Holocene tsunamis in the southern Caribbean: Evidence from stratigraphic archives and the coarse-clast record

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Abstract: *We present sediment cores from seven coastal geoarchives on Bonaire, southern Caribbean, containing layers of high-energy sedimentation. Tsunami deposition is inferred for some layers based on the presence of allochthonous reefal shells including articulated specimens and a high percentage of angular fragments, planktonic foraminiferal taxa and those from the deeper shelf (below storm wave base), basal unconformities and hiatuses of >1000 a, rip-up clasts, thin depositional sequences comprising basal traction carpets overlain by normally graded sand, a proximal sediment source (littoral) in the lower part of the deposit and a broad mixture (littoral, shelfal, terrestrial) in the upper part, and the lack of deposition during recent hurricane flooding. Several tsunami layers were precisely dated to 3300-3100 cal BP, whereas the record of further candidate tsunamis is more disjunct. Additional tsunami evidence is provided by the largest coastal boulders (up to 150 t; a-axis up to 10 m).*

Key words*: Palaeotsunami, Bonaire, Tsunami vs. Storm deposit, Hazard assessment*

Introduction

The island of Bonaire (Figure 1), Lesser Antilles, Leeward Islands, has one of the most extensively studied coarse-clast records of extreme wave events (hurricanes, tsunamis) in the Caribbean (e.g. Scheffers, 2005; Scheffers et al., 2006; Morton et al., 2008; Spiske et al., 2008; Watt et al., 2010). Strong hurricanes are known to have impacted the island in the recent past (e.g., Tecla in 1877, Lenny in 1999, Ivan in 2004; Scheffers, 2005), whereas no tsunami has been recorded in historical times. However, historical tsunamis are known from adjacent coasts (O'Loughlin & Lander, 2003). We present (i) large coastal boulders (a-axis up to 10 m, weight up to 150 t) from the N and NE coasts, and (ii) sediment cores from seven coastal geoarchives with layers of high-energy sedimentation likely associated with prehistoric tsunamis. Our approach is exemplified by a case study at Boka Bartol (Figure 1).

Methods

In order to test the tsunami hypothesis of Scheffers (2005), we applied a modified approach of Nott (2003) to reconstruct minimum heights of storm waves and tsunamis required to move the largest coastal boulders. Their edges were measured by DGPS. The point cloud was imported into ArcGIS and translated into 3D surfaces to calculate their volume (Figure 2). Individual densities were determined considering the different coralline lithotypes of the palaeo-reef blocks.

Holocene stratigraphic archives were sampled by percussion coring. Besides sedimentological documentation, a broad spectrum of proxy records was generated including grain size distribution, shell taphonomy, microfossils, high-resolution ITRAX XRF counts, semi-quantitative XRD, carbonate and organic contents. Chronostratigraphies are based on ^{14}C-AMS age estimates.

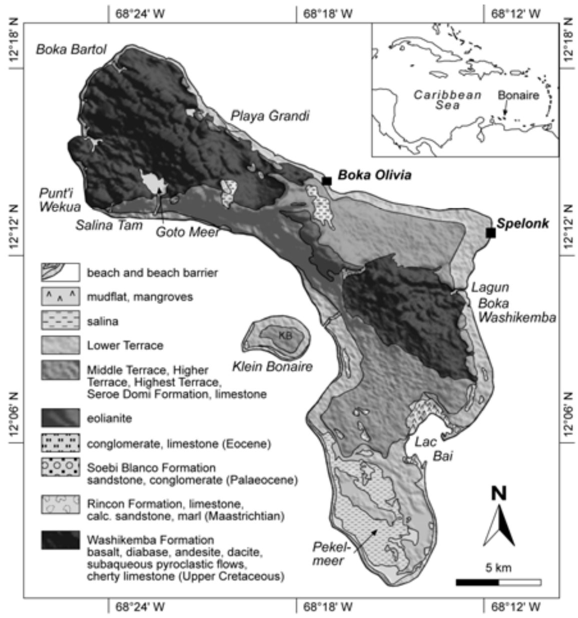

Figure 1: Simplified geological map of Bonaire showing the study sites (based on De Buisonjé, 1974, and other references therein; source of SRTM data: http://dds.cr.usgs.gov/srtm).

