Either the elevation or the timing of some of these deposits has been challenged. Here we summarize the current status of the literature with a brief assessment of the likely validity of the challenged data, as this is not the place for more detailed discussion.

Mylroie (2008) does not directly challenge the origin of the +20 m deposits in Bermuda, although his subjective dismissal of deposits in North Eleuthera, Bahamas brings into question the occurrence of this highstand globally. Lacking any scientific evidence, Mylroie (2008) opined that the +20 m beach deposits described in Hearty et al. (1999) are sediments tossed up by waves at some undefined time in the past. We argue that there were no cliffs when the MIS 11 beach sequence was deposited. In the Bahamas today, ooids are formed on a broad, energetic, and

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shallow shelves. Because of the abundance of ooids formed during both MIS 11 and 5e in North Eleuthera, we infer that there must have been an eastern shelf present during that interval. Mullins and Hine (1989) cite the morphological evidence of scalloped margins, and Freeman-Lynde and Ryan (1985) cite seismic data and observations from submersibles that indicate a Late Quaternary collapse of the bank margin along sections of the northeastern Bahamas. The eastern shelf of Eleuthera was apparently lost to erosion or collapse of the margin since MIS 5e (Hearty and Neumann, 2001). If there were no cliffs, there was no wave splash, no storm deposits, and no abrasion platform on which subtidal facies could form.

Furthermore, two outcrops of the deposits occur at +20 ± 2 m at two locations separated by several hundred meters. The beach deposits lie on an abrasion surface and are bedded, filled with fenestral porosity, and dip seaward. They are formed of pristine spherical ooids and contain no shells, intraclasts, fragments of older rocks, or anything comparable to the recent storm deposits. Mylroie's (2008) opinion is not supported by any evidence that would clearly establish the distinctively different sedimentological characteristics between wave splash deposits and a graded and bedded, ooid beach facies.

It has been suggested (McMurtry et al., 2008) that correlative deposits of the Kaena highstand in Oahu, Hawaii are in fact MIS 13, and were uplifted to their current position at +26 to +30 m over the past >500 ka. Hearty (2002a) established a MIS 11 age of these deposits based on uplift rates of about 0.020 ± 0.005 m/ka calculated primarily from a conspicuous, broad early MIS 5e bench and reef terrace at ca +5 m that is widespread on Oahu. The previously published dates from the Kaena highstand deposits are at the virtual limits of the U/Th method, and therefore even the slightest contamination would render them inaccurate as pointed out in Hearty (2002a). Furthermore, if the deposits were >500 ka and the entire +30 m is attributed to uplift from an original estimated eustatic position of −15 to −20 m for MIS 13 (cf. Lisiecki and Raymo, 2005), the required uplift rate would necessarily increase by a factor of four to five times (~0.1 m/ka), which is clearly incompatible with the established rate as determined from MIS 5e and MIS 1 benchmarks on the island.

5.3. *Why other lines of evidence may not reveal a +20 m spike in MIS 11*

Most of the reluctance to accept a sea-level rise of more than 20 m in the mid-Pleistocene derives from the perceived lack of corroboration from other fields of investigation. Although we cannot provide *direct* contrary evidence from these disciplines ourselves, we can offer some explanations for why evidence of a +20 m sea-level may not yet have been detected.

5.3.1. *The deep-sea marine isotope record*

At the outset, it should be recognized that geological measurements of marine deposits on palaeo-shorelines are far more direct and accurate than proxy methods such as isotope analyses. Rocks on the shoreline can be measured, dated, and analyzed for sedimentology and facies characteristics, from which sea-level position can be directly determined and interpreted. By definition, proxy methods cannot provide a concrete measure of sea-level position or global ice volume. Thus, seeking confirmation of a +20 m sea-level excursion using deep-sea isotope ratios is a challenge to the highest precision and optimal output of this technique.

Changes in oxygen isotopes trapped in the tests of foraminifera included in deep-sea sediments have been used to plot changes in ocean temperatures, and consequently in ice volume and sea-level (Poore and Dowsett, 2001; McManus et al., 2003). Generally, oxygen isotopes can provide only a relative indication of ice volume changes due to the uncertainties inherent in several elusive and perhaps stochastic variables. Each single δ^{18}O ratio is the iterative sum of the variable effects on the sample including ice volume, salinity, temperature, diagenesis, vital effects, and analytical error. Furthermore, every δ^{18}O ratio from each core level comprises a number of individual foraminifera (generally from 10 to 30). These foraminifera have most often been bioturbated for (at least) decimeters above and below core levels, which adds an additional uncertainty of many meters of sea-level equivalence and thousands of years. Further, the determination of average isotope ratios involves discarding non-Gaussian data points. If a sea-level event, for example, takes place over a geologically short span of time, isotope values from foraminifera deposited during this event could well be the very ones to be discarded in the process of averaging. A further difficulty is that direct dating of the δ^{18}O record is extremely limited and generally depends on "finger matching" or interpolation from the Brunhes-Matuyama magnetic reversal at 0.78 Ma to establish an *approximate* age.

