Coastal stratigraphies of eastern Bonaire (Netherlands Antilles): New insights into the palaeo-tsunami history of the southern Caribbean

Max Engel a,⁎, Helmut Brückner a, Volker Wennrich b, Anja Scheffers c, Dieter Kelletat a,d, Andreas Vött a, Frank Schäbitz f, Gerhard Daut 1, Timo Willershäuser a, Simon Matthias May a

a Institute of Geography, Universität zu Köln, Albertus-Magnus-Platz, 50923 Cologne, Germany
b Institute of Geography and Mineralogy, Universität zu Köln, Albertus-Magnus-Platz, 50923 Cologne, Germany
c School of Environmental Science and Management, Southern Cross University, PO Box 157, Lismore NSW 2480, Australia
d Institute of Geography, Universität Duisburg-Essen, Universitätsstr. 15, 45141 Essen, Germany
e Seminar for Geography and Education, Universität zu Köln, Gronewaldstr. 2, 50931 Cologne, Germany
f Institute of Geography, Friedrich-Schiller-Universität Jena, Löbdergraben 32, 07743 Jena, Germany

ARTICLE INFO

Article history:
Received 11 December 2009
Received in revised form 9 August 2010
Accepted 19 August 2010
Available online 26 August 2010
Editor: M.R. Bennett
Keywords:
Washover deposits
Tropical cyclones (hurricanes)
Tsunami
Holocene stratigraphy
Facies model
Coastal hazard

ABSTRACT

A sediment record of three alluvial sites along the east- and northeast-oriented shore of Bonaire (Netherlands Antilles) provides evidence for the recurrence of several extraordinary wave impacts during the Holocene. The interpretation of onshore high-energy wave deposits is controversially discussed in recent sedimentary research. However, it represents a powerful tool to evaluate the hazard of tsunami and severe storms where historical documentation is short and/or fragmentary. A facies model was established based on sedimentary and geochemical characteristics as well as the assemblage and state of preservation of shells and shell fragments. Radiocarbon data and the comparison of the facies model with both recent local hurricane deposits and global “tsunami signature types” point to the occurrence of three major wave events around 3300, 2000–1700 and shortly before 500 BP. Since (i) the stratigraphically correlated sand layers fulfill several sedimentary characteristics commonly associated with tsunamis and (ii) modern strong hurricanes left only little or even no sediment in the study areas, they were interpreted as tsunamigenic. However, surges largely exceeding the energy of those accompanying modern hurricanes in the southern Caribbean cannot entirely be ruled out. The results are partially consistent with existing chronologies for Holocene extreme wave events deduced from supralittoral coarse-clast deposits on Aruba, Bonaire and Curaçao as well as washover sediments from Cayo Sal, Venezuela.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The steady morphodynamic processes shaping the coastlines worldwide are well understood; long-term wave action and littoral drift, for example, contribute to cliff erosion and significantly modify paralic sedimentary environs on short geological time scales (Kraft, 1978; Stanley and Warne, 1994). In the past, overwash deposits or supralittoral coarse-clast accumulations were often solely attributed to exceptionally large storms or a temporary sea-level highstand (e.g. Lucia, 1968; de Buissonjé, 1974, regarding the case of Bonaire). But, especially since the works of Atwater (1987) and Dawson et al. (1988), tsunami have been increasingly taken into consideration as potential agents in littoral geosystems (Kelletat et al., 2005; Ruiz et al., 2005; May et al., 2007; Switzer and Jones, 2008a; Vött et al., 2009; Goff et al., 2010).

A growing number of detailed studies on sedimentation patterns of tsunami testify to the increasing perception of tsunami in coastal sedimentology and geomorphology. Among other coastal areas, sedimentary investigations on recent and sub-recent tsunami events were carried out in Oman (Donato et al., 2008), Chile (Cisternas et al., 2000), the Aegean (Dominey-Howes, 1996), at Kamchatka (Martin et al., 2008), and after the incidents on Flores 1992 (Shi et al., 1995), Hokkaido 1993 (Sato et al., 1995; Nanayama et al., 2000), Java 1994 (Dawson et al., 1996) and 2006 (Lavigne et al., 2007), Papua New Guinea 1998 (Gelfenbaum and Jaffe, 2003), at the Peruvian coast 2001 (Jaffe et al., 2003) and 2007 (Fritz et al., 2008), the Kuril Islands 2006 (MacInnes et al., 2009), Samoa 2009 (Richmond et al., 2010), and most of all on the Indian Ocean circumlittoral zone after 2004 (e.g. Richmond et al., 2006; Kelletat et al., 2007; Paris et al., 2007; Srinivasalu et al., 2007; Szczuciński et al., 2007; Paris et al., 2009).

Research on both modern storm and tsunami deposits (e.g. Nanayama et al., 2000; Switzer and Jones, 2008b) helps to improve the interpretation of onshore sedimentary archives and the reconstruction of large wave impacts in the past. Identifying, dating, and, if possible, classifying extreme wave deposits is an essential strategy to...
estimate recurrence rates and potential magnitudes of future catastrophic events.

In the Caribbean, strong hurricane activity is triggered by atmospheric easterly waves crossing the North Atlantic between 10 and 20° (Goldenberg and Shapiro, 1996). Since the mid-1990s, an increasing trend in their destructive potential along the Antillean Islands and the intra-American coasts has been observed which may be attributed to ongoing (anthropogenic?) climate change (Emanuel, 2005). Analysis of the decadal frequencies of hurricanes in ten Caribbean subregions based on climate data starting in 1870 identified Venezuela and the southern Dutch Antilles, including Bonaire (area of interest for this study; Fig. 1), as the region least affected by storm events (Reading, 1990). Nevertheless, several recent hurricanes have caused heavy surf damage to Bonaire’s coastal infrastructure (Table 1).

A broad range of triggering factors underlines the high tsunami risk of the Caribbean, such as strike-slip motion along the North American–Caribbean plate boundary (Grindlay et al., 2005), the subduction zone of the Lesser Antilles arc (O’Loughlin and Lander, 2003), various regional volcanic sources (Heinrich et al., 1999; Pararas-Carayannis, 2004), landslides (Teeuw et al., 2009) or even teletsunami originating off the Portuguese coast or the Canary Islands (Ward and Day, 2001; Barkan et al., 2009).

Not only the sources but also the effects are well-documented. The 500-year history of Caribbean tsunami represents 127 incidents with highly varying degrees of destructiveness (O’Loughlin and Lander, 2003). Beyond historical evidence, several sedimentary studies at calm back-barrier environments report on intercalations of high-energy wave facies and thus have the potential to extend the record until the mid-Holocene. While throughout the Caribbean most of these sand and carbonate-rich sediments are interpreted as hurricane-borne (e.g. Bertran et al., 2004; Donnelly and Woodruff, 2007; McCloskey and Keller, 2009; Urquhart, 2009), Weiss (1979) is one of the few scholars who has considered tsunami impact, in this case on the island of Cayo Sal, Venezuela.

Beside coarse-grained sediment layers in back-barrier stratigraphic sequences, geological imprints of extreme wave events also include boulder-sized deposits (Kelletat et al., 2005; Morton et al., 2008). Bonaire as part of the ABC Islands (Leeward Antilles) in the southern Caribbean exhibits the most extensive and best preserved record of high-energy wave debris of the entire intra-American seas, consisting of broad ramparts of imbricated coral rubble and large cliff-top...
boulders from the foreshore and littoral zone (Scheffers, 2002, 2004, 2005; Scheffers et al., 2009).

