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ORIGINAL PAPER

Probable tsunami origin for a Shell and Sand Sheet from marine ponds on Anegada, British Virgin Islands

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Abstract A distinctive Shell and Sand Sheet found beneath the marine ponds of Anegada, British Virgin Islands, was formed by a post-1650 AD overwash event, but its origin (tsunami or hurricane) was unclear. This study assesses the taphonomic characters of the shell and large clast material (>2 mm) to determine its provenance and origin. Pond-wide stratigraphic units (Shelly Mud, Shell and Sand Sheet, Mud Cap) were analyzed (12 samples) at four sites in Bumber Well and Red Pond along with eight samples from the Shell and Sand Sheet in a 2-km transect of Bumber Well. Mollusks in the pond muds include *Anomalocardia* spp. and cerithids with no allochthonous shells from the offshore reef-flat. Results show that the shells and clasts (>2 mm) are derived from the erosion and winnowing of the underlying Shelly Mud of the former marine pond, forming a distinctive sheet-like deposit with *Homotrema* sand. The Shell and Sand Sheet contains articulated *Anomalocardia* bivalves and moderate numbers of angular fragments (approximately 35%) that are likely from crab predation. Radiocarbon dates of articulated *Anomalocardia* specimens from the Shell and Sand Sheet range widely (approximately 4000 years), with shell condition (pristine to variably preserved) showing no correlation with age. The articulated condition of the bivalves with the wide-ranging dates suggests erosion and winnowing of the underlying Shelly Mud but minimal transport of the bivalves. The Shell and Sand Sheet has taphonomic characteristics indicative of a widespread tsunami overwash (sheet-like extent and articulated specimens) but lacks allochthonous reef-flat shells. Reef-flat shell material may not have penetrated the pond, as a tsunami would have to cross the reef-flat and overtop high dunes (2.2 m) hindering transport of larger shell material but allowing the *Homotrema* sand to penetrate. Processes including hurricane overwash, pond wave action, or tidal channel opening and closure are not favoured interpretations as they would not produce extensive sheet-like deposits. Taphonomic analysis is hampered by the limited (400–500 years BP) depositional history from Anegada's ponds and the lack of comparative data from other Caribbean locations.

Keywords Mollusk taphonomy · Event stratigraphy · Hurricane · Tsunami · Caribbean

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1 Introduction

A central question when considering the origin of event beds in coastal settings is whether they formed by storms or tsunamis, a question that is particularly important in active seismic settings. In the Caribbean with its prevalence of hurricanes, storm beds would be expected to be more frequent in the depositional record of coastal areas, however, a local or transoceanic tsunami origin cannot always be dismissed (e.g., Donnelly 2005). The 1755 Lisbon tsunami is a prominent example with reported effects in the Caribbean with estimated heights of 2–6 m east of Anegada, Hispaniola, and Cuba (Fig. 1; O'Loughlin and Lander 2003). However, although there are scattered written accounts of the 1755 Lisbon event in the Caribbean (2.6 m east of Anegada, west in Hispaniola and Cuba; O'Loughlin and Lander 2003), there is little geological evidence documenting its effects on the coastline and there are no reports for the US Atlantic seaboard (Barkan et al. 2009). Local Caribbean Plate boundaries have also produced tsunamis yet little is known about them (e.g., 1867 earthquake likely in Anegada Passage; Reid and Taber 1920; Zahibo 2003; Fig. 1; see Atwater et al. (2011) for full discussion).

Discerning between a storm or tsunami event bed is not always easy, and in Caribbean reef settings with their abundance of shelly material, shells can be significant components of these beds (e.g., Parsons-Hubbard 2005). However, most shell bed studies focus on the taphonomic effects of hurricanes and storms but few consider tsunamis (e.g., Miller et al. 1992; Martin and Henderson 2003; Parsons-Hubbard 2005). Unless transport has occurred over great distances (e.g., Morales et al. 2008) or the coastal setting allows separation of storm surges with elevation, there can be doubt on the origin of an event bed (e.g., Jones and Hunter 1992; Donnelly 2005; Parks et al. 2009). In many Caribbean islands, coastal lagoons and ponds are often very close to sea level and not far from the coast making it difficult to vet these deposits.

Stratigraphic information from ponds on Anegada, British Virgin Islands, shows a distinctive sheet-like shell and sand bed that post-dates AD 1650 and may coincide with the 1755 Lisbon event or other local tsunamis (e.g., Antilles 1690; Atwater et al. 2011). However, several known hurricanes (e.g., 1780, 1819) are also a possibility, and the goal of this study is to document and assess the taphonomic characters of the shelly material to determine its provenance and origin. Previous work (Reinhardt et al. 2006; Donato et al. 2008; Morales et al. 2008; Massari et al. 2009) has shown that shell taphonomic characters may be instructive for distinguishing a tsunami event but the approach has never been applied in a reef setting.

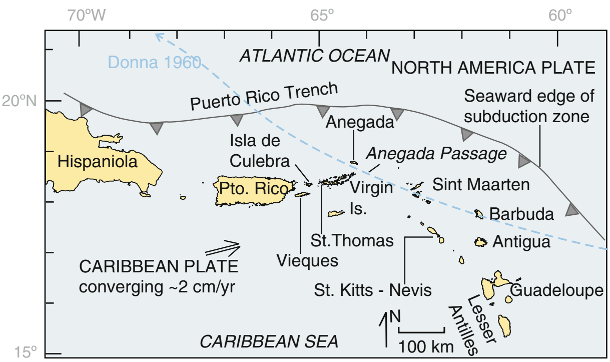

Fig. 1 Physiography of the northeastern Caribbean showing tectonic plates and the path of Hurricane Donna in 1960 (Modified from Fig. 1, Atwater et al. 2011; López et al. 2006; Dunn 1961)

2 Setting

Most seismicity in the Caribbean is concentrated on the Antilles arc from Hispanola to Trinidad where the Caribbean Plate is overriding the North American and South American Plates (Fig. 1; Tanner and Shedlock 2004). Anegada, British Virgin Islands, is 125 km south of the Puerto Rico trench that demarcates the North American and Caribbean Plate boundary with plate motions (2 m/100 years) nearly parallel to the trench (Fig. 1; ten Brink et al. 2004; Grindlay et al. 2005; Lopez et al. 2006). Expectations are that a Puerto Rico trench or transoceanic tsunami would leave an overwash record in the ponds of Anegada. There are several historical references for tsunamis generated by seismic activity near Puerto Rico and the Virgin Islands. Two of these were prominent, the Virgin Island tsunami of 1867 and the Puerto Rico tsunami of 1918 that caused extensive coastal inundations (see Atwater et al. (2011) for details).