In some rare cases, ocean sediments are weakly laminated and show little sign of bioturbation. Such an example exists in the Cariaco Basin north of Venezuela, where Poore and Dowsett (2001) provided isotopic evidence suggesting a sea-level from 10 to 20 m higher than present during MIS 11.

We suggest that the lack of isotopic confirmation of a +20 m sea-level may be rooted more in the fact that few serious investigations have looked for it rather than the event being absent. In the future, we anticipate more rigorous analyses of individual foraminifera from high-precision sampled core levels from the MIS 11 time span could potentially reveal the intense negative δ^{18}O excursion indicated by direct geological analysis of sea-level indicators.

5.3.2. *Ice cores*

During the Last Interglacial, Greenland was reduced by nearly half or more (Otto-Bliesner et al., 2006) and it can be reasonably inferred that other long and warm interglacials produced a similar result. Although there is no ice core record from Greenland beyond the Last Interglacial, Stanton-Frazee et al. (1999) observed from ODP Site 982 offshore of Greenland that for a period of 23 ka during MIS 11 there was no ice rafted debris (hence no icebergs; no ice). Melting of Greenland ice would raise sea-level about 6.5 m (Williams and Ferrigno, 2008)

The greatest contribution to MIS 11 sea-level was probably made from the marine-based West Antarctic ice sheet (WAIS) and adjacent ice drainages, as we have published elsewhere (e.g., Hearty et al., 1999) and there is evidence supporting the collapse of the WAIS during the middle Pleistocene as inferred from diatom assemblages and cosmogenic isotopes (Scherer et al., 1998). Melting of the WAIS would contribute another 8.0 m to global sea-level (Williams and Ferrigno, 2008), which would mean that the East Antarctic ice sheet would have to have contributed about 5.5 m in MIS 11 in order to raise sea-level to +20 m. Isotopic composition of the ice and air suggests no significant changes in surface elevation at Vostok or Dome C in the central part of East Antarctica (EPICA, 2004), which has been raised as an objection to the our contention of a 20 m rise, but this evidence comes from a distant part of East Antarctica which may have been less sensitive physically to ice drawdown on the opposite side of the continent.

5.3.3. *Why rapid spikes in sea-level may leave little evidence on coastlines*

Platforms and reefs in tropical areas would have responded slowly to a rapid rise of sea-level (Hearty et al., 2007b), or were submerged beyond their ability to "catch up" biologically (Neumann and MacIntyre, 1985). A deep inundation would leave

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few sedimentological traces, although those we observe are unambiguously diagnostic of the shoreline and sea-level position. We attribute this scarcity of traces to the much greater age and the brevity and instability of the sea-level position during the peak MIS 11 interval, to subsequent erosion and burial of sediments and traces, and to the general lack of older rock masses on low-lying islands above this elevation on which to preserve marine deposits (as explained elsewhere in Hearty, et al., 1999; Hearty, 2002a).

There is some supportive evidence from Barbados, however, where three mapped terraces have been correlated with MIS 11 (Schellmann and Radtke, 2004, p. 98 ff). The two lower ones at 100 and 110 m in the Christchurch-South Point traverse are the most extensive, while the highest at 120 m is poorly represented. Although it is inherently difficult to separate eustatic sea-level and tectonic movements in localities such as Barbados, the number and vertical spread of terraces and interpreted sea-levels (Schellmann and Radtke, 2004, their Fig. 4.24) resemble the MIS 11 sequences we have described elsewhere (Hearty and Olson, 2008). Likewise, the lithostratigraphic *succession* representing multiple sea-level oscillations from Oahu (Hearty, 2002a), Eleuthera, Bahamas (Hearty, 1998; Hearty et al., 1999), and other sites around the globe, when compared with the MIS 11 rock record from Bermuda, are too compelling to be due to coincidence and serendipity.