A facies model for the Holocene stratigraphy of three nearshore floodplains along the windward coast of Bonaire is presented, focusing on the identification of high-energy overwash deposits. The sites were chosen due to exposure to regular hurricane tracks and potential local tsunami or teletsunami approaching from the Atlantic Ocean. All sites of this study are close to previously studied boulder deposits which evidence impacts of high-energy waves (cf. Scheffers 2002, 2004; Morton et al., 2007). New age estimates for these sedimentary deposits as well as a discussion on their origin in the context of regional and global research on extreme wave deposits are provided. For the first time strong indication for tsunami deposits in fine-grained stratigraphies as well as an attempt of correlating them with supralittoral coarse-clast accumulations is presented for the southern Caribbean. This study contributes to local coastal hazard assessment and also to the recent controversial discussion on the interpretation of high-energy wave deposits in geoarchives worldwide.

2. Sedimentary signatures of extreme wave events

Although facies patterns of onshore tsunami deposits are gradually finding their way into textbooks of geomorphology and sedimemotogy (e.g. Bridge and Demicco, 2008), there is still a considerable lack of certainty concerning the interpretation of the field record. The accurate differentiation between storm and tsunami deposits is a major topic in recent publications (e.g. Morton et al., 2008; Engel et al., 2009a; Switzer and Burston, 2010).

In theory, different onshore accumulation patterns of the two varieties of high-energy wave impacts are associated with a higher potential wave run-up, increased inundation depth, accelerated flow velocity overland and, thus, higher transport capabilities of a tsunami. Sediments accumulated onshore by a tsunami either derive from the beach and adjacent land (Sato et al., 1995) where coastal erosion locally may result in shoreline retreat of more than 200 m or to a major extent (>75 %) from the sublittoral zone (Kelletat et al., 2007; Paris et al., 2009). The material is suggested to be primarily transported as suspension load, while the contribution of bedload to the sedimentary record is expected to be relatively small (Jaffe and Gelfenbaum, 2007). Onshore deposition occurs during flooding attenuation. Subsequent backflow dynamics depend on the nearshore topography and may be weakly developed or even absent in low coastal settings such as lagoons. More details on hydrodynamic characteristics of tsunami and hurricane-generated waves are provided by Morton et al. (2007) and Scheffers et al. (2009).

Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Max. category (SSH)</th>
<th>Distance</th>
<th>Hurricane track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenny</td>
<td>15 Nov 1999</td>
<td>4</td>
<td>375 km N</td>
<td>W–E</td>
</tr>
<tr>
<td>Ivan</td>
<td>08 Sep 2004</td>
<td>5</td>
<td>130 km N</td>
<td>E–NNW</td>
</tr>
<tr>
<td>Emily</td>
<td>15 Jul 2005</td>
<td>5</td>
<td>185 km NE</td>
<td>E–NNW</td>
</tr>
<tr>
<td>Felix</td>
<td>02 Sep 2005</td>
<td>5</td>
<td>60 km N</td>
<td>E–NNW</td>
</tr>
<tr>
<td>Omar</td>
<td>15 Oct 2004</td>
<td>5</td>
<td>145 km N</td>
<td>SW–NE</td>
</tr>
</tbody>
</table>

* a: Saffir-Simpson Hurricane Scale (cf. Meteorological Service of the Netherlands Antilles and Aruba, 2009).
* b: The minimum distance of the hurricane's center to the ABC Islands (12.5 N, 69.0 W).
* c: After a counter-clockwise rotation in the central Caribbean (Beven and Landssea, 2009).

have attempted to compile definite signature types (e.g. Tuttle et al., 2004; Kortekaas and Dawson, 2007; Morton et al., 2007; Switzer and Jones, 2008a). However, it is apparent that as more observations on event deposits appear, the more discrepancies between the criteria become exposed. For instance, while studying the sedimentological effects of Cyclone Nargis in Burma 2008, Bahlburg (2008) demonstrated that landward extent is not indicative of a tsunami deposit as previously suggested e.g. by Tuttle et al. (2004). Sediments accumulated by a tsunami are also supposed to show distinct basal unconformities where marine sand sheets truncate soils or lagoon mud of the back-barrier environment. Tsunami sands often contain intraclasts of reworked underlying material and consist of one or several fining-upward sequences. Especially in the upper part of the sequence, terrestrial sediment may be incorporated due to backflow dynamics. Several case studies also emphasized the bimodal grain size distribution, significantly poorer sorting and landward thinning of tsunamiites (Switzer and Jones, 2008a). However, these sedimentary features may form in storm deposits as well. Increased concentrations of geochemical indicators such as Ca, Sr or Na as well as marine faunal remains (molluscs, diatoms, foraminifera, etc.) may relate to flooding by seawater but thus far do not provide clear evidence for either tsunami or heavy storm wave impact (Kortekaas and Dawson, 2007; Szczucinski et al., 2007; Switzer and Jones, 2008a). The presence of heavy minerals is considered to be source dependent and therefore is also not a universally applicable indicator (Morton et al., 2007). While Babu et al. (2007) and Jagodziński et al. (2009) found increased percentages of heavy minerals in 2004 tsunami deposits at Kerala, India, and Kho Khao, Thailand, heavy mineral concentrations were significantly lower at the southwest coast of Sri Lanka compared to palaeo-storm deposits and the active beach (Dahanayake and Kulase, 2008). However, Switzer et al. (2005) noted that the presence of platy (immature) heavy minerals indicative of low-energy conditions found to co-exist with mature sediments from the nearshore may be indicative of tsunami from below storm wave base, if carefully considered within the context of site specific hydrodynamics.

In summary, universally applicable tsunami criteria do not exist in fine-grained stratigraphies and differentiation between tsunami and storm deposits “remains a serious challenge” (Bridge, 2008, p. 94). Thus, by interpreting the sedimentary record of extreme wave events, it is important to consider local modern analogues, i.e. sedimentary traces of either recent tsunami or hurricanes occurring at the same site. Reliable conclusions in terms of distinguishing between tsunami and storm deposits require a detailed analysis of the local coastal settings and the geomorphologic characteristics of the land–sea contact zone as well as the fulfilment of as many empirical sedimentary signatures as possible.

3. Physical setting

The geology of Bonaire (Fig. 1) comprises volcanic deposits of diabase and porphyrite with intercalated cherts and limestones of Upper Cretaceous age (Pijpers, 1933; Beets et al., 1977). They are exposed in the northwestern and central sections of the island and are separated from the sea by a sequence of Quaternary limestone terraces. The youngest of these palaeo-reef platforms (Lower Terrace) dates back to MIS 5 (Bandoian and Murray, 1974). Its surface is located slightly below sea level in the south and between 8 and 12.5 m a.s.l. (above mean sea level) in the northwestern part of the island (Alexander, 1961) due to slow tectonic uplift (0.05 mm/a) and tilting (Herweijer and Focke, 1978). At the wave-dominated eastern shore the Lower Terrace locally has a width of more than 600 m (Herweijer et al., 1977). Accordingly, except for the southern part, the coastline consists of steep limestone cliffs characterized by sea-level related notches and benches, mainly produced by bioerosion (e.g. by
limpets, litorinids, chitons) and bioconstruction (by coralline algae, vermetid gastropods) (Scheffers, 2005).

In contrast to the western leeward coast which is fringed by a flourishing reef body, living coral communities are lacking at the windward side due to heavy disturbances during extreme wave events. Large amounts of Holocene coral debris aggregated in ramparts on the windward Lower Terrace indicate destruction within the recent geological past (Scheffers, 2002; Scheffers et al., 2009).