Hurricanes would also be expected to leave overwash beds in the low-lying ponds of Anegada. Hurricane Donna (Fig. 1; Category 3; 1960; Dunn 1961) as a recent example passed Anegada 15 km to the south, but storm surge did not cause widespread inundation of the island (wave heights close to 2.5 m above MSL; Atwater et al. 2011). However, a larger hurricane might cause more extensive incursions. Notable historic events include the 1780 hurricane that is considered one of the most disastrous Caribbean hurricanes on record, and specifically for Anegada, a hurricane that struck nearby Tortola in 1713, and one that hit the island in 1819 closing an inlet (Millás and Pardue 1968; Pickering 1983).

Most of the British Virgin Islands are volcanic with high topographic relief while Anegada is small (54 km^2), low-lying (maximum 8 m, but mostly 2–3 m above MSL) and composed of limestone (Fig. 1, 2). The island is approximately 2–3 km wide and 17 km long with a long axis orientation approximately west to southeast. The northern windward side faces the Atlantic Ocean and has a fringing reef and a shallow reef-flat area that is wide (1.5 km) and shallow (1–2 m) at Windlass Bight (Fig. 2; Dunne and Brown 1979). The island core is reefal limestone likely Pleistocene in age (Howard 1970; Horsfield 1975)

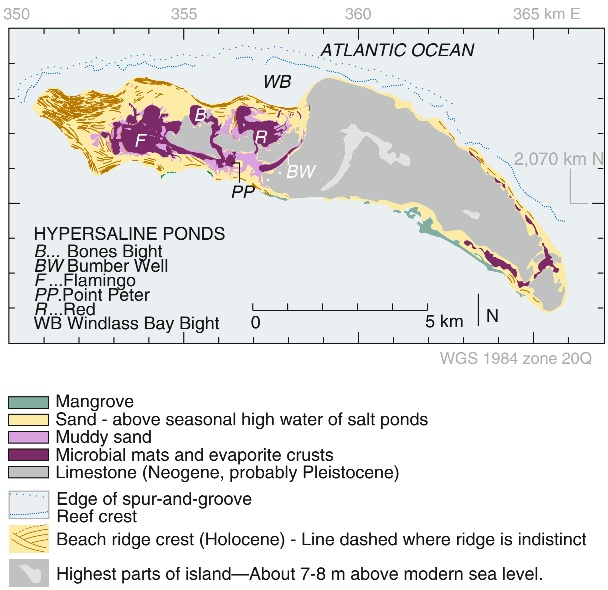

Fig. 2 Map showing geomorphic and geological features of Anegada (Modified from Fig. 2, Atwater et al. 2011)

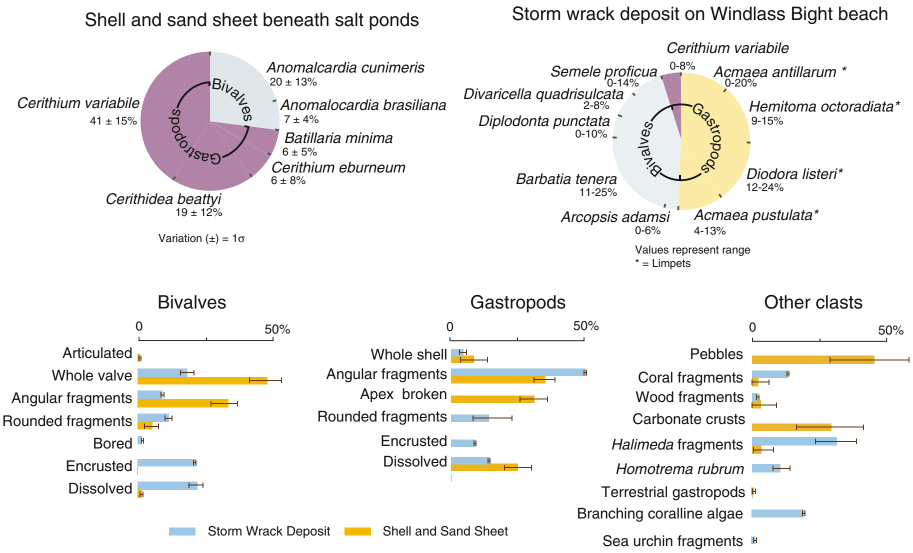

Fig. 3 Molluskan species, taphonomic and clast data from the Shell and Sand Sheet and the storm wrack deposit on Windlass Bight Beach. Eleven samples were analyzed from the Shell and Sand Sheet and two samples from the Storm Wrack Deposit—average values are reported with 1σ and the range of values. For the clast data, bars represent 1 σ

with a recent covering of carbonate sand (beach ridges) and mud deposits. Extensive hypersaline ponds (93–250 ppt measured in 1995; Jarecki and Walkey 2006) exist in the western half of the island confined by beach ridges (2–3 m in height) and contain extensive microbial mats on the bottom (Fig. 2). Water depths are shallow <20 cm as measured in Red Pond (1995), and the pond tidal ranges are considerably less (<3.5 cm) than the astronomical ocean tidal range that is approximately 40 cm. Evidence of less-restricted conditions are evidenced by tidal notches [Approximately 15–20 cm high; see Fig. 3g; Atwater et al. (2011)] in exposed limestone that surrounds the ponds and possible remanent tidal channels in the beach ridge topography (Atwater et al. 2011).