6. Conclusions

Various lines of scientific evidence over the last decade have led to the conclusion that the last million years of the Quaternary may be viewed as consisting of two disparate halves. The early portion (1.0–0.5 Ma) was a quiescent, stable period when fluctuating sea-levels were always below that of the present and this period is marked in many places by massive soil development. This was followed by a turbulent later half (0.5 Ma to present) in which the amplitude of sea-level fluctuations was much greater, resulting in several major interglacial flooding events. The point of transition is MIS 11, which has long been recognized as one of the longer and warmer Quaternary interglacial episodes (Howard, 1997; Droxler and Farrell, 2000; McManus et al., 2003; EPICA, 2004).

As we have established here and elsewhere, the MIS 11 highstand was in excess of 20 m, making this perhaps the single most important global event of the past million years, and all the more so for its potential heuristic predictive value as being the interglacial most similar to the present interglacial now in progress in terms of Milankovitchian forcing (Loutre and Berger, 2003). It thus becomes essential that the full extent and duration of the MIS 11 event be more widely recognized and acknowledged.

6.1. Past global implications of a +20 m sea-level highstand

A + 20 m sea-level would have ramifications well beyond geology and climate modeling. For the biota of coastal continental areas, and particularly for low islands and archipelagos, such a sea-level rise would have been catastrophic. For example, the Florida peninsula would have been reduced to a relatively small archipelago along the higher parts of the central ridge (Emslie, 1998: fig. 17). We have only to look at Bermuda to begin to assess the impact for terrestrial organisms or seabirds dependant on dry land for nesting sites. As yet we have no fossil record of the terrestrial biota that must have evolved on Bermuda during the long stable period of the first half of the Pleistocene (i.e., during the formation of the BRS) but to judge from what colonized and evolved subsequently (a tortoise, a crane, a duck, several flightless rails – Olson and Wingate, 2000, 2001; Olson et al., 2006) there must have been a substantial endemic element of terrestrial vertebrates. Of these, only two small passerine land birds and a lizard survived. Bermuda was so compromised as a nesting site for seabirds that at least one species of shearwater (Olson, 2008b) and the Short-tailed Albatross became extinct, the latter marking the end of all resident albatrosses in the North Atlantic (Olson and Hearty, 2003). The several species of plants supposedly endemic to Bermuda must either have evolved in less than 400 ka or are not true endemics and must have originated elsewhere (Olson, 2008a).

In the Pacific Ocean, the MIS 11 sea-level rise must have caused widespread extinctions of terrestrial organisms and a complete reorganization of seabird distribution that has never yet figured in any biogeographical considerations of populations of pelagic birds. The Tuamotus, most of the Line and Gilbert Islands, Wake Island, Ducie and Oeno in the Pitcairn group, the whole northwestern Hawaiian chain except Nihoa and Necker, just to name a few, would have been submerged or at the very least subject to storm overwash.

The Bahama Archipelago would have been reduced to a few islets that could probably have sustained only strand vegetation and an extremely low diversity of animal species. The implications of this are that all of the endemic elements of the Bahamas, which include some quite distinctive birds and reptiles and one species of mammal, must either have colonized and evolved in less than 400 ka, or they evolved elsewhere, colonized the Bahamas less than 400 ka ago, and became extinct everywhere outside the Bahamas in the interim. The time available for these patterns to emerge may be even less given a sea-level rise of 6–9 m in MIS 5e (Hearty et al., 2007a), but 400 ka is longest possible interval for evolution to have taken place on the low-lying islands of the world. Biogeographers, geneticists attempting to extrapolate divergence times and molecular clocks, conservationists trying to save endangered species, and many others in the biological sciences must take these findings into consideration.

6.2. Future global implications of a +20 m sea-level highstand

Not the least of the implications of the MIS 11 event is for the future. If sea-level rose to +20 m without human intervention during a warm interglacial of the past, there is no reason why it could not do so again in the future. A rapid and substantial rise in sea-level has far more ramifications than 400 ka ago now that about a billon humans are concentrated in coastal areas of the world. If the effects of anthropogenic greenhouse gas emissions exacerbate and accelerate melting of polar ice caps, the resulting rise might well be even more rapid and extensive than currently predicted (IPCC, 2007). Modeling of future instability of ice-sheets and consequent sea-level rise has focused almost exclusively on the Last Interglacial (MIS 5) (e.g., Overpeck et al., 2006). Our data suggest that perhaps equal attention should be giving to MIS 11 with its implications for collapse of polar ice-sheets and its potential impact on the ecology and biogeography of the world coastlines.