The semi-arid to arid climate and limited catchment sizes cause an episodic discharge regime as well as sheetwash and splash erosion (Zonneveld et al., 1977). Where the arroyos (locally: “rooinen”) approach the sea, accumulation zones such as floodplains, salinas and bokas form. The latter two landforms represent shallow inland bays, in some cases cut off from the sea and used for salt production in the past. At these coastal sections the small watercourse systems dissected the limestone terraces during Pleistocene periods of base level fall and build up nearshore sedimentary archives for the mid- and late Holocene (Scheffers, 2002). Floodplains at Lagun, Boka Washikemba and Playa Grandi on the wave-exposed windward coast of Bonaire were investigated with the aim of detecting and interpreting sedimentary traces of extreme wave events.

4. Methods

In a first step suitable geographies along the windward coast were determined by means of satellite images and field surveys. A total of twelve open and one closed vibracores of up to 8 m depth were taken for sedimentary analyses and facies determination. Positions and elevations of coring sites as well as the modern beach ridge of Playa Grandi were measured using a high-resolution DGPS (Leica SR 530).

After documentation of the vibracores in the field (colour according to the Munsell Soil Color Chart, grain size and rounding, texture and carbonate content as recommended by Ad-hoc-Arbeitsgruppe Boden, 2005, as well as macrofaunal remains), samples were taken for multi-proxy analysis with the aim of identifying facies changes and episodic marine sediment input. For a sufficient amount of sediment material each sample represented sections of 5–10 cm from significant stratigraphic units resulting in a maximum of 21 samples per core. Samples for geochemistry were air-dried and pestled by hand. Ca, Fe, Na, and K concentrations of the sand/mud fraction (< 2 mm) of all open vibracores were determined using atomic absorption spectrometry (Perkin Elmer A-Analyst 300). Samples were digested with concentrated HCl (37%). CaCO₃ was gas-volumetrically measured after the Scheibler method. Loss on ignition (LOI) was determined by oven-drying at 105 °C for 12 h and ignition in a muffle furnace at 550 °C for 4 h (Beck et al., 1995). Grain size distribution was analysed selectively. We applied the wet sieve-pipette technique (Köhn, 1928) after pre-treatment of the aliquots with H₂O₂ (30 %) and 0.5 n Na₃P₂O₇ (55.7 g/l) to remove organic carbon and for aggregate dispersion. The results were processed with GRADISTAT software (Blott and Pye, 2001). These stratigraphic proxies represent the main basis of distinct facies differentiation at the three sites of interest.

Sediment core BON 9 was preserved in PVC tubes which were split in the laboratory. XRF analysis and magnetic susceptibility measurements (Bartington MS2B sensor) with 1 mm resolution were carried out on the half cores. The inorganic element composition was determined using an ITRAX X-ray fluorescence (XRF) core scanner (Cox Analytical Systems). The ITRAX was equipped with a 3 kW Mo X-ray tube set to 30 kV and 30 mA to analyze semi-quantitative variations of elements from Al to U. Scanning was performed at 1 mm resolution and an exposure time of 20 s. Element amounts were presented as count rates as estimates of the relative concentrations in the sediment. Detection limits range between 2.2 % for Al and 5 ppm for heavier elements like Sr or Rb (Croudice et al., 2006).

Macrofaunal remains and coarse sand grains were quantitatively analysed in terms of taphonomic and morphoscopic characteristics similar to Donato et al. (2008). Certain features (articulation, angular/subangular breaks, encrustations, borings, dissolution or abrasion) and species composition relate to (i) transport processes and/or (ii) palaeo-environmental conditions and thus support the identification and classification of extreme wave events.

A chronostratigraphical framework was established by means of AMS and conventional ¹⁴C analyses carried out at the radiocarbon laboratories of the universities of Georgia at Athens (USA), Erlangen and Cologne (Germany). Radiocarbon dates of marine shells were corrected for a regional marine reservoir effect of ΔR = −49 according to Radtke et al. (2003). Since ¹⁴C dates of land snails in limestone habitats imply considerable age exaggeration due to the assimilation of ancient carbonate we considered an age anomaly of 1020 ± 430 years for the sample of Cerion uva (terrestrial snail) as calculated by Goodfriend and Gould (1996) after dating several specimen of this genus from the Bahamas. We adopted their value since differences in age anomalies of land snails depend on ecologic conditions and thus the variability within species or genera is rather low (Goodfriend, 1987). All dates were converted to sidereal years using CALIB 5.01 software and the datasets of Reimer et al. (2004) or Hughen et al. (2004). All ages are presented as 2σ sidereal years.

5. Holocene stratigraphy of nearshore geographies

5.1. Lagun

Lagun, located at the windward coast of Bonaire, is an embayment with open access to the sea (Fig. 2). Wave energy inside the embayment is significantly reduced due to the narrow inlet cutting the highly resistant Lower Terrace. Bathymetric data revealed a submarine sill where the Middle Terrace divides Lagun into two subbasins. To the north and south Scheffers (2002, p. 132) mapped the “most spectacular rampart formations and boulder assemblages” of the entire island distributed over the platform of the Lower Terrace. The closed sediment core BON 9 (Fig. 3) and the open core LGU 7 (Fig. 4) from the centre of the landward floodplain (Fig. 2) provide detailed information on variable energy levels during Holocene sediment accumulation processes. Since both cores show a very similar stratigraphic pattern they are described together.

The basal unit consists of grey, poorly sorted residual loam which is overlain by well-sorted clayey silt and dark brown peat with several shells of Crassostrea rhizophora and Cerithium sp. incorporated into the densely packed remains of Rhizophora sp. At 3.47 m b.s. values of bulk Ti content and magnetic susceptibility reflect an abrupt facies change. ¹⁴C analyses yielded ages of 6283–5999 cal BP (Erl10611) and 6406–6029 cal BP (Erl10609) (Fig. 4). A distinct erosional unconformity separates the mangrove peat from an overlying unit of shell debris in a carbonate-rich matrix. The thenatoecoensis is dominated by robust shells of Bullo striata and Chiome cancellata and fragments of Cerithium sp., Brachiodytes exustus, Trachycardium muriactum, Tellina cf. tampaenosa, Arca sp., Conus sp. as well as undetermined marine bivalves and gastropod remains (LGU 7/14 and LGU 9/2 in Table 4). Many shells show angular breaks; however, two articulated specimens of C. cancellata were also found (LGU 7/14 and LGU 9/2 in Table 3). Bulk Sr and Ca contents are significantly increased. Shells of Cerithium sp. revealed ages of 2333–2168 (UGAMS3207) and 2100–1921 cal BP (UGAMS3206) (Fig. 4).

Well-sorted clayey silt with several plant remains covers the allochthonous shell-rich facies passing into dark brown mangrove peat with values of Crassostrea rhizophora. Plant remnants from 1.44 m b.s. were radiocarbon-dated to 503–314 cal BP (Erl10610) while a piece of wood from 1.16 m b.s. revealed an age of 275 cal BP to modern (KN-5851). The top sediments of BON 9 are coarse and characterized by high magnetic susceptibility.
Analyses conducted with core LGU 7 revealed a normally graded pattern and a gradual upward increase in LOI and K and Fe concentrations in the prominent shell-rich unit. 14C dating of plant remains (roots?) from the uppermost part of this unit resulted in ages of 1705–1566 (UGAMS4200) and 455–299 cal BP (UGAMS4199) (Fig. 5).