3 Shell taphonomy

Shell beds, lags, or concentrations can be a common feature of shelf and coastal areas, and considerable research has been devoted to understanding their formation through taphonomic analysis (e.g., see Brett 2003). Shell beds can form through storm transport or winnowing of the substrate concentrating and amalgamating shelly deposits into a concentrated bed (e.g., Anderson and McBride 1996; Davies et al. 1989). Recent research has shown that shell beds may also form during a tsunami and may have distinctive shell taphonomy, bed geometry, and structure (e.g., Reinhardt et al. 2006; Donato et al. 2008). The premise of shell bed taphonomy and its utility for event stratigraphy (i.e., distinguishing storms vs tsunamis) is that large-scale processes will overprint background taphonomic characters providing information on the event. The amount of overprinting may relate to the magnitude or type of event and may be significant, or may leave little trace on the shell assemblage (e.g., Miller et al. 1992; Davies et al. 1989). For example, previous studies (e.g., Reinhardt et al. 2006; Donato et al. 2008) have shown tsunami shell beds to contain high concentrations of shells, articulated bivalves, and angular fragments with many allochthonous taxa, while background taphonomic processes do not produce these characters. Not all of these characters might be present in a tsunami unit, which is highlighted by recent research from Pliocene shell beds in Italy (Massari et al. 2009) which found articulated specimens but low angular fragmentation. The amount of fragmentation may depend on the availability of hard-grounds or presence of rocky shorelines which is the case in Reinhardt et al. (2006) and Donato et al. (2008). As discussed in Donato et al. (2008, 2009), it is a collective of taphonomic indices that is important for a tsunami determination (e.g., articulation, high angular fragmentation, provenance, and sheet-like geometry of shell bed). The lack of certain characters does not preclude a tsunami interpretation (e.g., Massari et al. 2009), but their presence may strengthen it. The overall bed geometry and extent has proven important (Massari et al. 2009; Donato et al. 2008) with sheet-like beds contrasting the more localized or lens-shaped storm shell concentrations (Meldahl and Cutler 1992). Characteristics of storm shell concentrations are itemized in Table 3 in Anderson and McBride (1996).

Recognition of a singular tsunami or storm event bed depends on taphonomic overprinting of the shells and preservation of the bed without subsequent exhumation and alteration. In ideal settings, deep scour of the substrate followed by rapid sediment infilling aids preservation of the event bed (Reinhardt et al. 2006; Donato et al. 2008; Goodman-Tchernov et al. 2009). Deep scour and subsequent burial aids preservation as background processes (i.e., seasonal storms or tidal currents) may not be significant enough to reexpose and alter the beds. However, in settings where these processes are more significant or where large events are frequent, singular beds may be amalgams of event beds with mixtures of taphonomic characters.

4 Methods

For the taphonomic analysis, samples were collected from ten trench sections from Bumber Well and Red Pond ($n = 21$) with two surface samples from a storm wrack-line deposit on the reef-flat beach at Windlass Bight (see map insets Fig. 4, 6). Detailed trench stratigraphy is provided in Atwater et al. (2011). Stratigraphic sections are predominantly from the pond margins where trenches could be excavated and sampled above pond water levels. Gouge cores were retrieved from the flooded central portions of Red pond. Geomorphic features were documented using air photos, maps, differential GPS (Watt et al. 2011) and survey level with elevations related to an approximate mean sea level (MSL) datum (Fig. 6). Shell and Sand Sheet samples were collected along the length of Bumber Well Pond to determine taphonomic trends along the suspected overwash path (see map inset Fig. 6). Two stratigraphic sections from Bumber Well (14 and 16) and Red Pond (13, 15) were also sampled to provide shell and clast data for all major stratigraphic units [Fig. 4; Atwater et al. (2011)]. Sediment sample size was large, at approximately 1.2 L providing representative quantities of shells and clasts for analysis. Samples were sieved using a 2-mm screen to quantify the mollusks and their taphonomic condition along with other clast material (e.g., carbonate crusts, wood fragments, pebbles; Fig. 3, 4, 6). Large samples were randomly split with shell and clast counts ranging from 1,000 to 8,000. Storm wrack-line samples on Windlass Bight provide comparative reef-flat data for assessing provenance of the shells and clasts in the Shell and Sand Sheet from the pond (probable overwash unit).