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Fauchald. For identification of specimens we are especially indebted to the late Warren Blow (crabs), Stephen Cairns (coral), David Pawson (sea urchins), Robert Purdy (fish), Ellen Strong and Rüdiger Bieler (marine gastropods), Jochen Gerber and Robert Herschler (freshwater and terrestrial gastropods), and Thomas Waller (bivalves). This manuscript was significantly improved and strengthened by suggestions from editor A. Long, as well as D. Tappin and another anonymous reviewer. This is contribution #151 of the Bermuda Biological Survey, of the Bermuda Government and the Bermuda Aquarium, Museum and Zoo.

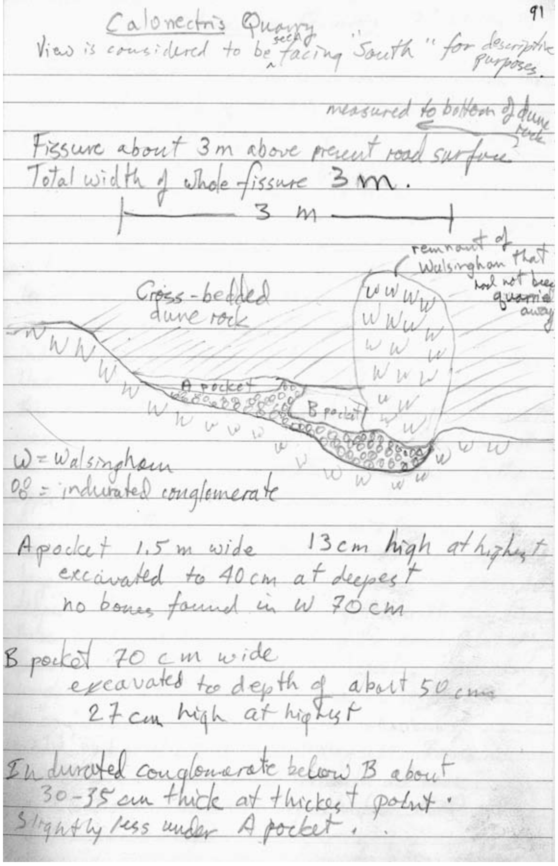
Appendix A. The fossil assemblage in Calonectris Quarry

With the exception of the coral from the underlying rubble, this diverse fossil fauna, a quintessential Concentration Lagersttätte, came entirely from the unconsolidated sands in the two small pockets indicated in the accompanying field sketch (Fig. 8).

Cnidaria, Scleractinia (stony coral): *Montastraea* sp., probably *Montastraea cavernosa*, U/Th dated sample (Hearty et al., 1999).

Echinodermata, Echinoidea (sea urchins): *Eucidaris tribuloides* and *Lytechinus variegatus*; ca 80 fragments of spines, mostly of the first species. These sea urchins are still common in Bermuda waters today. Although fragmentary, the specimens are much too large to have been components of the overlying eolianite and had to be water-transported.

Mollusca, Pelecypoda (bivalve mollusks): *Arca imbricata*, *Barbatia domingensis*, *Glycymeris pectinata*, *Hyotissa* sp., *Pododesmus*? sp., *Ctenoides scabra*, *Spondylus* sp., *Codakia orbiculata*, *Divaricella dentata*, *Chama* sp., *Pitar fulminatus*, *Chione cancellata*, *Ervilia nitens*. Of these 13 species of clams and oysters, all but the *Hyotissa* are still extant in Bermuda.



Calonectris Quarry
View is considered to be ^seen facing "South" for descriptive purposes.

measured to bottom of dune rock

Fissure about 3 m above present road surface
Total width of whole fissure 3 m.

W = Walsinghom
oo = indurated conglomerate

A pocket 1.5 m wide 13 cm high at highest
excavated to 40 cm at deepest
no bones found in W 70 cm

B pocket 70 cm wide
excavated to depth of about 50 cm
27 cm high at highest

Indurated conglomerate below B about
30–35 cm thick at thickest point.
Slightly less under A pocket.

Fig. 8. Field sketch by Olson of the Calonectris Quarry exposure as it appeared in 1984.

