



Coastal boulders emplaced by extreme wave events impacting the ABC islands (Aruba, Bonaire, Curaçao; Leeward Antilles, Caribbean)

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ABSTRACT

Large coastal boulders are ubiquitous geomorphological features that are emplaced along coasts by extreme marine events such as storms, hurricanes, and tsunamis. Many large coastal boulders have been identified on emergent fossil coral reefs on the windward sides of the Aruba, Bonaire, and Curaçao (ABC) islands in the Leeward Antilles of the Caribbean. Here, structure-from-motion/multi-view stereo techniques were used to map boulder sizes at several coastal sites in the ABC Islands as well as construct digital terrain models of the surrounding areas. Chronological constraints on boulder transport were established through the radiocarbon dating of the vermetids and coral colonies that comprised boulders located along a ridge on Aruba Island. A suite of hydrodynamic models was used to empirically derive the required flow thresholds for boulder displacement to determine whether tsunamis or hurricanes were responsible for detaching and transporting these boulders. Our results suggest that multiple tsunamis, most likely triggered by the El Pilar fault, located near the Venezuelan coast, were the cause of boulder detachment and transport in this region during the Holocene, between 4000 and 500 years BP.

1. Introduction

The impacts of extreme wave events are preserved in the geological record in several forms along the world's coastlines. In general, high-energy waves caused by extreme storms and tsunamis lead to the formation of out-of-size landforms as well as the deposition of out-of-place sediments (Nott, 2003a,b; Cox et al., 2020; Scardino et al., 2020 and references therein). These may occur as large coastal boulders (Nott, 2003a, 2003b; Nandasena et al., 2011b) or wide washover fans in backshore areas (Gianfreda et al., 2001; Vött et al., 2009; May et al., 2012). Several studies have investigated the scenarios that were most likely to be responsible for coastal boulder displacement in different

regions around the globe (Mastroruzzi and Sansò, 2000; Nott, 2003a; Goto et al., 2010, 2011; Evelpidou et al., 2020; Pedoja et al., 2023). In general, the literature suggests that more cases of boulder mobilization can be attributed to large storms, such as (extra-)tropical cyclones (Cox et al., 2018; Hall, 2011; Hall et al., 2006; Scicchitano et al., 2020; Terry et al., 2016), storm-induced energetic infragravity waves (Watanabe et al., 2023), or waterspouts (de Lange et al., 2006) than to tsunamis (Paris et al., 2010; Pignatelli et al., 2009; Scicchitano et al., 2007, 2012).

Differentiating between tsunami- and storm-generated coastal landforms is challenging and, in the case of coastal boulders, is commonly resolved by applying empirical equations to determine the

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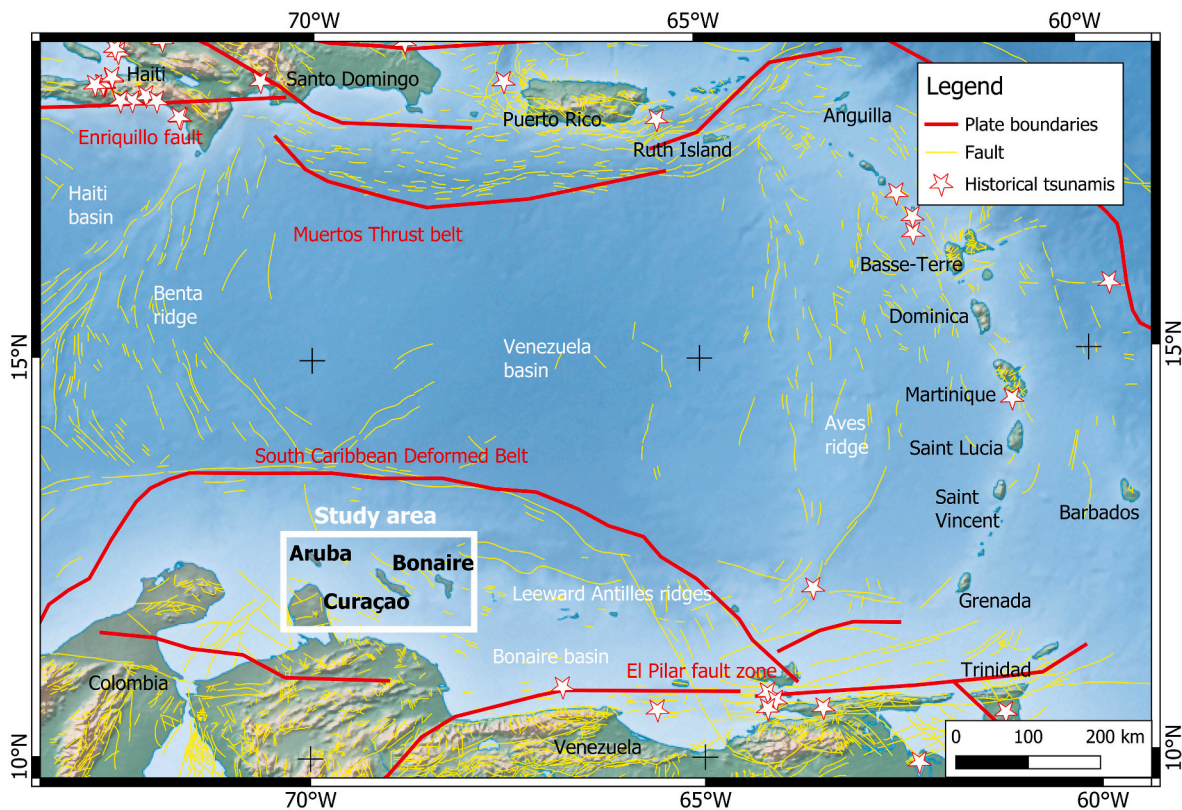


Fig. 1. The main study area in the context of the Lesser Antilles, including the main structural elements. The plate boundaries and fault structures follow French and Schenk (2004), and the locations of historical tsunami sources are obtained from Lander et al. (2002). The Aruba, Curaçao, and Bonaire (ABC) islands are highlighted in the white inset. Background map from Natural Earth Data (<https://www.naturalearthdata.com/>, accessed June 21, 2024).

minimum flow speed required to move the boulders observed at a given location (Nott, 2003a; Goto et al., 2009; Nandasena et al., 2011a, 2022; Weiss and Diplas, 2015; Roig-Munar et al., 2023). Despite the widespread application of this approach, distinguishing between the different types of extreme events responsible for boulder emplacement remains contentious (Weiss and Diplas, 2015; Cox et al., 2020; Roig-Munar et al., 2023; Dunán-Avila et al., 2024). Instrument records and eyewitness accounts of large boulder displacements provide a reliable basis for modeling extreme wave events (Scicchitano et al., 2020; Nandasena et al., 2022; Delle Rose, 2024). In addition, the reliability of the geological evidence can be improved by correlating it to historical sources (of known ages), which can provide additional details on the events and their effects (Delle Rose et al., 2020; Lario et al., 2020; Dewey et al., 2021). Furthermore, the integration of age constraints, such as radiocarbon dates, with numerical modeling can provide important insights into the extreme events that drive coastal boulder emplacement.

Here, we reviewed geological evidence of past extreme wave events recorded by coastal boulders on the Aruba, Curaçao, and Bonaire (ABC) islands of the Lesser Antilles (Caribbean). These boulders were likely emplaced by Holocene paleo-tsunamis and hurricanes (Scheffers, 2002; Scheffers and Kelletat, 2006); however, a consensus has yet to be reached on the origin and timing of these tsunamigenic events (Morton et al., 2008; Pignatelli et al., 2010; Watt et al., 2010; Engel and May 2012; Oetjen et al., 2015, 2020). To identify the most reliable source for these boulder displacements, we followed a forward modeling approach based on the dimensional features of the coastal boulders. We report new data on the geomorphological characteristics of the boulders and the surrounding rocky coasts, as well as new radiocarbon ages that provide constraints on the timing of boulder motion related to extreme wave events within the Holocene. We then compare the flow velocities obtained from our numerical models to the flow velocities calculated from empirical equations of incipient motion (Nandasena et al., 2022).

In this way, we identify the most reliable sources of boulder displacement from both chronological data and the dynamics of extreme wave events.

2. Study area

The ABC islands are located on the Leeward Antilles ridge (Fig. 1), which was formed by Cretaceous–Cenozoic tectonic interactions between the Caribbean and South American plates (Avé Lallemant, 1997; Beardsley and Avé Lallemant, 2007). The ABC islands are characterized by stepped Quaternary coral reef terraces that flank older Cretaceous volcanic cores (e.g., Alexander, 1961; Fouke et al., 1996; Muhs et al., 2012). The lowest of these terraces contain well-preserved fossil corals dated to marine isotope stage (MIS) 5e (~122 ka ago, Fig. 2a) (Obert et al., 2016; Lorscheid et al., 2017). The MIS 5e terrace (which is, at places, incised by fluvial erosional channels known locally as *bokas*; Fig. 2b) terminates in sea cliffs that are fronted by a recent subtidal reef platform, which has been colonized by the vermetid *Petalocochus* sp. (Hoeksema et al., 2022). Typical geomorphological imprints that can be observed on the rocky coasts of ABC Island include boulder ridges and ramparts (Scheffers, 2002; Scheffers et al., 2014).