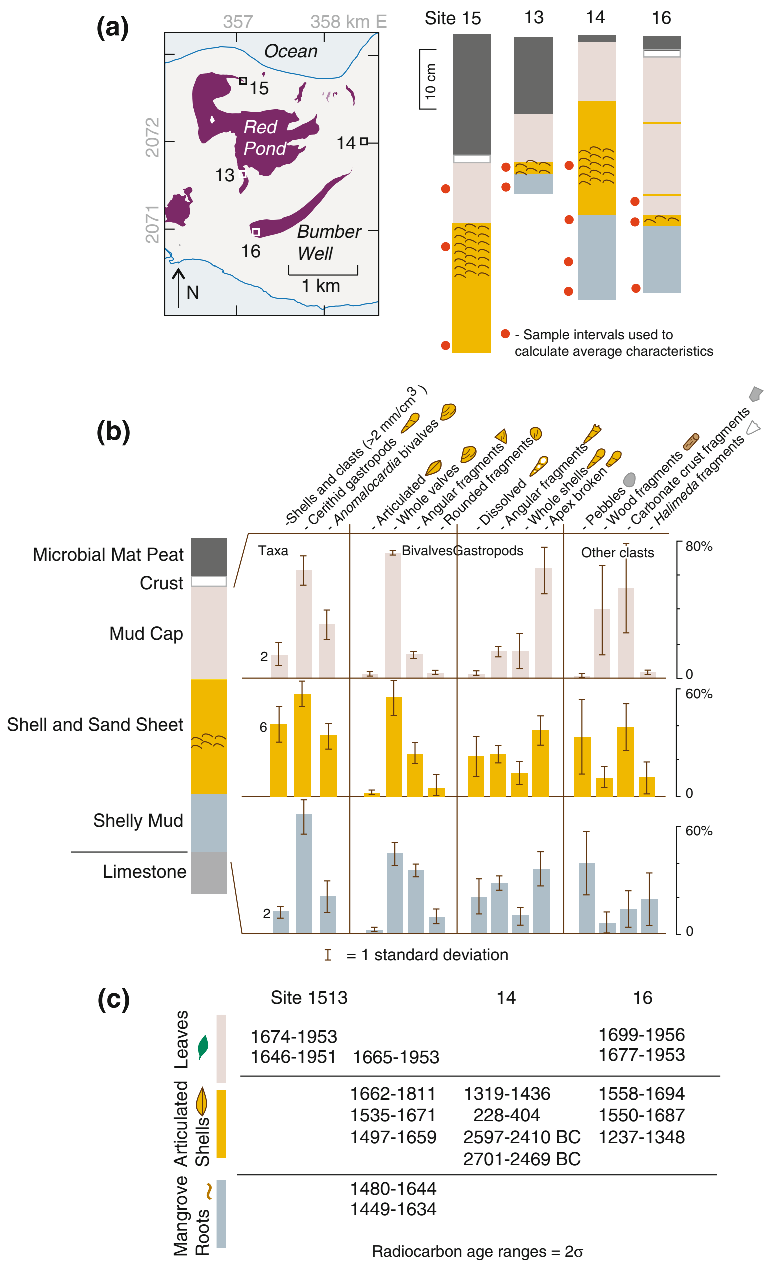

Fig. 4 **a** Location of trenches in Bumber Well and Red Pond and their stratigraphic logs showing sample resolution. **b** Mean values of dominant taphonomic and petrographic characters for the idealized stratigraphic section. **c** Distribution of radiocarbon dates in the analyzed stratigraphic sections (for details see Atwater et al. 2011)

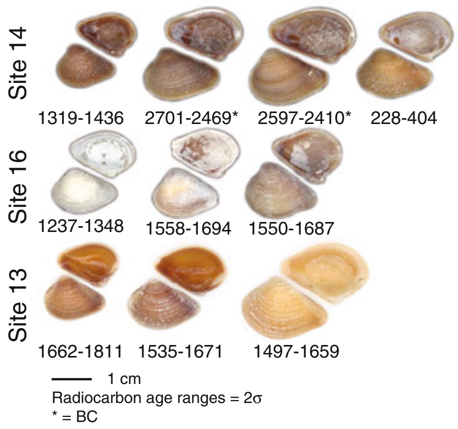

Fig. 5 Articulated *Anomalocardia* radiocarbon dates for the Shell and Sand Sheet illustrating the range in dates and the lack of taphonomic correlation

Species identification followed Mikkelsen and Bieler (2007) and Warmke and Abbott (1961). Bivalve taphonomic analysis used similar characters as Reinhardt et al. (2006) and Donato et al. (2008; Fig. 3; articulated, whole valve, angular and rounded fragmentation, bored, encrusted, and dissolved). Gastropod taphonomic characters were also quantified (Fig. 3; whole shell, dissolved, angular and rounded fragmentation, missing apex, bored, encrusted). Additional clast identification included, quantities of limestone pebbles (lithoclasts), terrestrial gastropods (undifferentiated), the foraminifer *Homotrema rubrum* (>2 mm), carbonate crusts (intraclasts), and fragments of coral, sea urchin, *Halimeda* (calcareous green alga), branching coralline algae, and wood. The relative abundance of large clasts and shells (>2 mm) per unit volume of sediment was tabulated to document stratigraphic trends. The <2-mm fraction was analyzed for foraminiferal taphonomy and also particle size, which is described and discussed in Pilarczyk and Reinhardt (2011).

Radiocarbon analyses (AMS) for the stratigraphic sections (Sites 13–16) were performed at Woods Hole (NOSAMS) on plant and shell material selected from stratigraphic units (Fig. 4, 5). Dates from all sections are provided in Atwater et al. (2011). Sample selection focussed on constraining the age of the Shell and Sand Sheet using terrestrial organic matter (e.g., leaves) and articulated shells (*Anomalocardia*). Radiocarbon ages were calibrated using Calib (v 5.01, IntCal04 calibration data; Reimer et al. 2004) for the terrestrial material and Marine04 (Hughen et al. 2004) for the shells. Only calibrated ages (2 σ) are reported with further details provided in Atwater et al. (2011).

5 Results

5.1 Stratigraphy and molluskan ecology

The stratigraphic sections (approx. 30) as documented in Atwater et al. (2011) show sedimentary units that are found throughout the extent of the ponds (Fig. 4). The base of the sections is defined by Neogene (likely Pleistocene; Howard 1970) reefal limestone ranging from approximately 0.5–0.75 m below MSL in the ponds but extends up to 8 m above MSL in western portions of the island. The basal stratigraphic unit (Shelly Mud) consists of lime mud with lower amounts of shells and clasts (2 clasts/cm^3) which is overlain by a Shell and Sand Sheet [6 clasts/cm^3; fine to medium sand; Pilarczyk and

Reinhardt (2011)]. The Shell and Sand Sheet is variable in composition and consists of well-sorted *Homotrema* bioclastic sand and/or shell with some units consisting of more poorly sorted muddy shell (Atwater et al. 2011; Pilarczyk and Reinhardt 2011). The shell concentrations are found mainly on the shallow margins of the ponds, while the *Homotrema* sand is found in the central portions of the ponds. Above this unit is a lime Mud Cap (mostly $\approx$ 10 cm) with a lower shell and clast concentration of 2 clasts/cm^3 which grades or sharply transitions (with a carbonate crust) to a Microbial Mat Peat (mostly 10–15 cm) which extends to the surface (Fig. 4). The Microbial Mat Peat variably contains sand and minor shell and evaporites.