Results and discussions

Investigation of the coarse-clast record

Boulders and blocks were investigated on top of an elevated Pleistocene reef platform at an elevation of 3.5–5 m above mean sea level and at a distance

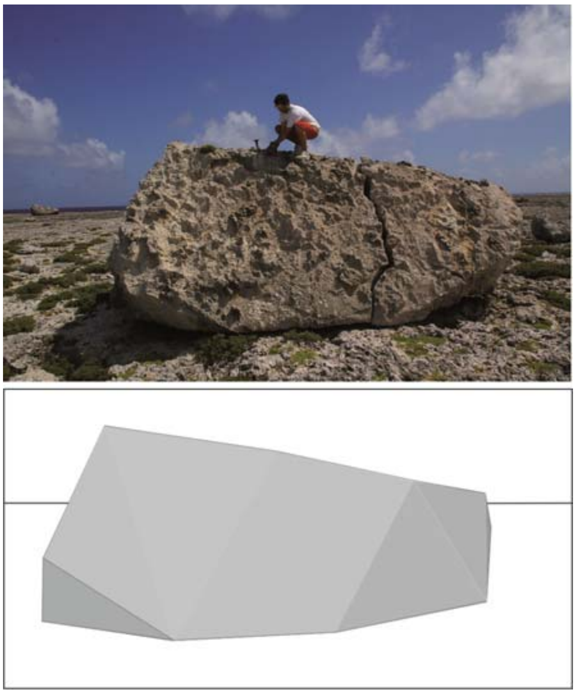

Figure 2: The example of boulder SPE 4 as photograph and DGPS-based 3D model for volume calculation (after Engel & May, 2012).

Boulder	H (tsunami) in m		H (storm wave) in m	
	Modified approach of Nott (2003)		Modified approach of Nott (2003)	
SPE 2	5.3	**Tsunami height** at Paria, Venezuela, 01 Sep 1530: c. **7.3 m** (NGDC, 2011)	21.2	
SPE 4	5.4		21.4	Max. height of a **breaking wave during Hurricane Ivan 2004,** Bonaire: c. **12 m** (Scheffers & Scheffers, 2006)
SPE 5	6.7		26.7	
SPE 6	6.7		26.8	
SPE 7	5.8	**Tsunami height** at Puerto Tuy, Venezuela, 29 Oct 1900: c. **10 m** (NGDC, 2011)	23.4	
SPE 8	5.2		20.8	
SPE 9	1.2		4.7	
BOL 1	7.3		29.3	
BOL 2	8.9		35.6	
BOL 3	1.8		7.3	

Table 1: Inferred minimum wave heights of tsunamis and storm waves required to quarry and transport each boulder, using the modified approach of Nott (2003) (after Engel & May, 2012). For comparison, values of regional extreme waves are given. SPE = Spelonk; BOL = Boka Olivia (see Figure 1).

of 40–120 m from the coast. Entrainment and transport occurred under extreme-wave conditions during the recent sea level highstand. A higher relative sea level can be excluded for the Holocene (Milne & Peros, 2013).

Values of DGPS-based volume measurements amount only approx. 50% of the multiplication of main axes indicating that previous volume-based reconstructions of minimum wave heights and velocity required to entrain boulder deposits might be overestimated. Boulder densities considering heterogeneous lithofacies composition range between 2.07 and 2.40 g cm^{-3}. The largest boulders identified to have been moved during recent hurricanes weigh 1 and up to 9 t. Those remaining immobile during these events weigh up to 150 t (Engel & May, 2012).

Reconstructed minimum storm wave heights for boulders moved during recent hurricanes (4.3 and 7.3 m, respectively) are within the range of real wave heights observed, e.g., during Hurricane Ivan (Scheffers & Scheffers, 2006). Storm wave heights calculated for the largest clasts of the boulder fields (up to 35.6 m) are three times higher and far beyond any observation ever made or data ever recorded in the southern Caribbean (Table 1). In contrast, inferred tsunami heights (up to 8.9 m) are in the range of historical tsunami heights reported from Venezuela and other sites in the southern Caribbean (NGDC, 2013). Even though the approach of Nott (2003) is based on simplifying assumptions concerning the quarrying and transport processes of boulders by waves, its legitimation is underpinned by the comparison of the boulders moved during recent tsunamis and the output of Nott-type models for these boulders (e.g., Bourgeois & MacInnes, 2010). Thus, we believe that results from this study support the tsunami hypothesis on Bonaire (Engel & May, 2012).