Imbricated boulder ridge deposits and isolated coastal boulders frequently occur on the windward side of the ABC islands atop the MIS 5e terrace (Scheffers, 2002, 2004). These deposits are parallel to the coastline 20–250 m from the cliff front and primarily consist of well-rounded coral fragments from the recent subtidal reef (Scheffers, 2002; Radtke et al., 2003; Spiske et al., 2008; Engel and May 2012) or parts of the MIS 5e reef. In the Caribbean, similar ridges generally extend approximately 15 km alongshore, with crest heights ranging from 3 to 8 m above mean sea level (Morton et al., 2008). In many cases, the ridges are either not or only slightly asymmetric (Scheffers, 2002; Scheffers and Kelletat, 2006; Scheffers et al., 2014), with a steep seaward slope and a

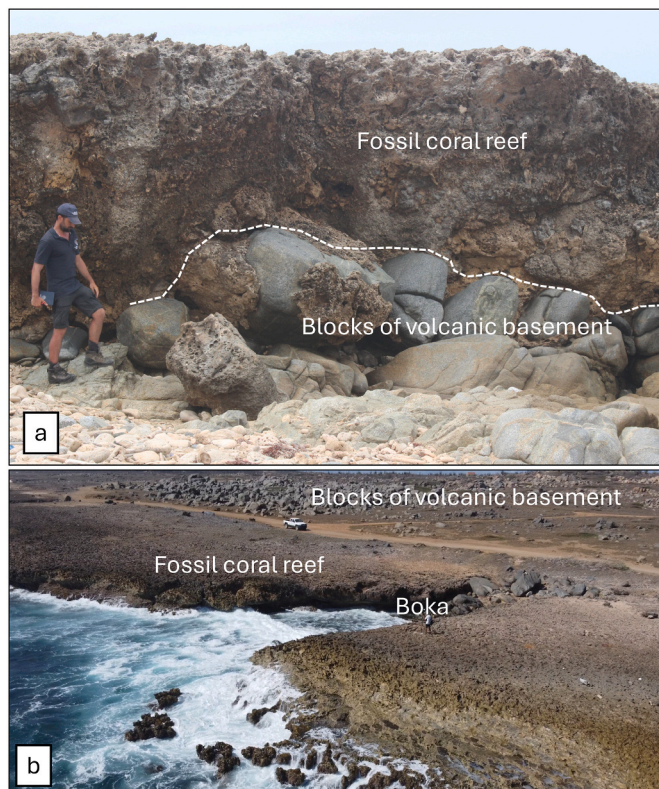


Fig. 2. Main geomorphological features found on the ABC islands: a) Contact between blocks of volcanic basement and fossil coral reef dated to the Late Pleistocene (MIS 5e), located in Aruba. b) Fossil coral reef terrace on the windward side of Aruba, incised locally by a fluvial erosional channel locally known as a *boka*.

gentle landward slope (Scheffers, 2005; Robinson et al., 2006; Morton et al., 2008). These ridges are irregularly punctuated by outsized coastal boulders that mostly occur at locations where the cliff front is near-vertical and the recent reef platform is relatively narrow (Focke, 1978; Scheffers, 2002; Pignatelli et al., 2010).

The ramparts consist of scattered, small-to medium-sized debris deposits with thicknesses ranging from decimeters to meters; these are generally located several meters from present-day coastlines or active cliff fronts and overlie a mildly sloping coast (Scheffers, 2002, 2004). Ramparts occur on both the leeward and windward sides of ABC Islands, with the most developed landforms observed in northeastern Curaçao and along the east-facing coastal stretch on Bonaire (Scheffers, 2002). They consist of debris and cobbles ranging from decimeters to around 1 m with a gently landward-sloping planar profile. These deposits are located up to 100 m inland from the coastline, at an elevation usually ranging from 6 to 10 m above sea level (asl), and become more scattered and thinner further inland (Scheffers, 2002; Scheffers et al., 2014).

2.1. Evidence of extreme waves on the ABC islands

The geomorphological records of the ABC Islands show that they have experienced various extreme storms and paleo-tsunamis (Table 1); these are particularly evidence in *bokas* and lagoonal areas (Engel et al., 2012a) as well as on the rocky coasts (Scheffers, 2002; Scheffers and Kelletat, 2006). Stratigraphic and geochemical data reported by Engel et al. (2012a), obtained through cores sampled from *bokas* and lagoons, revealed the occurrence of three main tsunami events that impacted the shores of these islands 3300, 2000, and 500 years before present (BP). Analyses of the boulders and some of the ridges atop the lower terrace of Bonaire revealed a sequence of extreme wave events that occurred between 4300 and 500 years BP (Scheffers, 2002, 2004, 2005; Scheffers et al., 2014). This broad sequence was identified through radiocarbon dating of vermetid reef and coral samples from the boulders (Scheffers, 2002). This sequence of events has been revised by other authors to

Table 1

Landforms that are evidence of extreme storms and paleo-tsunamis in the ABC islands. CE = Common Era, BP = Before Present, BCE = Before Common Era. References: 1—Scheffers, 2002; 2—Scheffers et al., 2009; 3—Scheffers (2005); 4—Engel et al., 2012a; 5—Baptista et al., 1998; 6—Engel and May, 2012; 7—Harbitz et al., 2012; 8—Engel et al., 2010; 9—Radtke et al. (2003); 10—Engel et al., 2012b; 11—Rixhon et al., 2018; 12—Kłosowska (2003).

Event (References)	Date	Dating method	Analyzed samples	Landforms and deposits	Location
Hurricane Lenny 1999 CE (1)	November 13, 1999 CE	–	<i>Acropora cervicornis</i>	Coral rubble spit	Washikemba NP, northwest Bonaire
Hurricane Tecla 1877 CE (2,3)	1877 CE	Radiocarbon, Electron-Spin- Resonance (ESR)		Ridge deposits	Salina Tarn, Bonaire
Tsunami 1755 CE (5,6)	November 1, 1755 CE				Great Antilles, Leeward Antilles
Tsunami 1530 CE (4,7,8)	1 September 1530 CE	Historical sources (4,7); Radiocarbon (8)	Vermetids	High-energy deposits	Lagun, Bonaire, ABC islands
Tsunami 500 BP (1,9)	1500 CE;	Radiocarbon	Vermetids, corals, gastropods	Rampart, ridges, boulders	ABC islands
Tropical cyclone 1000 BP (10)	950 CE	Radiocarbon	Gastropods	Normally graded strata separated by thin mud laminae	Salina Tarn, Bonaire
Tsunami 1500 BP (1)	400 CE	Radiocarbon	Vermetids, corals, gastropods	Rampart, ridges, boulders	ABC islands
Tsunami 1600 BP (8,11)	350 CE	Radiocarbon (8); ²³⁰ Th/U (10),	Plant remains (8); Flowstone layer(10)	High-energy deposits (8); Boulders (10)	Lagun, Bonaire(8); Spelonk, Bonaire (10)
Tsunami 2000 BP (8)	50 BCE	Radiocarbon	Plant remains (8)	Sublittoral sediments interrupting onshore sedimentary sequences	Lagun, Boka Washikemba, Bonaire
Tsunami 3100 BP (8)	1850 BCE	Radiocarbon	Plants remain	High-energy deposits	Playa Grandi, Bonaire
Tsunami 3300 BP (4, 9, 12)	1350 BCE	Radiocarbon	Plant fragment, C. cancellate, Corbula sp.	High-energy deposits with peat clasts	Klein Bonaire, Salina Tarn, Boka Bartol, Bonaire(4); Druif, Aruba (9); St. Michiel lagoon, Curaçao (12)
Tsunami 3500 BP (1)	1550 BCE	Radiocarbon	Vermetids, corals, gastropods	Rampart, ridges, boulders	ABC islands
Tsunami 3600 BP (8)	1650 BCE	Radiocarbon	Gastropods	Two thin graded beds of 2 and 1 cm thickness	Klein Bonaire



Fig. 3. Boulders surveyed on the ABC Islands: a) boulder composed of vermetids in Aruba; b) sampling of a boulder composed of *Diploria* sp. that was transported from a recent reef platform to the top of the MIS 5e terrace in Aruba; c) sampling of a boulder composed of vermetids along the ridge in northwest Aruba.

account for the effects of long-term coastal processes and hurricanes that may have moved the coastal boulders following their initial emplacement (Morton et al., 2006, 2008; Spiske et al., 2008).

The Caribbean region has been impacted by multiple tsunamis, as evidenced by historical accounts dating back to the 16th century (Lander et al., 2002). These tsunamis were caused by either earthquakes or non-seismic geologic events (e.g., volcanic eruptions, flank collapses, and submarine landslides). The largest recorded earthquake in the Caribbean was a magnitude 7.5–8 event between Guadeloupe and Antigua in 1843 (Bernard and Lambert, 1988). Only two trans-oceanic tsunami events have been reported in the Caribbean: the 1755 Lisbon earthquake (November 1st, 1755; Baptista et al., 1998; O’Loughlin and Lander, 2003) and the 1761 Lisbon earthquake (March 31st, 1761; O’Loughlin and Lander, 2003). A total of 65 earthquake-generated tsunamis have been reported by the National Geophysical Data Center (NGDC, 2021), the largest of which occurred on November 18th, 1867 after a strong MS 7.5 earthquake in the Virgin Islands (Zahibo and Pelinovsky, 2001).

An important tsunamigenic source close to the ABC islands is the El Pilar fault zone, a right-lateral strike-slip fault located offshore Venezuela, which accommodates most of the relative motion between the Caribbean and South American plates (Perez et al., 2018). The El Pilar fault structure has been responsible for several tsunamis, including events in 1530 and 1853, which were likely associated with offshore ruptures of this fault (Audemard, 2007). The kinematics of the El Pilar fault zone have been inferred from geodetic measurements published by Jouanne et al. (2011). Following the Haiti earthquake on January 12th, 2010 (Calais et al., 1998), the area was impacted by two tsunamis, one caused by the combined movement of a submarine landslide in the north of Haiti (Fritz et al., 2013) and the other generated by the displacement of the North Hispaniola and Enriquillo faults that cross-cut the island of Haiti (Pararas-Carayannis, 2010; Poupardin et al., 2020).

There are currently 12 active volcanoes located across 10 major islands throughout the Lesser Antilles. Volcanic flank collapses in this area have triggered several tsunamis (Boudon et al., 2007). In 1939, the Kick’em Jenny volcanic eruption caused a series of tsunami-like waves

with amplitudes of around 2 m in the Grenadines and Grenada Islands (Smith and Shepherd, 1993a, 1993b). It should be noted that tsunamis generated by a submarine landslide generally propagate radially away from the slide, while tsunamis generated by fault displacement typically propagate with crests parallel to the fault rupture (Harbitz et al., 2006, 2014). The largest submarine landslide that occurred near the ABC Islands was associated with the active margin of northern Colombia, another potential tsunamigenic source for the central Caribbean basin (Leslie and Mann, 2016).

In contrast to the relative rarity of tsunamis in the Caribbean, approximately 1000 tropical storms and around 200 hurricanes impacted this region in the past century (Scheffers et al., 2009; NHC-NOAA, 2024). Hurricane genesis generally begins above the Atlantic Ocean waters; the hurricanes then move westward across the Windward Islands, over the Caribbean Sea, and finally turn northwest. Hurricane Lenny in 1999 remains the only hurricane to date that formed within the Caribbean Sea and tracked east–northeast (Bries et al., 2004). In the Lesser Antilles, Curaçao was hit by a minor hurricane on September 23rd, 1877, which damaged infrastructure and deposited coral rubble (Spiske et al., 2008). More recently, Hurricane Ivan (September 7th, 2004) hit the ABC Islands causing significant structural damage to houses and other infrastructure; the greatest damage and heaviest rainfall was reported on Aruba (Scheffers and Scheffers, 2006).