Molluskan assemblages in the stratigraphic sections consist of variable amounts of cerithids (*Cerithium variabile*, *Cerithidea beattyi*, *Cerithium eburneum*, and *Batillaria minima*) and *Anomalocardia* spp. (*Anomalocardia cunimeris* and *Anomalocardia brasiliana*) indicative of a marine to hypersaline pond or lagoon environment (Figs. 3, 4). All sedimentary units have mollusk assemblages that are similar (except the Microbial Mat Peat), with variation only in their concentrations (2 vs. 6 clasts/cm^3; Fig. 4). *Anomalocardia* spp. are facultatively mobile infaunal (3–5 cm) suspension feeders found in marine ponds, mangroves, and lagoons throughout the Caribbean and are known to withstand high salinities (80 ppt; Britton and Morton 1989; Read 1964; Parker 1959; Emery et al. 1957). In Florida Bay, they have been found in lower salinity regimes ranging from 15 to 40 ppt (Brewster-Wingard and Ishman 1999). Similarly, cerithid gastropods (epifaunal vagile detritivores) are found in similar environments (15–40 ppt in Florida Bay; Brewster-Wingard and Ishman 1999) but often in high numbers with large accumulations on the bottom and margins of lagoons, ponds, and mangroves. The distribution of these taxa in the basal Shelly Mud, Shell and Sand Sheet, and overlying Mud Cap is consistent with a marine to hypersaline pond environment which is also evidenced with the foraminiferal data (dominantly miliolids—*Triloculina* sp, *Quinqueloculina* sp.) presented in Pilarczyk and Reinhardt (2011). The predominance of mud-sized sediment also indicates a restricted setting.

5.2 Former marine pond shell bed and reef-flat storm wrack comparisons

The reef-flat storm wrack deposit shares no common mollusk taxa with the Shell and Sand Sheet from the ponds (Fig. 3). The only common species is *Cerithium variabile* that is present in minor proportions in one of the samples and may be reworked from older pond deposits on the reef-flat. The main component (66%) of the Shell and Sand Sheet is cerithid gastropods (*Cerithium variabile*, *Cerithidea beattyi,* and *Cerithium eburneum*) with minor amounts of *Batillaria minima* (6%), all of which are common pond and lagoon taxa. This contrasts with the storm wrack deposit assemblage with its predominance of limpets (including false limpets). There are also no common bivalve taxa, the lagoonal *Anomalocardia* spp. (27%) dominates the Shell and Sand Sheet while the storm wrack deposit has a variety of reef dwelling taxa (Fig. 3).

The taphonomy is very different, with bivalves in the Shell and Sand Sheet predominantly preserved as whole shells and angular fragments, while the storm wrack deposit contains many encrusted and bored specimens. The Shell and Sand Sheet also contains articulated specimens, albeit in low proportions, but noteworthy due to their importance in previous tsunami studies (e.g., Donato et al. 2008; Reinhardt et al. 2006; Morales et al. 2008; Massari et al. 2009). Similarly, with the gastropods, there is a lack of encrusted specimens in the Shell and Sand Sheet but it contains higher amounts of angular shell fragments and dissolved shell. The high amounts of gastropod fragments is also dominant in the reef-flat environment, although likely from different processes (crab fragmentation vs. transport—see 5.3).

Likewise, other clast material shows little correspondence between the pond and reef-flat deposits. The Shell and Sand Sheet contains abundant angular to subrounded limestone pebbles and fragments of carbonate crusts ($\sim$0.25 cm thick) which are not present in the storm wrack deposit. In contrast, the storm wrack deposit contains abundant algae fragments (*Halimeda* and branching coralline algae) and coral fragments (Fig. 3). Large specimens (>2 mm) of *Hometrema rubrum* are not found in the Shell and Sand Sheet, but are abundant in the sand-sized fraction (>2 mm; see Pilarczyk and Reinhardt 2011).

5.3 Pond taphonomic and stratigraphic trends

The taphonomic and clast data are similar in all pond units, but there are some differences worth noting (Fig. 4). The Shell and Sand Sheet contains the same proportions of shells and clasts as the underlying Shelly Mud of the former marine pond, although the concentration of clasts is much higher at 6 versus 2 clasts/cm^3 and there are higher proportions of carbonate crust fragments (15 vs. 40%; Fig 4). The overlying Mud Cap is different than the underlying units as it has higher proportions of whole *Anomalocardia* valves, apex broken cerithids and contains few pebbles but many wood fragments. However, the concentration of shells and clasts (clasts/cm^3) is similar to that of the Shelly Mud.

Previous taphonomic studies placed importance on angular fragmentation and the presence of articulated bivalves (e.g. Donato et al. 2008) as a tsunami indicator. In Anegada’s ponds, the Shell and Sand Sheet did not contain higher proportions of angular fragmentation or articulated bivalves although the concentration of these characters is higher (clasts/cm^3). In this case, the fragmentation is likely due to crab or bird predation (see Zuschin et al. 2003) rather than physical fragmentation during an extreme event.

Taphonomic and petrographic characters of the Shell and Sand Sheet in Bumber Well pond (NE-SW oriented; Fig. 6) increase or decrease toward the central portion of pond. The concentration of shells and clasts (clasts/cm^3) generally decreases into the central pond, likely reflecting decelerating overwash flow entering from the northern and southern margins. The proportions of cerithids increase and likely reflect preferential entrainment and concentration of the epifaunal cerithids through transport. Cerithids would have been concentrated on the surface and margins of the ponds where dissolution would be high with fluctuating pond water levels. These specimens would be more readily transported versus the infaunal and larger size *Anomalocardia* (Fig. 6). Bivalve fragments also tend to have higher proportions in the central sections relative to the larger whole valves suggesting sorting with transport. Limestone pebbles (lithoclasts) tend to be more dominant in the central area of Bumber Well which may reflect a source effect. Exposed limestone is more prominent in the middle of the pond rather than at the northern and southern extremities (Fig. 2).