Investigation of the stratigraphical archives – the example of Boka Bartol

The Holocene sediment sequence of Boka Bartol, a ria-type embayment of NW Bonaire separated from the open sea by a barrier of coral rubble, comprises at least 9 m (cores BBA 8 and 10 in Figure 3). Unit I (9.00–6.86 m below surface [b.s.] at BBA 10) represents an open embayment fringed by mangroves. Unit II (6.86–6.67 m b.s.) shows several characteristics of high-energy sedimentation (Figure 4). Unit III (6.67–2.70 m b.s.) accumulated in a poly- to hypersaline lagoon with fluctuating hydrochemistry. Unit IV (2.70–0.00 m b.s.) represents (sub-)recent sediments of the prograding alluvial fan. Tsunami deposition for Unit III is inferred based on the presence of several tsunami signature types (e.g., Goff et al., 2012), such as allochthonous reefal shells including articulated specimens, foraminiferal taxa from the deeper shelf (below storm wave base), a basal unconformity and a hiatus of >2000 a, a rip-up clast, a basal traction carpet overlain by normally graded muddy sand, a proximal sediment source (littoral) in the lower part of the deposit (traction carpet), and a broad mixture (littoral, shelfal, terrestrial) in the upper part (suspension load), and the lack of deposition during recent hurricane flooding. Boka Bartol changed from an open mangrove-fringed embayment into a poly- to hyperhaline lagoon due to the establishment or closure of the barrier of coral rubble during or subsequent to the inferred tsunami. Four coeval ^{14}C ages from Unit II point to a deposition around 3300–3100 cal BP. The facies change after the deposition of Unit II from mangrove peat to evaporate-rich mud indicates subaerial growth of the barrier of coral rubble separating the boka from the open sea during or subsequent to the event (Engel et al., 2013).

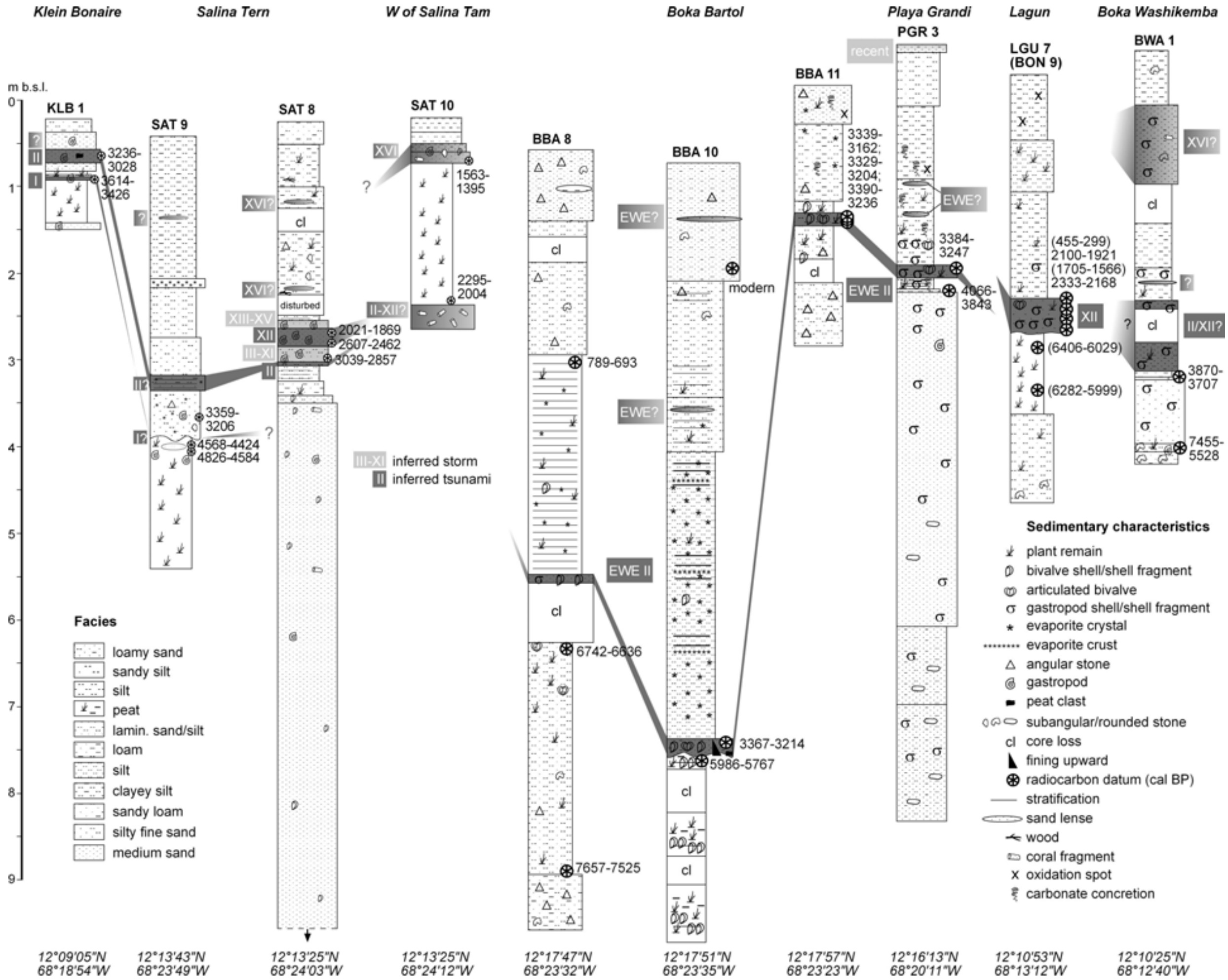

Figure 3: Synopsis of sediment cores from coastal stratigraphical archives on Bonaire and distribution of extreme-wave events (EWE, roman numeration) (Scheffers et al., 2013). The sites are shown in Figure 1. For detailed stratigraphical documentation, data and interpretation see Engel et al. (2010) for Lagun and Playa Grandi, Engel et al. (2012) for Klein Bonaire, Saliña Tern and west of Saliña Tern, and Engel et al. (2013) for Boka Bartol. ^{14}C datings were calibrated using Calib 6.0.1 (Reimer et al., 2009).