3. Materials and methods

This study adopts a workflow consisting of three main steps: i) geomorphological mapping of areas characterized by coastal boulders, including three-dimensional (3D) mapping of the largest boulders; ii) collecting samples of smaller boulders composed entirely of vermetids and corals emplaced along the ridges for radiocarbon dating (Fig. 3); and iii) running a suite of hydrodynamic models (Delft3D-Celeris-XBeach models) to compare the flow velocities required to displace the boulders—as calculated from empirical equations—with those generated by historical extreme wave events that have impacted the ABC Islands.

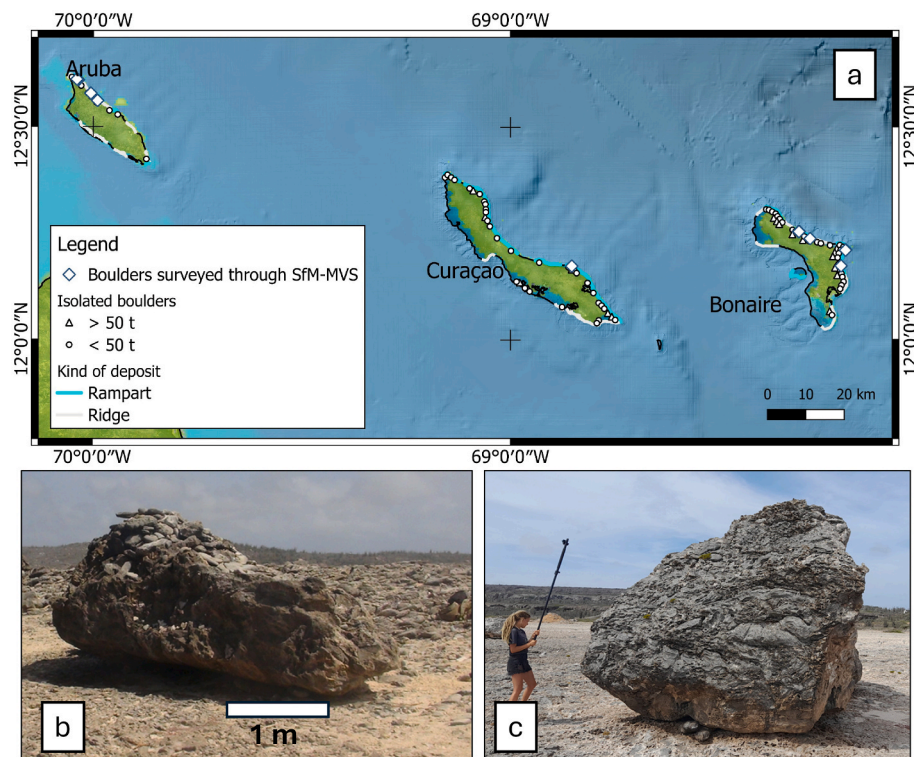


Fig. 4. a) Map showing the areas of the ABC islands that are characterized by boulder ridges or isolated boulders as reported in the literature (blue lines, Scheffers, 2002; Engel et al., 2012a). Boulders surveyed through close-range SfM/MVS in this study are represented using white diamonds; b) an example of a displaced boulder sitting on top of ridge deposits at South Ranchero Curason (Aruba); c) land-based SfM/MVS performed on a boulder in Boka Onima on Bonaire.

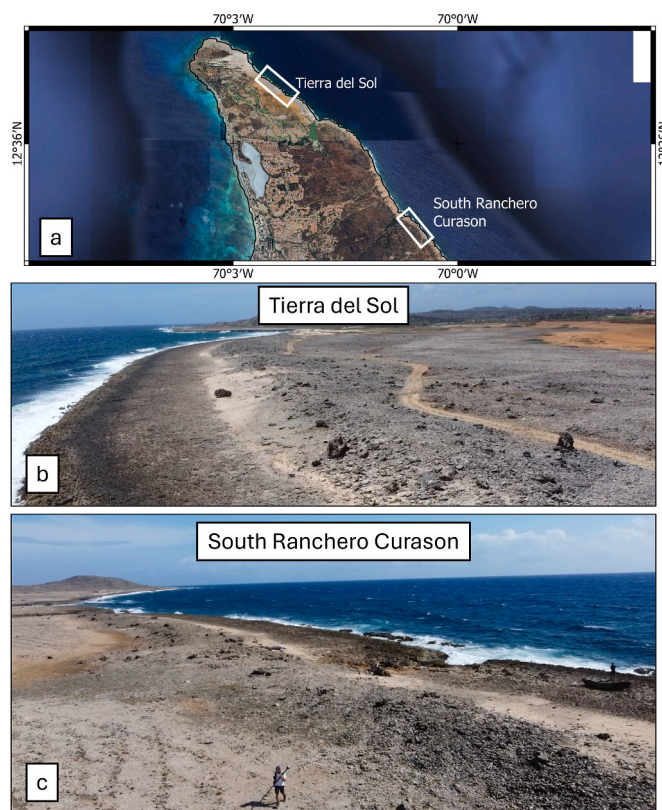


Fig. 5. Rocky coastlines surveyed by unmanned aerial systems (UAS) for the reconstruction of digital elevation models. a) Map showing locations of the areas surveyed using UAS. b) Boulder ridge deposits in Tierra del Sol. c) Boulder ridge deposits in South Ranchero Curason.

Geomorphological mapping was conducted using land-based structure-from-motion (SfM)/multi-view-stereo (MVS) methods to reconstruct the 3D features of boulders on the ABC Islands (Fig. 4). Morphotopographic surveys were also performed at two sites in Aruba, henceforth referred to as “Tierra del Sol”, and “South Ranchero Curason” (Fig. 5a). These two sites are characterized by large coastal boulders associated with ridge deposits. The date of the events related to boulder displacements was constrained by the radiocarbon dating of the biological materials that comprise the coastal boulders, which were composed of either vermetids or corals. To account for sea level changes at the time of boulder transport, we used local relative sea levels reconstructed from glacial isostatic adjustment models (ICE-7G) (Roy and Peltier, 2015, 2017, 2018). Empirical equations describing the incipient motion of these boulders were then applied to determine the minimum flow velocity required to displace these boulders based on their size and mass (Nandasena et al., 2022). Finally, hydrodynamic models of different tsunamis and hurricanes were used to reproduce the wave propagation, flow depth, and cross-shore velocity associated with these events. These results were compared with incipient modes to determine the most likely series of extreme wave events responsible for the boulder displacements.

3.1. Boulder surveys on the ABC islands

Land-based SfM/MVS methods were used to calculate the dimensions of the coastal boulders. Photos of each boulder were acquired at a distance of less than 10 m using a Sony DSC-RX100M3 camera (8.8 mm focal length; 5472 × 3648 resolution). Coded ground control points (GCPs) were measured using an EMLID RS2+ differential GNSS receiver. GCP measurements were corrected in post-processing. Scale bars were used during the SfM/MVS process to scale and optimize the model. Two kinds of base stations were used during post-processing: i) GNSS stations from NOAA Continuously Operating Reference Stations (CORS) located at Aruba and Curaçao (IDs CN19 and CN40); ii) an EMLID RS2+ base

station that was installed in Bonaire during previous surveys. The collected ellipsoid elevations were converted into geodetic elevations referenced to Earth Gravitational Model 2008; Pavlis et al. (2012).

The photos and GCPs were processed in the Agisoft Metashape Professional (v.2.0.2) software to reconstruct 3D polygonal models for each boulder. Point clouds were extracted for each boulder and imported into the CloudCompare software (v.2.13.1). We then extrapolated the “ab” and “ac” surfaces following the approach described by Nandasena et al. (2022). The surfaces were converted to meshes and translated to planar projections to determine their areas and axial lengths ($a > b > c$). Finally, the true volumes of each boulder were calculated in CloudCompare. Bulk densities were calculated by correlating the lithotype and coral species comprising each boulder and the associated density values reported in Spiske et al. (2008) for the same lithotype. Boulder weights were then calculated by multiplying each boulder’s volume by its bulk density.

Additionally, the largest boulders in Aruba were associated with an extended ridge deposit. Analogous ridge deposits have also been observed in Curaçao and Bonaire. Here, the boulders with a -axes greater than 0.5 m were mapped using a GoPro HERO Black11 camera (24.4 mm focal length and 5599×4927 resolution) and the same dGNSS positioning described above.

3.2. Radiocarbon dating

To provide chronological constraints on the timing of the formation of the boulder ridges, we collected 10 samples (weighing 100 g each) from the boulders composed of vermetids and two additional boulder samples. These samples were then analyzed using a single-stage accelerator mass spectrometer (SSAMS, NEC, USA) and AGE-3 Automated Graphitization Equipment (Ionplus AG, Zürich). The analysis was performed by the Vilnius Radiocarbon Lab (Center for Physical Sciences and Technology, Vilnius, Lithuania). Conventional ^{14}C ages were calibrated in the Calib software (v8.20, Stuiver and Reimer, 1993; Stuiver et al., 2021) using the Marine20 curve and a ΔR value of -308 ± 29 yr, as reported by DiNapoli et al. (2021) for Aruba.

3.3. Morpho-topographic surveys and bathymetric data

To model extreme wave events on the ABC islands, we combined the digital elevation model (DEM) obtained from the Tandem-X mission (12-m resolution and vertical accuracy of 1 m; Uemaa et al., 2020) with multibeam echo sounder (MBES) bathymetry data collected by the Dutch Ministry of Defense around the ABC islands (Dutch Caribbean, 2019). We then downsampled the data to match the GEBCO dataset (10-m resolution) and combined the two datasets. This allowed us to extend the DEM further offshore, allowing for the effective simulation of wave propagation for each modeled scenario. Aerial SfM/MVS methods were performed using a DJI Mini unmanned aerial system (UAS; 24 mm focal length and 8064×6048 resolution) at two locations: Tierra del Sol and South Ranchero Curason (Fig. 5). The UAS was flown at a height of 30 m above ground level and flight speed of ~ 2 m/s. Targets that were clearly visible in the UAS images and located along the cliff top were measured using GPS. The photos acquired by the UAS were processed following the same SfM/MVS workflow detailed in Section 3.1 to produce orthomosaics and georeferenced DEMs of the two areas with a cell resolution of 0.3×0.3 m.

To reconstruct the paleo-sea-level scenarios for extreme wave events, we utilized the ICE 7G glacio-isostatic model and compared it with field-based curves for Curaçao (Khan et al., 2017) and Bonaire (Engel et al., 2014).