5.2. Boka Washikemba

Boka Washikemba is another creek-like drainage feature dissecting the Lower Terrace approx. 900 m south of the entrance of Lagun (Fig. 2). Since its catchment area is smaller, the floodplain has a much lesser extent and mangroves are absent.

BWA 1 (Fig. 5), drilled at a distance of 150 m from the pocket beach, reveals poorly sorted loamy sediments overlying the weathered bedrock. A land snail (Cerion uva) at the bottom of this unit revealed an age of 7455–5528 cal BP (UGAMS3205). At 4.10–3.82 m b.s. the sediment consists of coarse calcarenitic sand, Halimeda grainstone and mollusc shell remains. Subangular and rounded components are dominating (BWA 1/9 in Table 3). A thin layer of peat, dated to 3870–3707 cal BP (UGAMS3204), separates the sand from an olive grey organic-rich silt unit with fragile and well-preserved bivalves and fresh-appearing shells of Cerithium sp. The peat is vertically confined by a unit of sandy loam with a plant remnant (root?) and several shells of Cerithium sp. showing a moderate degree of abrasion. Above the peat lies a core loss section which is overlain by poorly sorted loamy sand. An abrupt change in environmental conditions is indicated by the overlying well-sorted silt (2.90–2.00 m b.s.) containing well-preserved shells of Cerithium sp. The silt unit is interrupted by a thin intercalation of moderately to well-rounded carbonate sand. At 1.55–0.63 m b.s. the sediment coarsens again revealing a high percentage of CaCO₃, poor sorting and shells of Cerithium sp. as well as a large fragment of an elk-horn coral (Acropora cervicornis). The top sediment layer consists of silty clay with several gravel components (Fig. 5).

5.3. Playa Grandi

From a geomorphologic point of view the floodplain of Playa Grandi (Fig. 7) can be described as a weakly developed boka with rudimentary features of a ria-type coast (Scheffers, 2004). Two cores were taken from behind the beach ridge (PGR 3) and further landward near the road (PGR 1) (Figs. 6 and 7).

5.3.1. PGR 3

From 9.00–2.88 m b.s. PGR 3 consists of a massive unit of coarse sand (Halimeda grainstone and mostly subangular and rounded coral and mollusc shell fragments). The age of plant remains from its uppermost part is 4066–3843 cal BP (UGAMS4205). This basal section is vertically confined by silty clay with plant remains that shows significantly increased K values and numerous well-preserved fragile bivalves as well as ostracod valves and shells of Cerithium sp. A layer of coarse carbonate sand (2.72–2.58 m b.s.) interrupts the silty clay unit revealing features such as a basal unconformity, an articulated bivalve (Tellina cf. tampaensis, PGR 3/10 in Table 4), terrestrial plant fragments and a fining-up sedimentary pattern. It was dated to 3384–3247 cal BP (UGAMS4204). The sand components predominantly consist of Halimeda and fragments of worm tubes with more angular breaks and less dissolution and abrasion features compared to the sediment of the massive lowermost sand unit (PGR 3/10 in Table 3).

The overlying fine-grained sediment unit is characterized by low Ca as well as increased Fe and K values. At 2.20 m b.s., abundant shells of Cerithium sp. and fragile valves of Tellina cf. tampaensis (comprising two articulated specimens in living position), juvenile Bulula striata and Brachiodontes exustus occur (PGR 3/8 F in Table 4). Two thin layers
enriched with carbonate sand components are found in the upper sequence. In the surface layer coarsening is associated with poorer sorting and increased Ca values.

5.3.2. PGR 1

Core PGR 1 (0–4.35 m b.s.) was taken 150 m landward of PGR 3. The lowermost section is stratified and contains several entire shells and valves of Cerithium sp. and Brachiodontes exustus as well as undeterminable mollusc fragments (PGR 1/17 in Table 4). Plant remains were dated to 4518–4299 cal BP (UGAMS4203). At 4.12–4.10 m b.s., a shell pavement was identified. It is incorporated into the lagoonal silt and contains an articulated specimen of Tellina cf. tampaensis and a juvenile Bulla striata among other (fragmented) shells (PGR 1/15 in Tables 3 and 4). The age of plant remains from this layer is 3885–3720 cal BP (UGAMS4202). Cerithium sp. and an articulated specimen of Tellina cf. tampaensis were also found at 3.63 and 3.25 m b.s. A slight increase in mean grain size at 1.53–1.43 m b.s is coincident with a lowered Ca/K ratio.

6. Discussion

The main results and interpretation of sedimentary and geochemical analyses are compiled in Fig. 8. In combination with taphonomic findings (Tables 3 and 4) as well as sediment thickness and stratigraphic position (Playa Grandi), they relate to the differentiation of local facies units. The distribution of facies units within the back-barrier stratigraphies is shown in Figs. 3–5 and 7. Fig. 9 provides a summary of findings of high-energy wave deposits with their chronological interpretation.

6.1. The distribution of high-energy wave facies along the east coast

6.1.1. Lagun

At Lagun (BON 9: 3.25–2.65 m b.s. and LGU 7; 2.96–2.57 m b.s.) a sedimentary unit of shell debris (facies unit L4 in Fig. 8) was encountered which is also present in adjacent sediment cores (Willershäuser, 2008). It is vertically confined by compressed mangrove tree material (below, L3) and lagoonal mud (above, L2a). The macrofaunal remains mainly consist of C. cancellata (endobenthonic), Crassostrea rhizophora (sessile), Bulla striata, Cerithium sp. and Brachiodontes exustus and indicate a habitat of shallow soft-bottom areas covered by turtle grass (Thalassia testudinum) and fringed by flourishing populations of Rhizophora mangle (Mattox, 1949; Moore and Lopez, 1969; Vélez, 1991; Abbott and Dance, 2000). Even though some of the species occasionally occur at greater depths of reefal environments (Buitrago et al., 2006), a dense population of the bivalve C. cancellata in particular indicates that the entire deposit stems from the inlet of Lagun and its narrow reach. Communities of C. cancellata may reach a density of up to 162 per m² in intertidal muds while it declines down to < 1 per m² in deeper sublittoral environments (Moore and Lopez, 1969). Two articulated bivalves were also identified which is a prominent feature of tsunami deposits, as described in the case studies of Cesarea, Israel (113 AD) and Sur Lagoon, Oman (1945 AD) (Donato et al., 2008). Valves and shells are well-preserved with predominantly angular breaks (LGU 7/14 and LGU 9/2 in Table 3) indicating proximal dislocation from their habitat inside the open embayment (calm environment) into the former landward lagoon during a high-magnitude/low-frequency wave event. The erosional contact between the allochthonous shell layer and the truncated peat (Fig. 3) represents a stratigraphic feature typically associated with palaeo-tsunami deposits (e.g. Dawson et al., 1988; May et al., 2007; Vött et al., 2007; Jankaew et al., 2008; Vött et al., 2009) but has also been observed in sediments transported onshore by severe storms and hurricanes (e.g. Morton et al., 2007; Wang and Horwitz, 2007). Peaks in Ca, Sr and S (Fig. 3) concentrations as well as low values of K, Ti, Si and Rb resemble the geochemical pattern of tsunami-laid sands from 1755 AD inside the Tagus Estuary, Portugal (Andrade et al., 2003). However, a similar pattern of elemental concentrations may also be produced by hurricane activity (Jessen et al., 2008) or even a gradual marine transgression (Engel et al., 2009b).