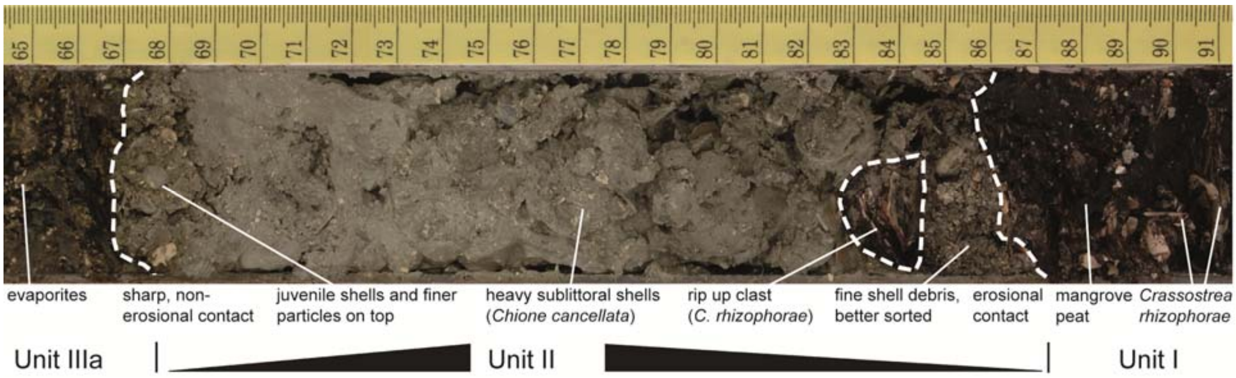

Figure 4: Section 6.91 – 6.65 m b.s. (below surface) of sediment core BBA 10 from Boka Bartol (Figures 1, 4) showing Units I–IIIa. The photograph depicts several sedimentary features which are often – though not exclusively – related to tsunami deposits: erosional lower contact, varying degrees of sorting, rip-up clast and larger ex-situ shells. It also illustrates the significant differences in sedimentation after the event (compare Units I and IIIa) indicating strong and long-lasting changes of the geo-ecosystem due to the final closure of Boka Bartol (Engel et al., 2013).

Unit II has counterparts on the east (Klein Bonaire, Saliña Tam, possibly between Saliña Tam and Punt'i Wekua) and west coasts (Playa Grandi, possibly Boka Washikemba). It is the best documented candidate tsunami on Bonaire (EWE II in Figure 4). Another possible tsunamite (EWE XII), dated to 2000–1700 cal BP, was detected at Lagun and Saliña Tam (Engel et al., 2012). Two further extreme-wave deposits (c. 3600 cal BP and post-1300 cal BP) show a very disjunct pattern (see KLB 1, SAT 10, BWA 1 in Figure 3).

Conclusions

The size of boulders and sedimentary patterns of extreme-wave deposits indicate that flooding events significantly exceeding the magnitude of recent cat. 5 hurricanes occurred in prehistoric times. We conclude that these flooding events with a recurrence interval in the order of 1000 years were tsunamis, even though remaining uncertainties regarding the significance of sedimentary criteria and the boulder transport equations should not be neglected.

Trigger mechanisms for a tsunami causing hazard on Bonaire include strong earthquakes along the El Pilar fault, coastal Venezuela, as well as other earthquake sources along the southern Caribbean Plate boundary. Furthermore, explosive volcanism at the Antilles island arc (e.g., Kick 'em Jenny Volcano, Windward Islands), regional submarine landslides or teletsunamis from the open Atlantic Ocean may play a role. The Caribbean-wide tsunami exercise CARIBE WAVE/LANTEX 13 on 20 March 2013 used a tsunami scenario induced by an earthquake of $M_w = 8.5$ at the N boundary of the Bonaire microplate, 200 km NW of Bonaire, causing run-ups of >5 m along the island's coast (UNESCO/IOC, 2012).

We demonstrated that tsunamis, even if not known on Bonaire from historical accounts and recent observations, represent a hazard on the island. It is, therefore, suggested to initiate a local tsunami assessment by estimating exposure, vulnerability and preparedness in order to develop appropriate mitigation measures.

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