The reconstructed cliffs in the two areas were modified based on the relative sea-level scenarios obtained from the ICE 7G curve, which assumes a radially symmetric viscosity profile for the Earth’s mantle referred to as VM6 (Roy and Peltier, 2017). Specifically, it assumes that the viscosity of the upper mantle—located between the base of the

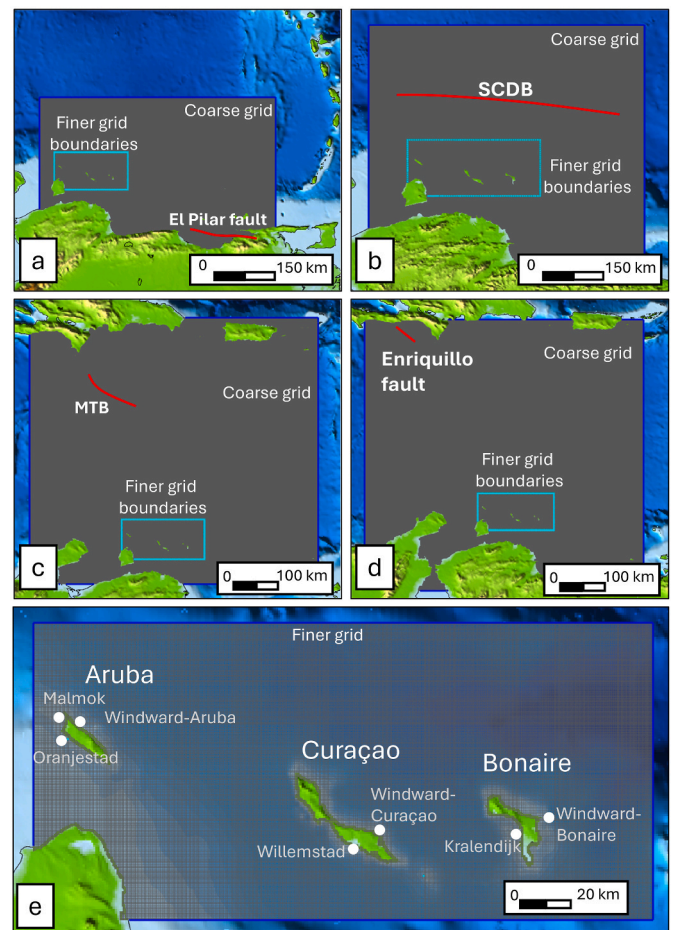


Fig. 6. Modeling grid for the Caribbean region built in Delft Dashboard. a) Coarse grid used for the El Pilar earthquake-generated tsunami; b) coarse grid used for the South Caribbean Deformed Belt (SCDB) earthquake-generated tsunami; c) coarse grid used for the Muertos Thrust Belt (MTB) earthquake-generated tsunami; d) coarse grid used for the Enriquillo earthquake-generated tsunami; e) finer grid used to extract water levels from time series data at the given locations.

lithosphere and the base of the transition zone at 660 km depth—is equal to 0.45×10^{21} Pa s. The chronological constraints obtained from radiocarbon dating were used to obtain the relative sea-level positions from the ICE 7G curve at different times. Isolines corresponding to the past sea-level positions were reported on the DEMs of Tierra del Sol to identify the position of the cliff base, assuming that a coral reef paleo-landscape also existed in the past. The DEMs were then modified in Surfer (v. 11.0), with the cliff slope extended seaward toward the past sea-level position to reconstruct the paleo-topography at the time of the extreme wave events corresponding to the annexed ridge deposits on the cliff top.

3.4. Water level and wave modeling

Three potential sources of the extreme waves that impacted the coasts of the ABC islands were considered: i) earthquake-generated tsunamis, ii) landslide-generated tsunamis, and iii) tropical cyclones. Wave propagation modeling of the tsunami and storm events was performed at two different spatial scales (Fig. 6), with coarse grids used offshore (500×500 m) and a finer grid used in the study area, closer to the ABC Islands (80×80 m).

The boundary conditions of offshore wave propagation for earthquake-generated tsunamis were set using the Delft Dashboard toolbox, which was then passed into a Delft3DFlow and Delft3DWave

Table 2

Tsunami sources and hurricane events considered for wave propagation modeling in the Lesser Antilles. References: 1—Brink et al. (2020); 2—Schubert, 1994; 3—Colón et al., 2015; 4—Pousse Beltran et al., 2016; 5—(Brink et al., 2008); 6—Boudon et al., 2007; 7—Lindsay et al., 2005; 8—Boudon et al., 1984; 9—Le Friant et al., 2003; 10—Dondin et al., 2012; 11—Joint Typhoon Warning Center (JTWC); National Hurricane Center (NHC); Unisys Weather.

Earthquake-generated tsunamis							
Name of structure (references)	Length (km)	Strike	Dip	Width (km)	Focal depth (km)	Slip	Mw
Enriquillo faults, Haiti (1)	60	132°	84°	20	15.5	–2.6 m left-lateral 1.8 m reverse	7.1
El Pilar fault zone, Venezuela (2,3,4)	270	88°	87°	20	15	1.6 m	7.7
South Caribbean Deformed Belt (SCDB) (5)	550	74.5°	17°	100	10	7.8 m	8.5
Muertos Thrust Belt (MTB) (5)	188	92.1°	10°	61	24 km	3 m	7.8
Subaerial landslide-generated tsunamis							
Name of landslide (references)	Length (km)	Thickness (m)	Density (kg/m ³)	Width (km)	Volume (km ³)	Age	
Debris avalanche, Santa Lucia (6,7)	6	100	3100	5		39 ky BCE, 1760 CE	
Soufriere (8,9)	1.5	200	3100	4	2	3100 BCE	
Kick'em, Jenny (7,10)	6	20	2000	3.5	4.4	From 1939 to 2001 CE	
Tropical cyclones							
Name of hurricane	Date	Mean sea-level pressure (hPa)				Wind speed (km/h)	
Hurricane Cesar (11)	24 July–06 August 1996	945				215	
Hurricane Ivan (11)	2–24 September 2004	910				210	
Hurricane Felix (11)	31 August–5 September 2007	929				280	
Hurricane Matthew (11)	28 September–9 October 2016	934				270	

models (Le Quéré et al., 2020). Delft3D is a 3D coupled hydrodynamic numerical model that solves nonlinear shallow water equations on a staggered 3D grid using a finite difference scheme. The fault parameters and magnitude of the seismic event must be defined in the Delft Dashboard tsunami toolbox to generate the initial wave conditions. The fault parameters used in this study were derived from two main earthquake-generating seismic structures in Haiti and Venezuela that had previously impacted the Lesser Antilles in the last century (Table 2). The tsunamis were modeled using fault parameters obtained from marine geophysical campaigns reported by Brink et al. (2020).

Three significant landslide bodies were considered for landslide-generated tsunami wave propagation, which was conducted using a Boussinesq-type Geowave model (Watts and Tappin, 2012). The first landslide-generated tsunami model was based on the chaotic mass flow deposit associated with a horseshoe-shaped structure near offshore St. Lucia (Mattioli, 1995). A second landslide-generated tsunami was associated with the magmatic eruption of the Soufriere Hills that occurred at 3.1 ka BP (Boudon et al., 1984; Le Friant et al., 2003). Finally, the main volcanogenic tsunami threat is represented by the active submarine Kick'em Jenny volcano (northwest of Grenada), which is particularly prone to future collapse based on monitoring measurements (Smith and Shepherd, 1993b; Lindsay et al., 2005; Dondin et al., 2012).

The impact of storm waves on the ABC island was modeled in Delft3D by hindcasting the four main hurricanes that impacted the Lesser Antilles in the past 30 years. Simulations were performed in Delft3D Flow coupled with Delft3D Wave. Among the studied events, Hurricane Ivan (September 2004) had the strongest effect on the ABC Islands; its track passed 130 km north of the study area and affected the windward sides of the islands, with the strongest effects felt northwest of Aruba (Engel and May 2012). This event featured a peak flow depth of 1.5 m at the cliff's edge, with a flow velocity ranging from 5 to 7 m/s (Scheffers, 2005; Scheffers and Scheffers, 2006).

Wave propagation in the nearshore areas was performed on a finer grid using the Boussinesq model within the Celeris software (grid size 5 × 5 m) to assess coastal inundation (Tavakkol and Lynett, 2017, 2020). For each event, waves were resolved using the JONSWAP spectrum and characterized by the root-mean-square wave height and common peak period. These parameters were defined from the Delft 3D outputs at the coarse-grid boundaries. The relative sea level was also included in the model based on the outputs of the ICE-7G model (Roy and Peltier, 2015, 2017, 2018) after comparison with field-based sea-level curves (Engel et al., 2014; Khan et al., 2017).

To model the non-linear evolution of the wave field, we performed

Table 3

Coefficients used to calculate the minimum flow velocity required to transport boulders.

Coefficient	Value	Reference
Drag	1.5	Nandasena et al. (2022)
Lift—submerged/sub-aerial boulders and joint-bounded blocks	0.7	Nandasena et al. (2022)
Lift—cliff-edge blocks	2.0–2.7	Rovere et al., 2017
Static friction	0.177	Field data

1D simulations using the non-hydrostatic XBeach module. These simulations use a bed profile, tide conditions, and wave spectra as input parameters. The bed profiles were extracted from the bathymetric and morpho-topographic data for each island, using the coastal stretch in which the largest boulders were identified. These areas were chosen to simulate the cross-shore velocity in areas impacted by the highest waves. The tide conditions were assumed to be constant for the entirety of the simulation and were referenced from their respective paleo-relative sea-level datum. The same wave spectrum used for the Boussinesq model was also used in the XBeach-1D simulation.

3.5. Threshold flow for boulder transport

The boulder displacement caused by a wave's impact is determined by a matrix of forces and moments applied to the boulder when the water hits its surface. As the wave impacts the boulder, drag and lift forces act to move the boulder, while reduced-gravity forces (i.e., boulder mass minus buoyant force) and frictional forces resist motion. To assess the minimum flow velocity required to move each of the surveyed boulders in the study area, we applied the incipient-motion formula developed by Nandasena et al. (2022). Three different initial conditions (i.e., pre-transport boulder positions) were considered following the approach reported in Nandasena et al. (2011a, 2011b): i) subaerial/submerged, ii) joint-bounded, and iii) cliff-edge. For sub-aerial/submerged boulders, the three types of incipient transport modes are i) sliding, ii) rolling/overturning, and iii) saltation/lifting. Boulders starting from initial cliff-edge conditions may be transported by rolling/overturning and saltation/lifting, while joint-bounded boulders can only be lifted from their socket before the wave impact (Nandasena et al., 2013). Previously published coefficients were used for all incipient-motion calculations (Table 3). The static friction was determined by applying the approach described by Pollyea and Fairley (2012)

Table 4

Dimensional features of the studied boulders as obtained from close-range SfM/MVS analyses; densities were obtained through the correlation between lithotype/coral species and Archimedeian buoyancy measurements reported in [Spiske et al. \(2008\)](#).