Mollusca, Gastropoda (snails): Larger marine taxa: *Astraea tecta*, *Astraea phoebia*, *Euchelus guttarosea*, *Dendropoma*? sp., *Cerithium litteratum*, *Batillaria minima*, *Pisania auritula*, *Nitidella nitida*, *Olivella nivea*, *Hyalina* cf. *avena*, *Conus mus*. Smaller marine taxa (these are represented by 1–4 individuals): Trochidae (*Dentistyla*?), Turbinidae, Caecidae (*Caecum*), Vermetidae, Triphoridae (3 spp.), Columbellidae, Marginellidae, Cylichnidae (*Acteocina*). Freshwater and brackish taxa: Hydrobiidae (ca 200 individuals), Ellobiidae, *Myosotella myosotis* (ca 200 individuals). Terrestrial taxa: *Succinea bermudensis* (1 individual), *Hojeda hypolepta* (2 individuals), *Poecilozonites* (*Poecilozonites*) cf. "*cupula*" ca 80–100 individuals. The last belong to the group containing the largest land snails endemic to Bermuda, which was interpreted by Gould (1969) as comprising a great radiation of species, which is incorrect (Olson and Hearty, 2007). They are most similar to those that have been identified as *P. cupula*, though smaller. We are uncertain of the total number collected because a number of them were sent to Gould in 1981 for identification and were misplaced. These snails feed on detritus in vegetated areas and would not have occurred on a sandy beach except perhaps through falling from the cliff above.

Crustacea, Decapoda (crabs): claws of at least 7 small species, including one Majidae, all probably subtidal.

Pisces (fish): Although fish bones are relatively scarce (ca 100, mostly vertebrae) the diversity (at least 9 species including one Plectognathi and one Sparidae) is relatively high given the small sample.

Reptilia, Scincidae (lizard): *Eumeces longirostris*, 116 specimens from a minimum of 5 individuals (Olson et al., 2006). This endemic lizard would have occurred anywhere on dry land and individuals probably foraged among wrack along the beach.

Aves (birds), Diomedeidae (albatrosses): *Phoebastria albatrus*, numerous mostly fragmentary remains of 2 pre-fledging juveniles. The living Short-tailed Albatross is now confined to the Pacific but occurred in the North Atlantic from at least the early Pliocene (Olson and Rasmussen, 2001) until mid-Pleistocene, this being the last known occurrence (Olson and Hearty, 2003). Fossil remains of a breeding colony near present sea-level at another locality on Bermuda were interpreted as representing an earlier stage of MIS 11 (Olson and Hearty, 2003).

Procellariidae (petrels): *Pterodroma cahow* 12 bones from a minimum of 2 individuals. The living Cahow, a gadfly petrel endemic to Bermuda, is the most abundant species of bird in later Quaternary deposits on the island and was so at the time of human colonization.

Calonectris sp., hundreds of bones from a minimum of 26 individuals. A shearwater of the genus *Calonectris* is the most abundant vertebrate in the deposit. This was about the size of *Calonectris diomedea diomedea* of the Mediterranean, but represents an undescribed, extinct species endemic to Bermuda (Olson, 2008b). The nearest islands in the North Atlantic (Azores, Canaries, Madeira) are occupied by a larger taxon *Calonectris diomedea borealis*. The Bermuda species is known only from this deposit and has not been found in any of Bermuda's many younger fossil localities (Olson et al., 2005; Olson, 2008b).

Puffinus parvus. 22 bones from a minimum of 3 adults and 1 juvenile. This small shearwater was also a Bermuda endemic (Olson, 2004) and apparently persisted up until the time of human colonization but became extinct before it could be discovered as a living species. Like the preceding 3 species, it is entirely pelagic and comes to land only to nest.

Rallidae (rails), genus and species indeterminate. This is represented only by a single distal end of a tarsometatarsus. Rails are somewhat fowl-like land birds that readily colonize oceanic islands and become flightless (Olson, 1973). This happened at least 3 times later in the Pleistocene of Bermuda (Olson and Wingate, 2000, 2001). The individual from Calonectris Quarry may be one of the

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last remnants of the flightless rails that surely existed on Bermuda during the very long period during the early Pleistocene when the Bermuda platform was exposed but for which there is no terrestrial fossil record (Olson et al., 2005).

Passeriformes (song birds), Parulidae (wood-warblers), genus and species indeterminate. 9 bones from a minimum of 1 individual. These fossils are from an undescribed large species of wood-warbler that was endemic to Bermuda and persisted into the early colonial period (Olson, unpublished data). It would have been an inhabitant of brushy vegetation.

Passeriformes, Emberizidae (buntings), *Pipilo* sp. 38 bones from a minimum of 5 individuals. This is an undescribed large extinct finch (towhee) that was also a Bermuda endemic that persisted into the early colonial period (Olson, unpublished data). It would have been a ground inhabitant of scrubby vegetation.

Mammalia, Chiroptera (bats), Vespertilionidae, *Lasiurus borealis*. 6 bones from 1 individual. This material was identified as being from a vagrant individual of the migratory eastern red bat that probably died at sea or on the beach (Grady and Olson, 2006).

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