Sedimentary analyses from LGU 7 provide supplementary information on the transport process of the shell debris layer (L4). Normal grading as well as a continuous upward increase in LOI (Fig. 4) in combination with the distinct erosional unconformity indicate accumulation by a single major impulse and the mixing with terrestrial material during flow attenuation. By comparing bedform structures of both tsunami and typhoon deposits generated during modern events on southwestern Hokkaido, Nanayama et al. (2000) concluded that tsunamiogenic sediments consist of normally graded sedimentary sequences each representing a single wave. The authors suggest that tsunami deposits often consist of basal sands deposited by inflow and a mixture of marine and non-marine sediment and plant remains due to backflow deposition. The shell debris layer L4 (Figs. 3 and 4) identified at Lagun meets a broad range of empirical tsunami signatures (cf. Dominey-Howes et al., 2006, Switzer and Jones, 2008a). The fact that waves of recent severe hurricanes approaching Bonaire from the east (Table 1) flooded the nearshore floodplains but left no significant sedimentary imprint at Lagun and Boka Washikemba may also indicate its deposition during a more powerful hydrodynamic process. According to 14C dates (Figs. 3 and 4; Table 2), the event occurred after 2000 and most probably before 1700 BP (Fig. 9) based on molluscs from the deposit representing maximum ages (2333–2168 [UGAMS3207] and 2100–1921 cal BP [UGAMS3206]), and roots which penetrate the deposit and thus provide minimum ages (1705–1566 [UGAMS4200] and 455–299 cal BP [UGAMS4199]). The large hiatus between L4 and the underlying unit L3 (Fig. 4) may indicate the high erosional potential of the overland flow. Thus, the deposit is assumed to be tsunamiogenic, even though a powerful hurricane that made landfall on Bonaire cannot be ruled out completely.

The wave impact seems to have entirely transformed the nearshore ecosystem and destroyed a major part of the lumph mangrove population based on preliminary results of pollen counts of core BON 9. After the impact, Rhizophora sp. pollen declines drastically in favour of grasses accompanied by an increase in charcoal particles which indicates the presence of high amounts of dead wood (Engel et al., 2009a).

6.1.2. Boka Washikemba

The vertical distribution of marine facies (B4a, B4b in Figs. 5 and 8) at the Boka Washikemba floodplain reveals discrepancies compared to Lagun — although both sites are proximal to one another and have the same orientation. The lowermost marine intrusion (B4a) above the weathered bedrock (B1) and a thin layer of terrestrial facies (7455–5528 cal BP; B2a/b) is interpreted as beach sands of the Holocene marine transgression based on observations on regional sea-level history. Relative sea-level curves from Curacao and Venezuela based on 14C data of peat deposits (Rull et al., 1999; Klosowska, 2003) and comprehensive model predictions (Milne et al., 2005) as well as approximations inferred from reef growth (Focke, 1978) indicate that relative sea level during the Holocene has never been higher than today. The high postglacial rate of eustatic sea-level rise decreased significantly during the mid- and late Holocene. This break usually occurs around 6000–5000 BP and marks the maximum flooding surface at many coastal sedimentary environments worldwide (cf. Stanley and Warne, 1994; Engel et al., 2009b) including the narrow inlet of Boka Washikemba.

Accordingly, facies unit B4a is likely to represent the Holocene maximum landward displacement of the shoreline at Boka Washikemba while the overlying peat stratum (3867–3705 cal BP) of B2a/b belongs to a mid- to late Holocene regressive sequence produced by sediment input from the hinterland and moderate tectonic uplift outpacing the slow eustatic sea-level rise (Fig. 5). According to this interpretation, the recurrence of marine facies in the upper strata of
BWA 1 remains enigmatic. A B4b unit (3.71–2.90 m b.s.) confines the thin terrestrial layer (B2a/b) representative of a lagoonal ecosystem. The loamy sand of B4b most likely interrupts the mid- to late Holocene sequence as the imprint of a high-energy wave event. Marine provenance is inferred from the presence of coral rubble, a high portion of subangular and rounded Halimeda grainstone and abraded Cerithium shell fragments. Compared to facies B4a (beach), the geochemical pattern in B4b reveals more terrestrial influence and a smaller percentage of eulittoral Halimeda sand due to the incorporation of terrestrial material and/or post-depositional alteration (Fig. 8). Chronological evidence from the underlying unit indicates post-3800 BP deposition. The layer may even correlate with the post-2000 BP candidate tsunami deposit at Lagun according to its stratigraphic position.

Another high-energy wave event left its thin sedimentary imprint at 2.70 m b.s. (B4b in Fig. 5). Whether it corresponds to a hurricane surge or a tsunami remains uncertain since thickness of sand-sized deposits is not indicative for either tsunami or storm surge impact. Deposits related to both hydrodynamic processes reach from several millimetres (tsunami: e.g. Gelfenbaum and Jaffe, 2003; tropical cyclone: e.g. Donnelly and Woodruff, 2007) to more than 80 cm (tsunami: e.g. Paris et al., 2007; tropical cyclone: e.g. Morton et al., 2007), depending on the availability of source material, the hurricane centre’s distance and intensity or tsunami run-up and approaching angle, distance to the shoreline as well as the pre-impact coastal topography.

Between 1.55 and 0.63 m b.s. (Fig. 6), the regressive Holocene sequence (B2a/b, B2c) is once again interrupted by a marine layer (B4b) representing a possible extreme wave impact. Higher concentrations of terrestrial material and/or post-depositional alteration (Fig. 8). Chronological evidence from the underlying unit indicates post-3800 BP deposition. The layer may even correlate with the post-2000 BP candidate tsunami deposit at Lagun according to its stratigraphic position.

Fig. 4. Sediment core LGU 7 with projected data of mean grain size ($x_G$), grain sorting ($\sigma$), Ca/Fe ratio and LOI. For site location see Fig. 2. Facies characteristics are summarized in Table 2. The legend also applies for Figs. 5 and 7.
Fig. 5. Sediment core BWA 1 with projected data of mean grain size ($x_\text{G}$), grain sorting ($\sigma$), Ca/Fe ratio and LOI. For site location see Fig. 2. Facies characteristics are summarized in Fig. 8. Details concerning radiocarbon data are provided in Table 2. A legend is available in Fig. 4.

Fig. 6. Overview of Playa Grandi displaying coring sites PGR 1 and 3 on the floodplain (Google Earth). A–A’ indicates the altitudinal transect of the boulder beach.
500 years while it should not exceed 1000 years. At Lagun no stratigraphical counterpart was detectable. Sato et al. (1995) emphasize on the importance of source supply for the creation of the sedimentary record and the minor significance of local run-up heights after conducting post-tsunami surveys at Hokkaido in 1993. Accordingly, extensive sand accumulations on top of the Lower Terrace of Bonaire which are linked to older extreme wave events (Scheffers and Scheffers, 2006) may have served as sediment sources for BWA 1 rather than for LGU 7/BON 9 further landward causing discrepancies in the sedimentary record. The essential role of available source material is also substantiated by a coral rubble sequence of up to 1.5 m at Playa Funchi, northwest Bonaire (Spiske and Jaffe, 2009). According to post-hurricane surveys and the interpretation of multi-temporal aerial photographs, the deposit is exclusively associated with hurricane Lenny in 1999 and has hardly been modified by subsequent hurricanes of comparable magnitude (e.g. hurricane Felix in 2007, hurricane Omar in 2008, cf. Table 1). A vivid framework of Acropora cervicornis inhabiting the sublittoral of Playa Funchi collapsed due to the spread of the white-band disease in the early 1980s (Bries et al., 2004) providing large quantities of coral rubble to be mobilized by the waves induced by Lenny in 1999.