Boulder ID	Location	Lat. (N)	Lon. (E)	Elevation (m asl)	a-axis (m)	b-axis (m)	c-axis (m)	Projected ab (m ²)	Projected ac (m ²)	Volume (m ³)	Lithotype/corals species	Bulk density (kg/m ³)	Mass (tons)	Distance from the surf zone (m)
Ar1	Aruba (South Ranchero Curason)	12.5615	−69.9895	4.60	3.26	2.28	1.75	6.24	5.03	12.186	<i>Acropora</i> sp. and rudstone matrix	2290	29	32
Ar2		12.5616	−69.9898	5.80	2.17	1.82	1.56	2.59	2.70	3.507	<i>Acropora</i> sp. and rudstone matrix	2290	8.35	55
Ar3		12.5615	−69.9898	5.80	2.68	1.98	1.62	3.31	2.78	5.198	<i>Acropora</i> sp.	2290	12.37	55
Ar4		12.5787	−70.0062	4.50	4.56	2.59	2.12	8.12	6.28	12.845	<i>Acropora</i> sp.	2290	30.57	41
Ar5		12.5784	−70.0059	4.90	2.00	1.82	0.58	3.47	0.87	1.262	Serpulid reef rock	1770	1.77	38
Ar6	Aruba (Tierra del Sol)	12.6102	−70.0363	4.26	2.67	1.811	1.6	4.26	1.56	2.216	<i>Acropora</i> sp. and <i>Orbicella</i> sp.	2290	5.27	28
Ar7		12.6103	−70.0364	3.80	2.57	1.56	0.98	3.8	2.22	2.620	<i>Acropora</i> sp. and rudstone matrix	2290	6.24	25
Ar8		12.6099	−70.0357	4.46	3.07	2.3	1.16	4.46	3.11	2.990	<i>Acropora</i> sp. and rudstone matrix	2290	7.39	30
Ar9		12.6101	−70.0366	4.15	2.01	0.95	0.72	1.84	1.2	0.416	Biocalcarenite	2720	0.99	51
Ar10		12.6099	−70.0360	4.15	1.51	0.66	0.62	0.67	0.74	0.220	Biocalcarenite	2720	0.53	52
Ar11	Curaçao	12.6114	−70.0391	3.80	2.21	1.69	1.15	2.52	1.77	1.416	<i>Acropora</i> sp.	2290	3.37	16
Ar12		12.6114	−70.0391	3.80	2.07	1.2	1.15	1.99	1.81	1.145	<i>Acropora</i> sp.	2290	2.73	16
Ar13		12.6114	−70.0394	3.20	2.52	1.28	0.38	3.20	0.92	0.640	Serpulid reef rock	1770	1.02	48
Cu1		12.1737	−68.8530	4.8	7.73	2.65	1.77	16.05	10.86	18.09	Biocalcarenite	2720	43.24	47
Bo1		12.2529	−68.3106	4.70	6.76	4.48	4.47	13.91	19.43	50.753	<i>Acropora</i> sp.	2290	120.79	150
Bo2	Bonaire (Boka Onima)	12.2533	−68.3089	5.00	6.41	4.10	3.75	15.37	16.39	52.611	<i>Acropora</i> sp.	2290	125.21	52
Bo3		12.2531	−68.3094	5.40	4.59	4.47	3.03	14.60	9.46	40.247	<i>Acropora</i> sp.	2290	95.79	96
Bo4	Bonaire (Arawak/Boka Oliva)	12.2374	−68.2825	7.10	7.94	5.15	5.14	33.12	20.28	79.943	<i>Acropora</i> sp. and rudstone matrix +10% <i>A. cervicornis</i> and rudstone matrix	2290	175.08	50
Bo5	Bonaire (Lighthouse)	12.2109	−68.1972	6.50	3.35	1.78	1.00	4.13	2.63	3.476	<i>Acropora</i> sp. and rudstone matrix	2290	8.59	24
Bo6		12.2100	−68.1977	6.80	4.16	4.02	1.77	13.63	6.04	15.054	<i>Diploria</i> sp. and rudstone matrix	1040	37.18	51
Bo7	Bonaire (Washikemba)	12.1732	−68.2086	6.00	4.36	3.46	2.36	7.65	5.52	16.993	Biocalcarenite	2720	45.97	85

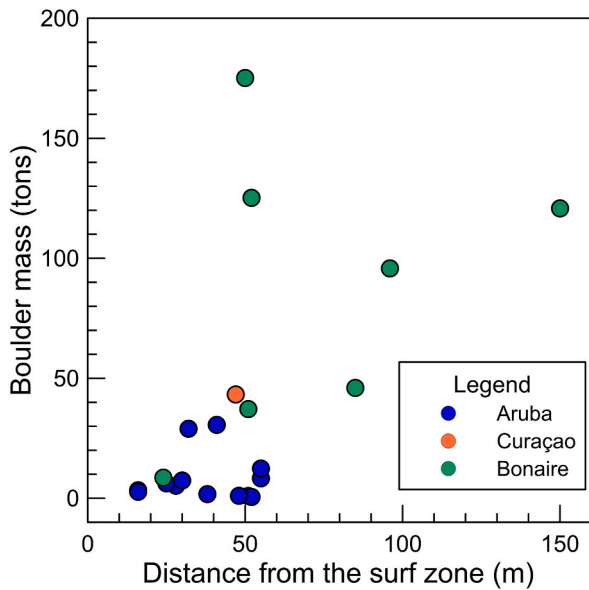


Fig. 7. Plot showing the relationship between distance from the surf zone (x-axis) and mass of the surveyed boulders on the three islands (y-axis).

on the point clouds obtained from SfM/MVS techniques.

4. Results

4.1. Size and minimum flow thresholds for coastal boulders

A total of 21 boulders were mapped using SfM/MVS (13 in Aruba, seven in Bonaire, and one in Curaçao). The surveyed boulders were composed of Pleistocene reef calcarenite and biocalcarenes and varied between 0.5 and 175 tons. The boulders were located at variable distances from the coast, ranging between 16 and 250 m from the shoreline, and at elevations between ~ 3 and ~ 7 m above present sea level

(Table 4). In general, the boulders in Bonaire were larger, heavier, and were located farther from the coast than those observed in Curaçao and Aruba (Fig. 7). This observation provides some initial evidence that the boulders in Bonaire would have required more energy to transport compared to those in Curaçao and Aruba, irrespective of the mode of transport under consideration (Fig. 8). In Bonaire, the flow required to initiate boulder movement—regardless of the mode of transport—was 5.72 ± 3.46 m/s on average (1-sigma). The equivalent value for Aruba was 3.47 ± 1.8 m/s (1-sigma), while the only boulder we measured in Curaçao would have required an average flow velocity of 5.02 ± 1.09 m/s (1-sigma). Higher minimum flow velocities are required for the saltation/lifting mode in subaerial and submerged conditions, for lifting in joint-bounded conditions, and for rolling in cliff-edge conditions (see Fig. 9).

4.2. Chronological constraints on boulder motion

The boulders surveyed using SfM/MVS were composed of Pleistocene reef limestone; no biological remains could be attributed to organisms that died during transportation, which would potentially provide a hard constraint on the timing of the displacement event. Consequently, the next best proxy was the age of the boulder ridge, which comprises smaller boulders of Holocene corals (*Diploria* sp. and *Orbicella* sp.) and vermetids (*Petalconchus* sp.). These were likely transported from subtidal environments (for corals) or the intertidal area (for vermetids) to the top of the MIS 5e reef terrace. Sampling was performed in the two areas surveyed by UAS: eight samples were collected in Tierra del Sol, while two samples were collected from South Ranchero Curason. The dates obtained from these samples were correlated with the eight large boulders that were sampled from Tierra del Sol and used in the flow velocity assessment.

The age distribution of the boulders within the ridge at Tierra del Sol and South Ranchero Curason shows that the ridges are polycyclic, with the boulders being emplaced within the last 4000 years (Table 5) by different extreme events during relative sea-level rise driven by glacial isostatic adjustment processes (Fig. 10). Only one boulder dates back to ~ 7 ka BP; this boulder was emplaced with a relative sea level several

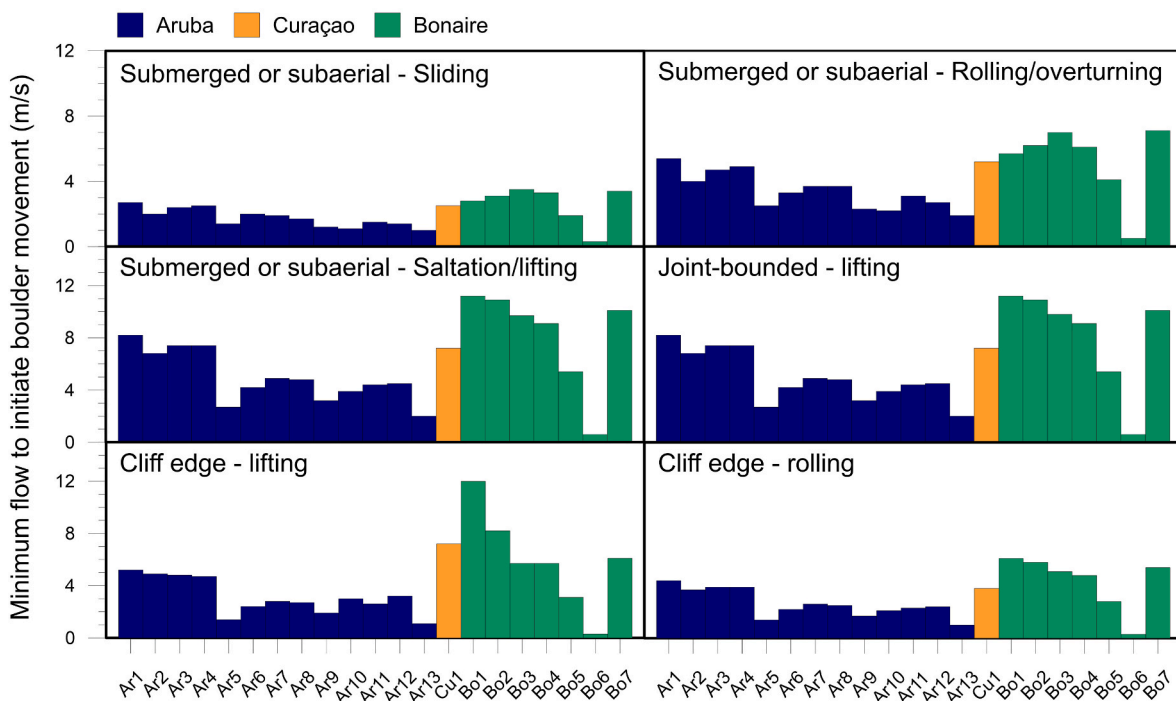


Fig. 8. Minimum flow velocity required to initiate boulder displacement for different pre-transport scenarios as calculated following the empirical equations reported in Nandasena et al. (2022). More details can be found in the Supplementary Information.