The lack of coarse (>2 mm) allochthonous reef-flat shells in the Shell and Sand Sheet is perhaps the most significant observation. There are some reef-flat *Halimeda* fragments present in the pond muds, but these could have been windblown as the segments are very light (Fig. 4). The marine pond provenance for the shells and clasts (>2 mm) is in contrast with the sand-sized *Homotrema rubrum* that originated from the beach or reef-flat (Pilarczyk and Reinhardt 2011).

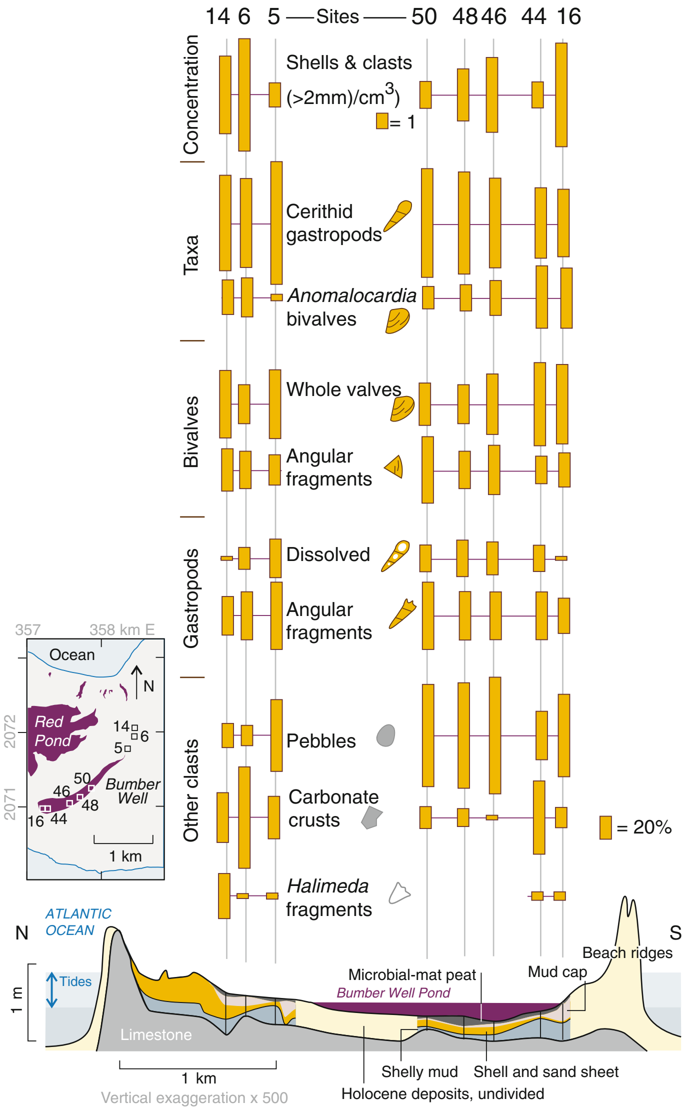

Fig. 6 Distribution of the dominant taphonomic and petrographic characters of the Sand and Shell Sheet in Bumber Well Pond showing spatial trends. Stratigraphic cross-section from Atwater et al. (2011)

5.4 Radiocarbon dates

Radiocarbon dates on both terrestrial and shell remains show some similarities but also some important differences, particularly with the shell material (Figs. 4c, 5). A full discussion of the dates is provided in Atwater et al. (2011); here, the focus is the taphonomic significance. The dates for the articulated *Anomalocardia* shells show a large range but many of them date to the sixteenth to seventeenth century AD. The dates in Site 14 show the greatest range at ~4000 years even though they have good color and show little taphonomic alteration

(Fig. 5). In contrast, the shells from Site 16 have the worst taphonomic condition (grade) with loss of color and a thin carbonate crust but have a narrow age range at ~500 years. Similarly, Site 13 dates have a narrow range (~300 years) but have better preserved color (Fig. 5). The wide range in dates at Site 14 indicates significant time averaging of articulated *Anomalocardia* shells. This finding is not unusual when radiocarbon dating individual valves (e.g., Flessa et al. 1993), but it is unusual to have such a range of dates for articulated bivalves. The articulated specimens of *Anomalocardia* were difficult to separate for radiocarbon dating and required use of a dissecting knife to separate the valves. It was unclear what caused the valves to adhere so strongly, but this may have allowed dead articulated specimens to be eroded and transported in lower current regimes. Crab or bird burrowing may have exhumed older articulated bivalves (and other shell material) which may have been available for transport on the surface (Flessa et al. 1993). Articulated bivalves are often selected for radiocarbon dating vs individual valves that may be thousands of years too old (e.g., Simms et al. 2009; Kidwell et al. 2005). However, in low-energy conditions, and perhaps only with *Anomalocardia*, this assumption may not always be valid.

The dominant sixteenth to seventeenth century AD age range for the articulated *Anomalocardia* is consistent with the terrestrial organic matter dates. The two radiocarbon dates from the Shelly Mud below the Shell and Sand Sheet (mangrove roots) have a slightly earlier age range from the mid-fifteenth to mid-seventeenth century AD, while the overlying Mud Cap dates from plant leaves range from the mid-seventeenth to twentieth century AD (narrowed to 1650–1800 with the collection of dates; Atwater et al. (2011); Fig. 4c). Dates from other trench sections have similar age relationships and are discussed in Atwater et al. (2011).