6.2. The distribution of high-energy wave facies along the northeastern shoreline

No evidence for marine sediment input was found at PGR 1 (Fig. 7), located at a distance of c. 250 m from the shore. In contrast, just behind the beach ridge of coral rubble a sequence was cored (PGR 3) comprising the uppermost part of the early to mid-Holocene transgressive sequence (P4a in Fig. 7) and the mid- to late Holocene highstand sequence (upper part of P4a to ground surface in Fig. 7). More than 6 m of the lower sediment core reveal a massive ancient beach ridge testifying to mid-Holocene shoreline retreat. Regression set in well before 4046–3843 cal BP when the site was already

---

**Fig. 7.** Stratigraphy of PGR 1 and PGR 3 with projected data of mean grain size ($X_g$), grain sorting ($\sigma$), Ca/Fe ratio and LOI. For site location see Fig. 6. Facies characteristics are summarized in Fig. 8. Details concerning radiocarbon dates are provided in Table 2. A legend is available in Fig. 4.
The sample of B3 was solely used for radiocarbon dating.
invaded by prograding backswamps (P3) and a lagoon (P2a) characterized by dense, thin-walled bivalve populations (PGR 3/12 and PGR 3/11 F in Table 4).

A lens of marine sand (P4b, Fig. 7) indicates the occurrence of a high-energy wave event. Articulated bivalves as well as an increased percentage of angular breaks on mollusc shells and significantly fewer abrasion or dissolution features and borings (sample PGR 3/10, Table 3) allow the discrimination of this unit (P4b) from the beach facies (sample PGR 3/17, Table 3). A promising approach in deducing a certain hydrodynamic process from facies unit P4b is a comparison with the surface unit P4c which represents the sedimentary contribution of recent hurricanes (Fig. 7). There, single events contributed only low amounts of carbonate sands which are mixed with autochthonous fine-grained alluvial matrix.

The interpretation that the sand section of P4b represents a tsunami event is based on the following observations: a sharp erosional contact at the base of P4b (tsunami layer) which is absent in P4c (hurricane layer). There is also a significantly higher percentage of angular shapes and less abrasion or dissolution features on grains and shell material of layer P4b (Table 3). Based on the mollusc shell assemblage both deposits have similar source supply which is the contemporary active beach and sub littoral environment.

The taphonomic results of this study (Table 3) show that the approach presented by Donato et al. (2008) may provide a useful tool in discriminating between palaeo-storm and palaeo-tsunami deposits. The fact that percentage values of certain morphometric parameters of the Oman tsunami layer and the P4b layer differ is due to local preimpact sedimentary, ecological and mineralogical settings. Nevertheless, in all cases common tendencies were observed.

A plant remnant from the upper part of the tsunami sand sequence, where terrestrial material is incorporated due to backflow dynamics, revealed an age of 3384–3247 cal BP (UGAMS4202) representing a maximum age for the corresponding event.

Two thin sand layers (2.08 and 1.65 m b.s.) provide evidence for additional extraordinary wave impacts during the late Holocene (Fig. 7). The lower layer may correlate with the major wave event after 2000 BP deduced from deposits from Lagun (Figs. 3 and 4). The upper sand lens represents an unknown event of short-term marine inundation.

6.3. Correlation with the coarse-clast record of Bonaire

Dislocated boulders and extended ridges of coral rubble on top of the Miocene Lower Terrace of Bonaire are attributed to strong tsunami events that occurred before the arrival of the Europeans and after sea level started to decelerate in the middle Holocene (Scheffers, 2002, 2004, 2005). Based on geomorphologic interpretation of these deposits and a data set of more than 80 radiocarbon dates from Bonaire and the wider Caribbean as well as 120 ESR (Electron-Spin-Resonance) dates from Bonaire – all representing maximum ages for certain extreme wave events – a chronology of strong tsunami impacts around 500 BP, 1200 BP, 3300 BP, 3900 BP and 4300 BP was proposed by Scheffers (2005). Due to the wide span of radiometric ages and the underestimation of long-term coastal processes and minor wave events in the discussion of the genesis of the circum littoral sedimentary record, this chronology has recently been challenged (Morton et al., 2006, 2008; Spiske et al., 2008). By reviewing studies on coastal sedimentary transport, Morton et al. (2006) concluded that ridges and ramparts may have been generated by periodically occurring storm waves.

However, the tsunami chronology deduced from coarse deposits is only partially supported by the present study. The post-2000 BP major wave impact – possibly a tsunami – reflected by the floodplain stratigraphy of the eastern shore (Figs. 4 and 5) does not match the chronology of Scheffers (2002, 2004, 2005). A major incident around 500 BP inferred by Scheffers (2005) based on investigations on Bonaire and Weiss (1979) based on a sedimentary sequence from Cayo Sal, c. 150 km ESE of Bonaire, may correspond to the findings at BWA 1, while at Lagun we observed no evidence for such an event. The main reasons for these particular discrepancies may be (i) errors in sampling for dating purposes, (ii) fluctuations in sediment availability in the eulittoral and sublittoral zones during certain events and/or (iii) incompleteness of the stratigraphical record due to

---

**Fig. 8.** Facies model for the Holocene stratigraphy of Lagun (left column), Boka Washikemba (centre) and Playa Grandi (right) based on sedimentary (percentage of sand, mean grain size, sorting) and geochemical (LOI, K, Fe, CaCO3) parameters. Rows indicate specific depositional environments. Each spider chart shows heptagons similar in shape representing a certain local lithofacies unit. Each heptagon represents one sediment sample. Facies abbreviations are valid for the text and the sediment cores (Figs. 3–5 and 7). The geochemical and sedimentary fingerprint of possibly tsunamigenic facies is highlighted (grey). Discrimination between different marine subunits (e.g. P4a, P4b, P4c) is not solely based on results compiled in this figure but also on taphonomic analyses (Table 3), as well as sediment thickness (P4a) and stratigraphic position (B4a, P4c).

**Fig. 9.** Sedimentary evidence for and chronological interpretation of major wave events from geoarchives along the eastern and northeastern coast of Bonaire. Chronological data of Scheffers et al. (2006) from supralittoral boulder deposits of the coastal area between Spelonk Lighthouse and Lac Bai (Fig. 1) is added. The results of the present study indicate the occurrence of three major wave events during the last 4500 years that significantly exceeded the energy of strong modern hurricanes (Table 1). Their sedimentary traces vary significantly from site to site.
erosion. At Playa Grandi a major wave event was indicated by a sand deposit from c. 3300 BP or younger (Fig. 8) which is coeval with the interpretation of the coarse-clast tsunami record by Scheffers (2005).

The conclusion of Morton et al. (2008, p. 636) that, according to the wide span of 14C dates available along the shoreline of Bonaire, coarse-clast accumulation results are the accumulation of “long-term coastal deposition by many extreme wave events” must be slightly modified. Severe episodic influence on the nearshore environments was unambiguously identified; findings from this study imply large-scale erosion and sedimentation and sustained alteration of the boka ecosystems by major wave events at a very low frequency. These extraordinary events presumably had significant effects along the coasts of the entire southern Caribbean region. However, we fully agree with Morton et al. (2008) that the resulting landforms and sedimentary imprints were subsequently modified in many cases by long-term wave action and periodically occurring wave events.