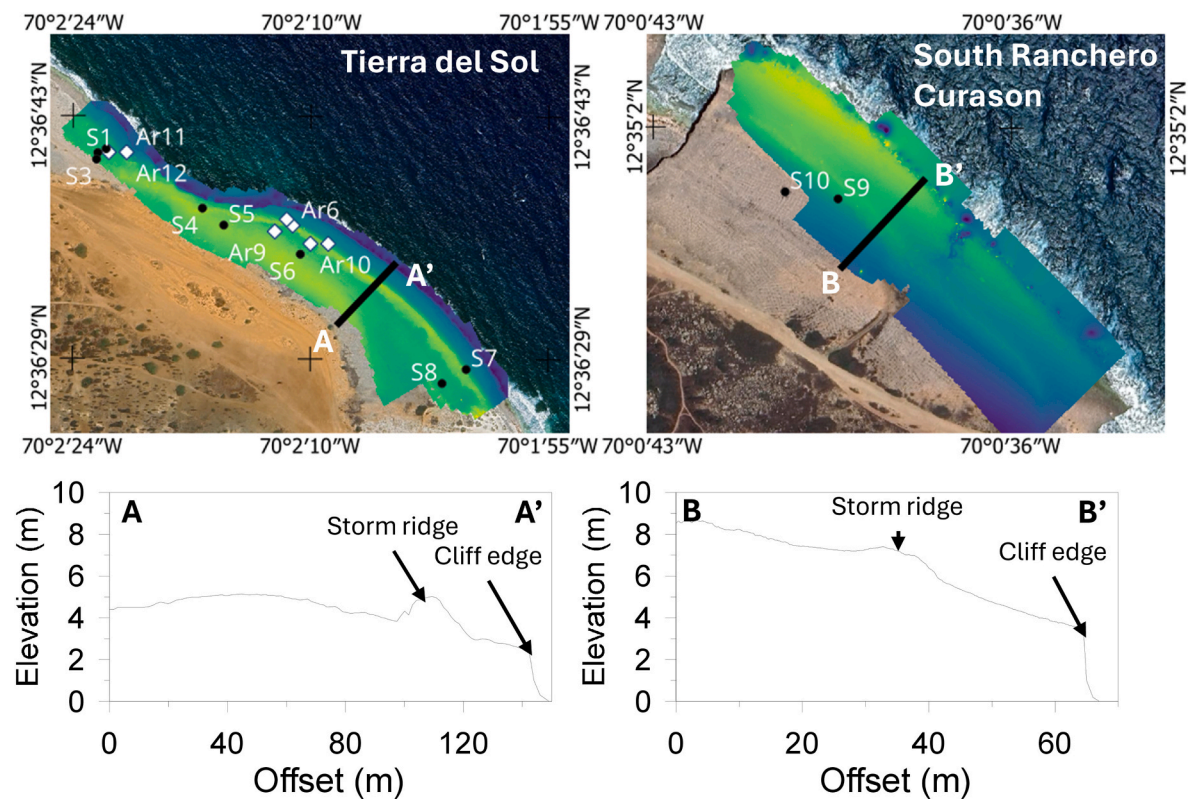


Fig. 9. DEMs obtained from SfM-MVS in Tierra del Sol and South Ranchero Curason. The locations of the boulder samples are presented as black dots, while the boulders processed for flow assessment are shown as white diamonds. The profiles show the cliff elevations and storm ridge locations.

Table 5
Location and radiocarbon ages obtained from the vermetid and coral boulders that comprise the boulder ridge at Tierra del Sol and South Ranchero Curason. CE = Common Era; BCE = Before Common Era.

ID	LAB CODES	Latitude	Longitude	Dated material	Age (years BP)	pMC	Calibrated age 95.4%	Calibrated age 99.4%	Age (cal years BP, 2-sigma)
S1	FTMC-HW32-1	12.611456	−70.039446	<i>Petalocnchus</i> sp.	2161 ± 27	76.42 ± 0.26	84 BCE–83 CE	167 BCE–163 CE	1948 ± 165
S2	FTMC-HW32-2	12.611391	−70.039586	<i>Petalocnchus</i> sp.	1995 ± 27	78.01 ± 0.26	124 CE–286 CE	50 CE–373 CE	1742 ± 81
S3	FTMC-HW32-3	12.611283	−70.039606	<i>Petalocnchus</i> sp.	3623 ± 29	63.70 ± 0.23	1876 BCE–1703 BCE	1959 BCE–1612 BCE	3741 ± 173
S4	FTMC-HW32-4	12.610480	−70.037820	<i>Petalocnchus</i> sp.	1522 ± 27	82.74 ± 0.28	658 CE–785 CE	602 CE–871 CE	1226 ± 135
S5	FTMC-HW32-5	12.610201	−70.037460	<i>Petalocnchus</i> sp.	3875 ± 28	61.73 ± 0.22	2206 BCE–2023 BCE	2304 BCE–1937 BCE	4072 ± 184
S6	FTMC-HW32-6	12.609726	−70.036168	<i>Diploria</i> sp.	3004 ± 28	68.80 ± 0.24	1108 BCE–931 BCE	1201 BCE–854 BCE	2975 ± 174
S7	FTMC-HW32-7	12.607833	−70.033370	<i>Petalocnchus</i> sp.	937 ± 28	88.99 ± 0.31	1257 CE–1382 CE	1187 CE–1429 CE	641 ± 121
S8	FTMC-HW32-8	12.607601	−70.033775	<i>Orbicella</i> sp.	4192 ± 30	59.34 ± 0.22	2630 BCE–2451 BCE	2745 BCE–2356 BCE	4493 ± 195
S9	FTMC-HW32-9	12.583610	−70.010970	<i>Petalocnchus</i> sp.	4521 ± 29	56.96 ± 0.21	3035 BCE–2870 BCE	3162 BCE–2780 BCE	4909 ± 191
S10	FTMC-HW32-10	12.583648	−70.011266	<i>Petalocnchus</i> sp.	6730 ± 31	43.27 ± 0.17	5468 BCE–5331 BCE	5541 BCE–5252 BCE	7350 ± 145

meters lower than the present day.

As the relative sea-level position at the time of boulder transport influences onshore wave propagation, we used two different paleo relative sea-level scenarios during the modeling; these were derived from the glacial isostatic adjustment models shown in Fig. 10, which show a gradual increase in the relative sea level starting from −2.35 m (4500 years BP) to −0.26 m (500 years BP) (Fig. 11a). This shift in Holocene sea-level would have significantly changed the position of the cliff and reef platform (Fig. 11 b–c), with a coastline located farther out

to sea than its present-day position. Assuming the same relative sea-level scenario for the fringing reef during the Holocene, the DEM obtained from the aerial SfM/MVS method on Aruba was merged with bathymetric data and corrected using the two different cliff positions that corresponded to the 500 years BP and 4000 years BP scenarios, respectively (Fig. 11):

- cliff base located at −0.26 m, with a coastline displacement toward the sea of 25 ± 5 m (scenario for 500 years BP)

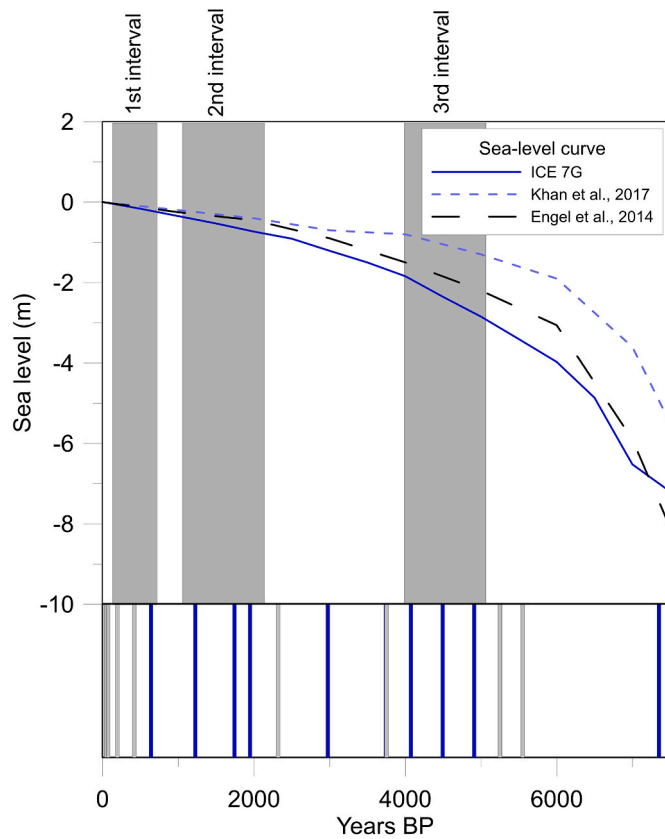


Fig. 10. Relative sea level resulting from glacial isostatic adjustment processes in the ABC islands. Intervals with tsunami events are reported in gray boxes. The lower part of the graph shows the average ages of boulders dated in this work (blue lines; Table 5) and the occurrence of tsunamis that impacted the ABC islands as reported in other studies (gray lines; Table 1).

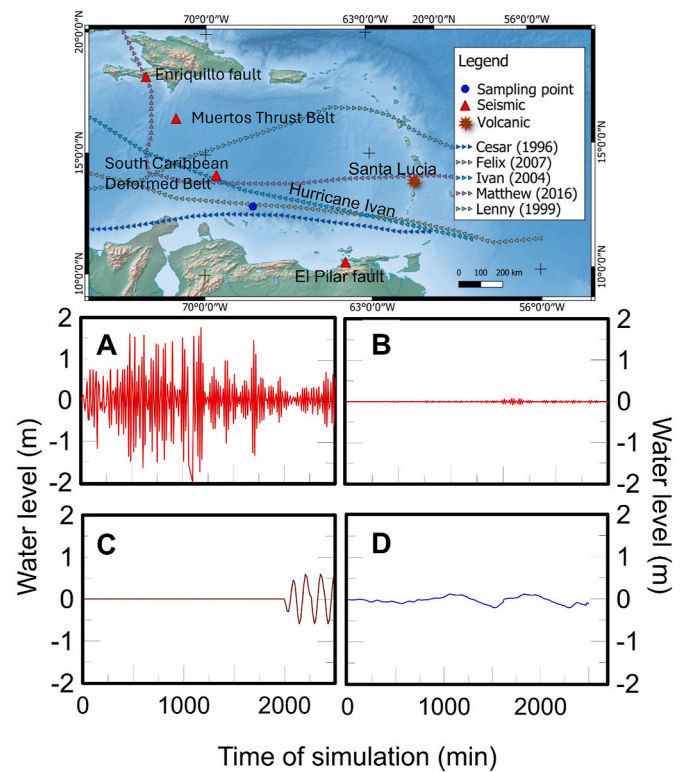


Fig. 12. Water levels for different extreme wave events modeled in the Caribbean region: a) El Pilar fault-generated tsunami, b) Enriquillo fault-generated tsunami, c) tsunami generated by the flank collapse of the Santa Lucia volcano, and d) storm surge modeled in response to Hurricane Ivan (September 2004).