6 Discussion

6.1 Pond taphonomic processes

In Anegada's shallow ponds, the background taphonomic processes would include dissolution of shells exposed on the surface, abrasion due to wave action and fragmentation from crab and bird predation (Zuschin et al. 2003). Individual articulated bivalves might be expected to be scattered in the pond muds but not in a concentrated bed. Concentration of shells into beds would not be a dominant process in the restricted pond environment as seasonal currents would be wind driven which would be minimal considering the small fetch distances. Storms and/or tsunamis in the past might have overprinted these background taphonomic characters, by sorting and concentrating the shells into beds or concentrations, and transporting shells from an outside provenance through overwash (e.g., a reef-flat source). Shells might also be concentrated through winnowing wave action in the shallow waters of the ponds with high winds during a hurricane (e.g., Martin and Henderson 2003) or may become concentrated due to lower sediment inputs or higher biological productivity (storm winnowing vs episodic starvation models; Dattilo et al. 2008). This may have been more pronounced in the past if tidal channel connections with the open ocean allowed currents to remove muds.

6.2 Does the Shell and Sand Sheet represent an event bed?

The preliminary consideration is whether the Shell and Sand Sheet in Anegada's ponds represents an event deposit. A large-scale event (hurricane or tsunami) that erodes beach ridges opening older relict tidal channels and/or causes widespread overwash across beach ridges would be expected to contain reef-flat shells. The lack of reef-flat shells in the Shell and Sand Sheet is problematic for an event bed interpretation. However, the stratigraphic association of the shells with the *Homotrema* sand and its probable reef-flat/beach provenance does suggest a large overwash event (Pilarczyk and Reinhardt 2011) rather than reduced sedimentation rates or increased biological productivity in the ponds (Dattilo et al. 2008).

The radiocarbon dates indicate that the stratigraphic sequence in the ponds formed over a relatively short time period, with deposition occurring at similar times in both Bumber Well and Red Pond suggestive of one large event rather than multiple. At Site 13 (Red Pond), the deposition of the Shelly Mud, Shell and Sand Sheet, and the Mud Cap all span several 100 years with similar ages found in Site 16 (Bumber Well) for the Shell and Sand Sheet and the Mud Cap. The large range in radiocarbon dates (2701BC–1436 AD) from Site 14 (Bumber Well) may reflect erosion or burrowing of older pond deposits under the beach ridges, but the youngest age (1319–1436 AD) from the articulated shells is similar to the ages obtained from Site 13 and 16. It is possible that the Shell and Sand Sheet at Site 14 represents an amalgam of event beds or a continuously deposited sequence (condensed bed) spanning approximately 4000 years, but in context with the other data this does not seem plausible. The presence of *Homotrema* sand with common stratigraphic position and extent within the individual ponds along with the timing of deposition from the radiocarbon dates (Site 13 and 16) suggest one large event rather than multiple amalgamated beds.

6.3 Shell and Sand Sheet characteristics and a tsunami origin

The Shell and Sand Sheet from Anegada's ponds shares some of the previously documented characteristics of a tsunami deposit, but there is not yet a criterion for recognizing tsunami vs storm deposits in all settings (Goff et al. 2004; Morton et al. 2007). In previous shell bed research, articulated bivalves, abundant angular fragmentation, allochthonous shells from an outside provenance, and sheet-like geometry were found to be important for determining tsunami vs storm deposition. The mixture of angular fragments and articulated bivalves are judged to be important indicators of substrate scour and live transport of bivalves with angular fragmentation indicating large-scale currents and turbulence (Reinhardt et al. 2006; Donato et al. 2008, 2009; Morales et al. 2008; Massari et al. 2009). However, in the case of Anegada's restrictive ponds, the presence of articulated specimens does not necessarily indicate live transport, although it does likely indicate minor scour of the substrate. Currents concentrating the shells must have been high enough to erode older shells from the substrate, but not high enough to disarticulate the shells or cause fragmentation. Older shells may have been available in the shallow subsurface, brought there through burrowing crabs and birds and may have remained articulated. The angular fragmentation in this case could not be confidently associated with transport and is likely from predation by crabs and birds in the ponds. The shells did not originate from outside areas (i.e., reef-flat), and all shells and clasts came from scour (and/or winnowing) of the Shelly Mud of the former marine pond. Trends in taphonomic and petrographic characters along Bumber Well reinforce this, indicating possible transport directions from northern and southern margins which may explain the shell and sand stratigraphy (see Atwater et al. 2011).

The pond-specific origin for the >2-mm shells and clasts is in contrast with the finer fraction (<2 mm) that shows a possible reef-flat or beach source for the *Homotrema* *rubrum* (Pilarczyk and Reinhardt 2011). The *Homotrema rubrum* from the Shell and Sand Sheet are large with well-preserved color compared to the underlying Shelly Mud and the overlying Mud Cap. The source of the larger and better preserved specimens is the beach or reef-flat, but they could have originated from older sediments underlying the existing beach ridges defining the ponds (Pilarczyk and Reinhardt 2011). The lack of coarser reef-flat clasts (and *Homotrema*; Pilarczyk and Reinhardt 2011) in the Shelly Mud indicates no large tidal channel connection with the reef-flat in the former marine pond. The former marine pond as represented by the Shelly Mud was a marine to hypersaline environment based on the molluskan and foraminiferal data, so there was some connection, but it was likely very limited [probably from the south—see Atwater et al. (2011)]. This may explain the lack of coarser clasts from the reef-flat in the Shell and Sand Sheet, as with tsunami overwash, water crossing the reef-flat and overtopping the beach ridges may have prevented the coarser fraction from making its way into the pond during the event (Wei et al. 2010). Erosion may have occurred in plunge pools (and relict tidal channels) behind the ridges as documented in the aerial photos (Atwater et al. 2011). This may have eroded older underlying beach sands and *Homotrema rubrum* transporting it into the pond (Pilarczyk and Reinhardt 2011).