### 7. Conclusions

Tsunami and hurricane-generated waves represent a real threat to the southern Caribbean. In this paper stratigraphic evidence for three major wave impacts along the windward coast of Bonaire is presented (Fig. 9).

Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth b.s. (cm)</th>
<th>Material</th>
<th>Lab ID</th>
<th>14C (% C)</th>
<th>14C age (BP)</th>
<th>Age in sidereal years (2σ cal BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BON 10/1-1</td>
<td>116–111</td>
<td>Wood</td>
<td>KN-5851</td>
<td>−26.95</td>
<td>130±30</td>
<td>275–modern</td>
</tr>
<tr>
<td>BON 4/18 PF</td>
<td>353–360</td>
<td>Peat</td>
<td>Erl10609</td>
<td>−22.7</td>
<td>5469±61</td>
<td>6404–6029</td>
</tr>
<tr>
<td>BON 10/1-4</td>
<td>144–145</td>
<td>Wood</td>
<td>Erl10610</td>
<td>−27.4</td>
<td>366±46</td>
<td>503–314</td>
</tr>
<tr>
<td>BON 10/4-1</td>
<td>385–396</td>
<td>Peat</td>
<td>Erl10611</td>
<td>−26.8</td>
<td>5369±60</td>
<td>6282–5999</td>
</tr>
<tr>
<td>BWA 1/8</td>
<td>380–382</td>
<td>Wood</td>
<td>UGAMS3204</td>
<td>−26.00</td>
<td>3520±25</td>
<td>3870–3707</td>
</tr>
<tr>
<td>BWA 1/21 M</td>
<td>466</td>
<td>Cerita uva (terr. gastropod)</td>
<td>UGAMS3205</td>
<td>−0.67</td>
<td>8480±25</td>
<td>7453–5528</td>
</tr>
<tr>
<td>LGU 2/10 G</td>
<td>270–280</td>
<td>Ceritid sp. (marine gastropod)</td>
<td>UGAMS3206</td>
<td>−26.60</td>
<td>2330±25</td>
<td>2100–1921</td>
</tr>
<tr>
<td>LGU 2/11 G</td>
<td>315–325</td>
<td>Ceritid sp. (marine gastropod)</td>
<td>UGAMS3207</td>
<td>−2.09</td>
<td>2540±25</td>
<td>2333–2168</td>
</tr>
<tr>
<td>LGU 7/8</td>
<td>256–257</td>
<td>Plant remains</td>
<td>UGAMS4199</td>
<td>−26.2</td>
<td>300±25</td>
<td>455–299</td>
</tr>
<tr>
<td>LGU 7/12</td>
<td>271–274</td>
<td>Plant remains</td>
<td>UGAMS4200</td>
<td>−26.85</td>
<td>1730±25</td>
<td>1705–1566</td>
</tr>
<tr>
<td>PGR 1/15 H</td>
<td>411</td>
<td>Plant remains</td>
<td>UGAMS4202</td>
<td>−24.58</td>
<td>3530±25</td>
<td>3885–3720</td>
</tr>
<tr>
<td>PGR 1/17 H</td>
<td>431–435</td>
<td>Plant remains</td>
<td>UGAMS4203</td>
<td>−23.03</td>
<td>3960±25</td>
<td>4518–4299</td>
</tr>
<tr>
<td>PGR 3/10 PR</td>
<td>258</td>
<td>Plant remains</td>
<td>UGAMS4204</td>
<td>−25.50</td>
<td>3100±30</td>
<td>3384–3247</td>
</tr>
<tr>
<td>PGR 3/13</td>
<td>288</td>
<td>Plant remains</td>
<td>UGAMS4205</td>
<td>−25.79</td>
<td>3620±30</td>
<td>4066–3843</td>
</tr>
</tbody>
</table>

### Table 3

Taphonomy of shells and Halimeda particles from the sediment cores of Lagun, Boka Washikemba and Playa Grandi. The parameters were selected according to Donato et al. (2008), data repository item — Table DR1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth m b.s.</th>
<th>Facies</th>
<th>n</th>
<th>Articulated bivalves</th>
<th>Whole valve</th>
<th>Shell fragment</th>
<th>No break</th>
<th>Angular break</th>
<th>Subangular/Boring</th>
<th>Encrustation</th>
<th>Dissolution/abrasion</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGU 7/14 Ref</td>
<td>2.93–2.83</td>
<td>L4 (tsunami)</td>
<td>243</td>
<td>18.11</td>
<td>81.89</td>
<td>9.05</td>
<td>82.72</td>
<td>8.23</td>
<td>11.11</td>
<td>–</td>
<td>20.16</td>
</tr>
<tr>
<td>LGU 9/2Ref</td>
<td>2.95–2.85</td>
<td>L4 (tsunami)</td>
<td>247</td>
<td>31.58</td>
<td>68.42</td>
<td>16.19</td>
<td>68.93</td>
<td>14.98</td>
<td>15.79</td>
<td>0.40</td>
<td>22.67</td>
</tr>
<tr>
<td>BWA 1/6</td>
<td>1.30–1.20</td>
<td>B40 (tsunami)</td>
<td>64</td>
<td>3.13</td>
<td>96.88</td>
<td>–</td>
<td>28.13</td>
<td>81.25</td>
<td>–</td>
<td>–</td>
<td>87.50</td>
</tr>
<tr>
<td>BWA 1/3 *</td>
<td>2.71–2.68</td>
<td>B40 (sand lense)</td>
<td>147</td>
<td>–</td>
<td>–</td>
<td>100.00</td>
<td>–</td>
<td>17.01</td>
<td>82.99</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BWA 1/19 *</td>
<td>4.10–4.05</td>
<td>B4b, sand lense (tsunami?)</td>
<td>159</td>
<td>1.26</td>
<td>98.74</td>
<td>–</td>
<td>8.18</td>
<td>91.82</td>
<td>1.89</td>
<td>0.63</td>
<td>93.71</td>
</tr>
<tr>
<td>PGR 1/15 *</td>
<td>4.12–4.10</td>
<td>P2a (shallow lagoon)</td>
<td>383</td>
<td>0.26</td>
<td>2.87</td>
<td>97.13</td>
<td>1.31</td>
<td>95.30</td>
<td>3.39</td>
<td>–</td>
<td>2.35</td>
</tr>
<tr>
<td>PGR 1/17 Sand *</td>
<td>4.35–4.26</td>
<td>P3 (coastal marsh)</td>
<td>17</td>
<td>11.76</td>
<td>88.24</td>
<td>–</td>
<td>29.41</td>
<td>70.59</td>
<td>47.06</td>
<td>–</td>
<td>76.47</td>
</tr>
<tr>
<td>PGR 3/Surf *</td>
<td>0.08–0.00</td>
<td>P4c (hurricane)</td>
<td>236</td>
<td>0.85</td>
<td>99.15</td>
<td>0.42</td>
<td>8.47</td>
<td>91.10</td>
<td>5.51</td>
<td>–</td>
<td>81.78</td>
</tr>
<tr>
<td>PGR 3/8 F *</td>
<td>2.25–2.15</td>
<td>P2a (shallow lagoon)</td>
<td>169</td>
<td>0.81</td>
<td>43.20</td>
<td>55.52</td>
<td>40.24</td>
<td>59.97</td>
<td>1.78</td>
<td>0.59</td>
<td>–</td>
</tr>
<tr>
<td>PGR 3/10 F *</td>
<td>2.72–2.62</td>
<td>P4b (tsunami)</td>
<td>296</td>
<td>0.34</td>
<td>3.72</td>
<td>95.95</td>
<td>40.05</td>
<td>27.03</td>
<td>69.26</td>
<td>5.07</td>
<td>–</td>
</tr>
<tr>
<td>PGR 3/11 F *</td>
<td>2.84–2.82</td>
<td>P2a (shallow lagoon)</td>
<td>352</td>
<td>0.21</td>
<td>2.87</td>
<td>97.13</td>
<td>1.31</td>
<td>95.30</td>
<td>3.39</td>
<td>–</td>
<td>2.35</td>
</tr>
<tr>
<td>PGR 3/12 Sand *</td>
<td>2.86–2.85</td>
<td>P3 (coastal marsh)</td>
<td>220</td>
<td>42.27</td>
<td>57.73</td>
<td>37.27</td>
<td>61.82</td>
<td>0.91</td>
<td>–</td>
<td>40.09</td>
<td>1.36</td>
</tr>
<tr>
<td>PGR 3/17 *</td>
<td>4.80–4.70</td>
<td>P4a (beach)</td>
<td>240</td>
<td>5.00</td>
<td>95.00</td>
<td>2.50</td>
<td>11.67</td>
<td>85.83</td>
<td>14.58</td>
<td>–</td>
<td>82.50</td>
</tr>
</tbody>
</table>