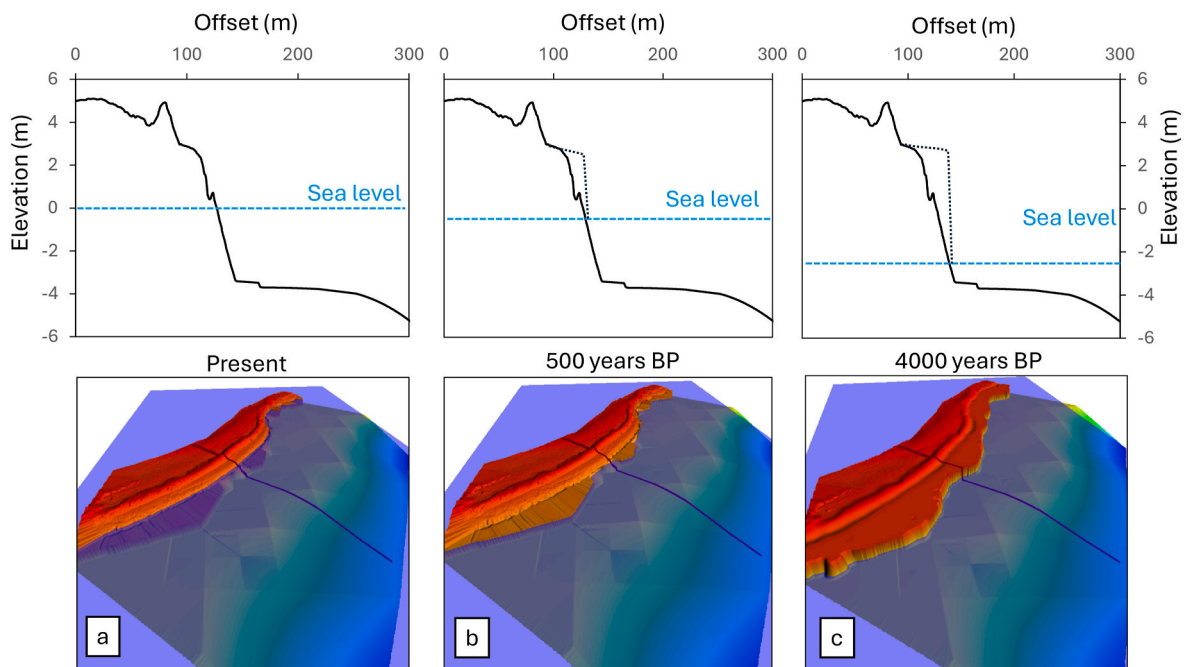


Fig. 11. Reconstruction of topography from the DEMs obtained from UAS surveying at Tierra del Sol (Aruba island): a) DEM of the current sea-level position, b) DEM with the coastline at -0.26 m (500 years BP), and c) DEM with the coastline at -1.65 m relative to the DEM in 11b (4000 years BP).

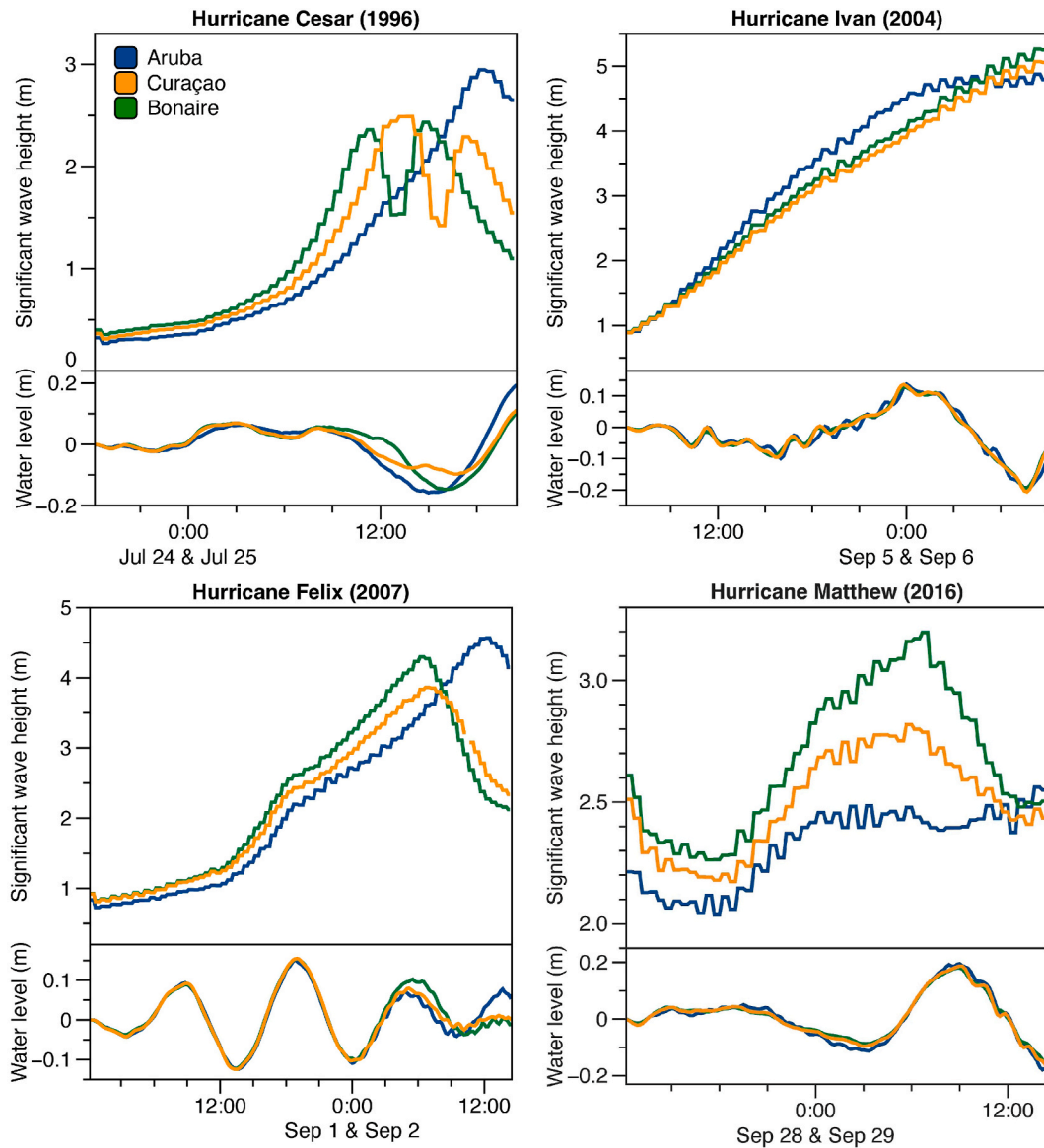


Fig. 13. Water level and significant wave height modeled for the main hurricanes that impacted the ABC Islands (events are described in Table 3, while sampling points are reported in Fig. 12).

- cliff base located at -1.65 m, with a coastline displacement toward the sea of 62 ± 5 m (scenario for 4000 years BP)

4.3. Modeling of extreme wave events

Mesoscale wave propagation modeling provides insights into the nature of the waves that could have emplaced the surveyed boulders in the ABC islands. While the models for landslide-generated tsunamis caused by volcanic flank collapses indicated that these waves would have completely dissipation over the Aves ridge (eastern Caribbean), the modeled earthquake-triggered tsunamis produced high water levels on the windward side of the ABC islands, where the boulders were emplaced. Of the two fault systems modeled in this study, the Haiti-sourced seismogenic tsunami produced very low water levels, while the seismogenic tsunami driven by slip along the El Pilar fault resulted in high water levels (Fig. 12). The models indicate that the activation of this fault system triggers a westward-propagating wave that results in high water levels on both the leeward and windward sides of the ABC Islands.

In terms of hurricanes, Hurricane Ivan (2004) resulted in the

displacement of coastal boulders weighing up to 2.5 tons in Bonaire (Bries et al., 2004; Scheffers and Scheffers, 2006; Engel et al., 2012b). However, although the path of this hurricane crossed the Caribbean region approximately 140 km north of the ABC Islands, it generated swell waves that were amplified by cliff fronts, reaching heights of around 12 m on the windward side of Bonaire (Scheffers and Scheffers, 2006). Our model of these events indicates that the ABC Islands were impacted by water levels of about 0.15 m asl, with significant wave heights of 6 m (Fig. 13). Another major event that impacted the ABC Islands was Hurricane Felix (2007), whose predicted water level and significant wave height values were 0.15 m and 4.5 m, respectively. Simulations of Hurricane Cesar (1996) and Hurricane Matthew (2016) exhibited water levels of about 0.2 m and wave heights of around 3 m along the coast of ABC Islands.

Among the modeled extreme events, the highest water levels along the coasts of the ABC islands were generated by tsunamis triggered by the El Pilar fault and the South Caribbean Deformed Belt (SCDB) structures. The estimated first arrival times from the tsunami generated by the El Pilar earthquake were 50 min in Bonaire, 60 min in Curaçao, and 80 min in Aruba (after the initialization of the simulation).