The widespread distribution of the Shell and Sand Sheet throughout the ponds and the consistent dates to the mid-seventeenth to nineteenth century AD suggest one widespread event (tsunami) rather than a hurricane that would produce more limited overwash lobes or wedges on the pond margins (see below). The proposed tsunami scenario would cause instantaneous and widespread overwash across the beach ridges creating pond-wide flows which is consistent with the taphonomic data showing a winnowing and concentration effect (see Atwater et al. 2011). The suspended mud would then accumulate after the event which is consistent with the Mud Cap (mostly 10–15 cm thick) seen throughout the ponds. The radiocarbon dates on leaves have very consistent ages (see Fig. 4) suggesting a pond-wide accumulation rather than isolated scour and fill. If this is correct, it also indicates that much of the mud was not exported from the ponds, suggesting that there were no significant openings created during the event.

6.4 Hurricane considerations

Sustained hurricane wave action (vs a tsunami) might erode and reactivate choked tidal channels with storm surge transporting sand from older underlying beach deposits into the pond. Storm surge and wave action in the ponds may have eroded and transported shells and clasts from the Shelly Mud substrate onto the margins of the ponds. Winnowing and export of muds would continue after the event, but beach ridge accretion would cause renewed restriction and mud deposition (Mud Cap). However, hurricane Donna (1960 Cat 3, Dunn 1961) with its maximum sustained wind speeds of 110 knots produced no breaches through the beach ridges of Windlass Bight as evidenced with airphotos taken in 1945 and 1969. Obviously, larger events are possible and may have had a greater effect on the ponds and cannot be dismissed.

Hurricane deposits from other Caribbean locations show some similarities but also some significant differences with the Anegada deposits. Hurricane Floyd (1999) produced shell concentrations (30 cm thick) consisting of articulated *Anomalocardia* and abundant cerithids on the margin of Osprey Pond, San Salvador, Bahamas (Martin and Henderson 2003). The extent of the shell bed, and whether it formed a sheet-like deposit in the pond was not reported, but the concentration was formed through wave-generated currents in the pond rather than an overwash event. Other ponds in the Bahamas and Puerto Rico have evidence of sandy overwash and shell concentrations (mainly cerithids) which have been attributed to hurricanes and possibly tsunamis (Dix et al. 1999; Parks et al. 2009; Donnelly 2005). No articulated bivalves or any large allochthonous reef-flat clasts were noted in the shell/sand concentrations but this may be a sampling bias as the core barrels were narrow (estimated at 3–7 cm in diameter) and there were only 1–3 cores recovered. In the Salt Pond (San Salvador, Bahamas) example, hurricane Frances (2004) produced surge heights of 4.8–5.5 m which overtopped a low-lying sand ridge forming a sand wedge in the pond with foraminifera, mollusks (unidentified), and seeds (McCabe and Niemi 2008; Parks et al. 2009). In the ponds of Anegada, Wei et al. (2010) conclude, based on hydrodynamic modeling, that a hurricane could not cause significant overwash (vs a tsunami) with the broad reef-flat and the 2.2-m beach ridge elevation at Windlass Bight. So although the Shell and Sand Sheet in the ponds of Anegada do share some similar characters as these other hurricane examples, it does not appear to be wedge or lobate in shape (e.g., see Fig. 2 in Liu and Fearn 2000). This bed geometry combined with the hydrodynamic modeling and boulder results suggest a tsunami origin rather than a hurricane (Wei et al. 2010; Buckley et al. 2011; Watt et al. 2011).

6.5 Stratigraphic comparisons

Interestingly, the age of the stratigraphic sequence is skewed to the last 400–500 years [approximately 50–60 cm of accumulation see Fig. 8, Atwater et al. (2011)] suggesting rapid deposition and large-scale events that have eroded the western side of the island where the ponds are situated. By 500 years BP, the platform should have been flooded by rising sea level and should contain earlier deposits (Toscano and Macintyre 2003). The reworked *Anomalocardi*a radiocarbon ages and cerithid dates (Atwater et al. 2011) indicate that the ponds existed for several 1000 years or more (oldest ages are 2400–2700 BC), which corresponds with the sea level record for the Caribbean (Toscano and Macintyre 2003). The lack of older deposits makes comparisons difficult, as there were no significant shell beds found in the sections that could be directly attributed to a storm or hurricane. Similar environments (ponds) in the Bahamas have higher accumulation thicknesses and their basal dates are much older. Dune Pass Bay Pond has approximately 130 cm of accumulation with basal ages at ~3000 years BP (uncorrected reservoir age vs corrected age at ~1500 years BP; Dix et al. 1999). Salt Pond from San Salvador Island has approximately 65 cm of accumulation since ~3800 years BP (Parks et al. 2009) and Isla de Culebrita, Puerto Rico has approximately 200 cm with a basal age of ~2200 years BP (Donnelly 2005). The short sedimentary record in Anegada ponds does seem unusual based on these comparative examples.

7 Conclusions

The resolution of the radiocarbon dating cannot constrain the age of the Shell and Sand Sheet to a particular tsunami (e.g., Antilles 1690; Lisbon 1755) or a hurricane event in Anegada's history, and there is no strong taphonomic indicator to narrow the determination. Characteristics of the deposit suggest a widespread overwash event in the pond involving erosion and winnowing of the former marine pond's substrate into a sheet-like geometry. The event eroded and concentrated articulated bivalves and gastropods along with other clasts from areas on the pond margins (e.g., pebbles). The stratigraphic sections found in the ponds were relatively young in age (approximately last 400–500 years) indicating that there may have been previous events that have eroded the western half of the island. This lack of temporal stratigraphic data hampered the analysis, as it did not provide any prior events for comparison. Although limited in extent, other pond studies from Bahamas show different characteristics for a hurricane deposit that does not seem to match those from Anegada, but these results are difficult to assess due to the lower sampling resolution (cores).

Making a firm conclusion on the Anegada deposit is difficult as some of the established taphonomic characters for a tsunami are not present (e.g., provenance). Further research on event beds in Caribbean ponds coupled with better eyewitness accounts of known events may establish better criteria for assessing shell bed origins in reef settings. However, based on the balance of data from the other studies (boulders and hydrodynamic modeling), the Shell and Sand Sheet does appear tsunamigenic in origin.

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