a Grain/shell fragment size = 0.63 mm.
b Grain/shell fragment size = 1 mm.
c Grain/shell fragment size = 2 mm.
d Grain/shell fragment size = 6.3 mm.

* Data adapted from Donato et al. (2008).
The distribution of mollusc remains in the sediment cores of Lagun, Boka Washikemba and Playa Grandi (ws = whole shell; f = fragment). At Lagun (LGU) the high abundance of robust shells of Bulla striata and Chione cancellata indicates that elevated wave energy disturbed a geo-ecosystem which is well prepared against long-term wave action. LGU 7 and LGU 9 represent the same site. At Boka Washikemba (BWA) and Playa Grandi (PGR) intertidal or sublittoral species are rare since the habitat in the foreshore zone is small compared to Lagun. Especially at Playa Grandi the slope dips with a high angle. More details on facies characteristics are provided in Fig. 8. The depth of the samples can be inferred from Table 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Facies (environment or morphodynamic process)</th>
<th>Cerithium sp.</th>
<th>Bulla striata</th>
<th>Marine gastropod undet.</th>
<th>Chione cancellata</th>
<th>Brachiodontes exustus</th>
<th>Tellina cf. tampaensis</th>
<th>Crassostrea rhizophora</th>
<th>Bivalve undet.</th>
<th>Other taxa/ macrofaunal remains (n&gt;5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGU 7/14 Ref</td>
<td>L4 (tsunami)</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td>22</td>
<td>–</td>
<td>16</td>
<td>11</td>
<td>111</td>
<td>–</td>
</tr>
<tr>
<td>LGU 9/2</td>
<td>L4 (tsunami)</td>
<td>5</td>
<td>–</td>
<td>4</td>
<td>8</td>
<td>11</td>
<td>–</td>
<td>18</td>
<td>18</td>
<td>58</td>
</tr>
<tr>
<td>BWA 1/6</td>
<td>B4b (tsunami)</td>
<td>2</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BWA 1/13</td>
<td>B4b, sand lense (tsunami?)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BWA 1/19</td>
<td>B4a (beach)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PGR 1/15</td>
<td>P2a (shallow lagoon)</td>
<td>4</td>
<td>22</td>
<td>1</td>
<td>–</td>
<td>2</td>
<td>7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PGR 1/17 Sand</td>
<td>P3 (coastal marsh)</td>
<td>2</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>PGR 3/8 F</td>
<td>P4a (hurricane)</td>
<td>2</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>11</td>
<td>–</td>
</tr>
<tr>
<td>PGR 3/10</td>
<td>P4b (tsunami)</td>
<td>5</td>
<td>14</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>16</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PGR 3/11 F</td>
<td>P2a (shallow lagoon)</td>
<td>13</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>16</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PGR 3/12 Sand</td>
<td>P3 (coastal marsh)</td>
<td>78</td>
<td>18</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PGR 3/17</td>
<td>P4a (beach)</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>8</td>
<td>1</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
The Holocene stratigraphy of the northeasterly exposed shore (Playa Grandi) indicates a major wave event — possibly a tsunami — around 3300 BP as well as two subsequent high-energy wave events. Sublittoral sediments interrupting onshore sedimentary sequences on the eastern shore (Lagun, Boka Washikemba) provide evidence for a major wave impact after 2000 BP which most likely corresponds to a tsunami. Another comparable event may have occurred shortly before 500 BP (Fig. 9).

We found that the application of tsunami signatures which are based on investigations on sedimentary characteristics of recent onshore tsunami deposits worldwide reveals certain difficulties, since they strongly depend on local topographic settings as well as sedimentary environments and thus vary considerably. Even if a large number of tsunami signatures are identified, the interpretation of the field record still remains a serious challenge. Hence, considering local analogues, i.e. comparing a candidate deposit with the sedimentary imprint of recent local events, provides more promising key to understanding event stratigraphies. In this study, the marginal sedimentary input of severe hurricane swells of the last decade (cf. surface sediment composition of Lagun, Boka Washikemba and Playa Grandi; Figs. 3, 4, and 7) in particular points to tsunamis as the hydrodynamic process responsible for the accumulation of certain sublittoral sand and shell layers. Deducing magnitudes of extreme wave events from the thickness of corresponding onshore deposits is subject to large uncertainties. The sublittoral environment of Lagun stores significantly more sediment compared to Playa Grandi, where the slope descends steeply offshore. Thus, vertical extent of event layers onshore will likely be greater. The irregular occurrence of sublittoral high-energy wave deposits between Playa Grandi and the Washikemba area may also indicate the importance of the pre-impact topography, the approaching angle of wave trains and post-depositional erosion or modification.

The results of the present study provide only partial coherence with previous palaeo-tsunami chronologies of the southern Caribbean based on investigations on supralittoral coarse-clast deposits on the ABC Islands (Aruba, Bonaire, Curaçao). Further studies on onshore stratigraphies — especially in the well-preserved and undisturbed geochronarches of the northwestern part of Bonaire — are necessary to increase the accuracy of information on the frequency and magnitude of Holocene extreme wave events in the southern Caribbean.

Acknowledgements

Funding by the Deutsche Forschungsgemeinschaft (German Research Foundation) is gratefully acknowledged (BR 877/26-1). We appreciate the administrative and logistic support by Frank van Slobbe, DROB (Government of the Island Territory Bonaire/Deartment of Environment and Natural Resources) and Elsmarie Beukenboom, Fernando Simal, Ramon de Leon and Doni Domacassé at STINAPA (Bonaire National Parks Foundation). Michael Amler (Munich) kindly supervised the determination of mollusc remains. Armine Shahnazarian (Cologne) supported the XRF analyses. We are indebted to Ronald Martin (Newark) for his helpful comments on the manuscript. We are also grateful for the helpful reviews of two anonymous reviewers.

References


Clausen, M., Costa, J., Contreras, J., Grane, S., 2005. Living macromolluscs from a paleo-reef region on the northeastern Venezuelan continental shelf. Estuarine, Coastal and Shelf Science 66, 634–642.


www.weather.an/reports/index.asp (last access: 10-14-2009).