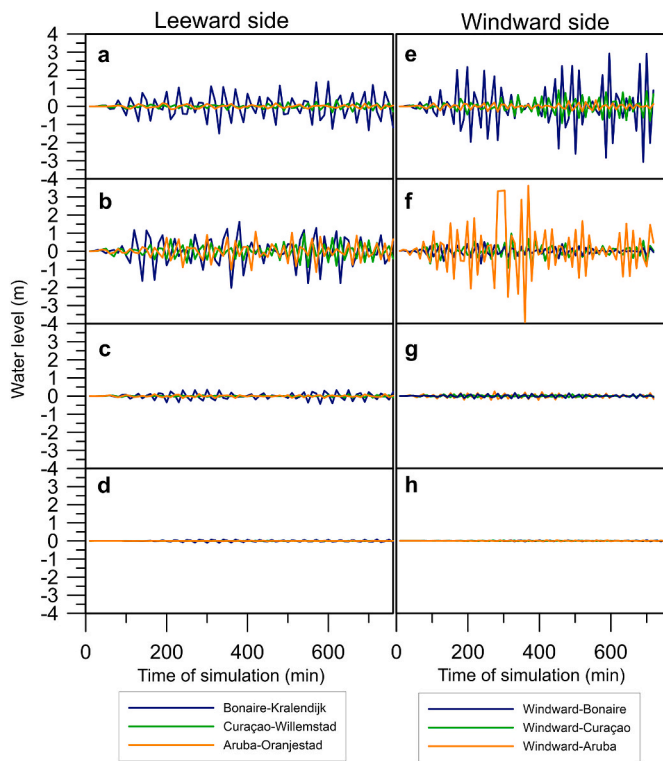


Fig. 14. Time series of the modeled earthquake-generated tsunamis. Water levels of the leeward side of the ABC islands as modeled for the a) El Pilar, b) SCDB, c) MTB, and d) Enriquillo faults; water levels of the windward side of the ABC islands as modeled for the e) El Pilar, f) SCDB, g) MTB, and h) Enriquillo faults.

However, the estimated first arrival times from the tsunami generated by the SCDB structure were 20 min in Aruba, 30 min in Curaçao, and 80 min in Bonaire. Furthermore, the raised water levels produced by the tsunami generated by the El Pilar fault were observed to dissipate as they progressed towards Aruba, with higher water levels (~ 3 m) modeled in Bonaire that became progressively lower in Aruba and Curaçao (~ 1 m; Fig. 14a–e). In contrast, tsunamis generated by the SCDB structure exhibited higher water levels in Aruba (~ 4.3 m) compared to Curaçao and Bonaire (~ 0.8 m; Fig. 14b–f). Water levels observed in models of the Enriquillo fault and Muertos Thrust Belt (MTB) structures exhibited values lower than 0.5 m (Fig. 14c–h).

4.4. Cross-shore velocity modeled in XBeach 1D

A 1D non-hydrostatic XBeach model was used to calculate the flow velocity generated by the highest tsunami waves shown in Fig. 14. The water level and cross-shore velocities were extracted along each transect reported based on the non-linear wave field modeled in XBeach 1D (Fig. 15). The results show an increased cross-shore velocity at the edge of the cliff, with values exceeding the flow velocity threshold needed to initiate boulder transport. The maximum cross-shore velocities in the 500 years BP and 4000 years BP scenarios were approximately 7.5 m/s on Aruba, 8 m/s on Curaçao, and 12 m/s on Bonaire. The highest water levels occurred in the 500 years BP scenario, ranging from 5 to 7 m. These values could strengthen the hypothesis of a tsunami impact capable of moving the observed boulders, as these values are greater than the c-axis values of the surveyed boulders.

5. Discussions

5.1. Limitations on the minimum flow for extreme wave scenarios

The distribution of coastal boulders in the ABC Islands provides a clear indication of the impact of extreme wave events capable of dislodging the boulders. Boulders weighing more than 50 tons are found only in Bonaire and Curaçao, with the largest ones located on the western side of Bonaire (Scheffers, 2002; Scheffers et al., 2014), indicating that the minimum flow required to initiate boulder movements was higher in Bonaire than in Curaçao and Aruba. The inverse modeling presented in this study shows that tsunamigenic sources located in the eastern part of the Caribbean basin—such as the El Pilar fault—are most likely to have caused boulder displacement. The strongest swells were also associated with storms arriving from the eastern side of the Caribbean basin. In contrast, several other probable sources could be responsible for boulder displacements that may have impacted from other directions, including the SCDB structure located offshore on the northern side of the ABC Islands (Brink et al., 2008; UNESCO, 2012). Considering the minimum flow velocities reported in Fig. 8, a singular marine event is not capable of transporting boulders more than 100 m (Goto et al., 2010; Nandasena et al., 2011a). Flows measured in similar conditions during the 2011 Great East Japan tsunami showed that boulder displacements exceeding 100 m require flow velocities of 7.5–23.7 m/s (Nandasena et al., 2013); consequently, based on the geographic context of the ABC islands, it is more realistic to consider multiple wave events that may have contributed to the observed cumulative different boulder displacements.

It should be noted that some criticisms have been leveled against the application of the incipient motion formula to distinguish types of wave events responsible for boulder movements in the ABC Islands (Engel and May 2012; Costa et al., 2021). In particular, the wave energy can be underestimated if the pre-transport setting and transport mode are not clearly defined. For example, the boulders of Boka Olivia (Bonaire) have their a-axis sub-parallel to the coastline, suggesting a saltation transport mode (Watt et al., 2010). However, evidence of detachment surfaces and notches on the boulders can provide additional insights into their transport mode (Pignatelli et al., 2010; Engel and May 2012); a comparison between the transport mode and minimum flow required to initiate boulder movement is reported in Table 6 based on the field evidence reported in Engel and May (2012).

Boulder Bo4 is the largest boulder surveyed in this study and overlies a 0.7 m high pedestal, indicating a long period of protection from solution agents on the order of many hundreds or even thousands of years (Engel and May 2012). There is a notch at the base of Bo4, suggesting that the most likely pre-transport setting is that of a joint-bounded emplacement. Furthermore, Bo4 is the heaviest boulder recorded in this study, and the minimum flow required for its displacement is a useful benchmark for the application of the inverse modeling approach. Indeed, the modeled cross-shore velocities were higher than those indicated by the incipient mode for both the 4000 years BP and 500 years BP scenarios.

5.2. Attribution of the most reliable tsunamigenic source

Chronological constraints were obtained from the radiocarbon dating of subtidal and intertidal samples transported onto the MIS 5e terraces of Aruba island. The calibrated ages revealed three key horizons during which multiple wave events would have been capable of dislodging the boulders of ABC Islands: 500, 2000, and 4000 years BP. The 500 years BP horizon is consistent with other geological evidence of a tsunami that occurred on September 1st, 1530, such as debris avalanches into the sea of the eastern Islands (i.e., Basse-Terre, Guadeloupe, St. Lucia, Grenada) (Boudon et al., 1984, 2007) and fine-grained extreme wave deposits on the lagoonal areas of Lesser Antilles (Engel et al., 2012a; Engel and May 2012).

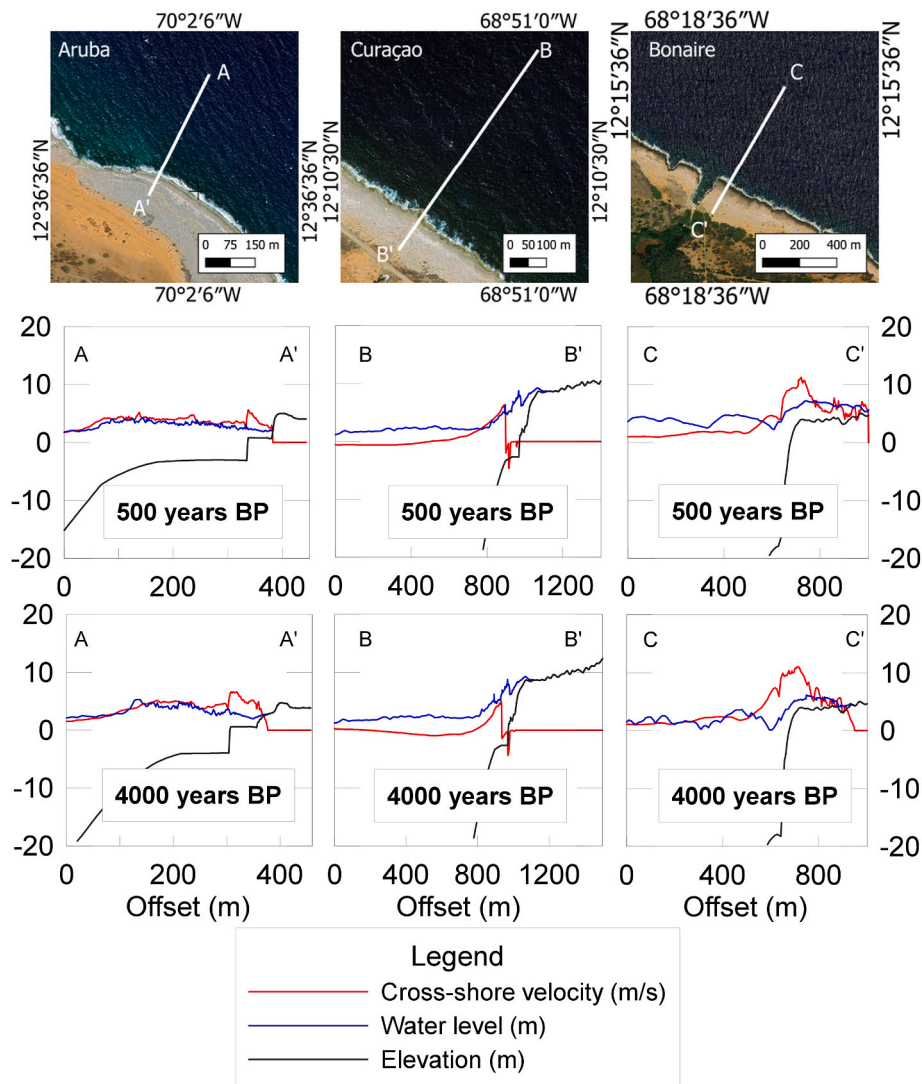


Fig. 15. Non-hydrostatic simulation outputs obtained through the XBeach model of the ABC islands. The different times were extracted from the calibrated ages, while the topographic profiles were extracted from the paleo-landscape of the relevant sea-level scenarios.

Table 6

Pre-transport settings of the surveyed boulders as well as the correlation between their masses and the minimum flow velocities required to initiate boulder movements as calculated from the equations described in [Nandasena et al. \(2022\)](#).

ID boulder	Pre-transport setting	Transport mode	Location	Event	Mass (t)	Minimum flow required to initiate boulder displacement (m/s)	Modeled cross-shore velocities (m/s)
Bo2	Cliff-edge boulder	Cliff edge - Rolling/overturning (Rixhon et al., 2018)	Boka Onima	Tsunami 1200 BP	125.21	8.2	12
Bo5	Joint-bounded	Cliff edge - Rolling/overturning (Rixhon et al., 2018)	Spelonk Lighthouse	Tsunami 1200 BP	8.59	5.4	
Bo4	Joint-bounded	Cliff edge - Rolling/overturning (Engel and May, 2012b); Saltation (Watt et al., 2010)	Boka Olivia	–	175.08	9.1	

The current positions of the coastal boulders suggest that they were displaced by more than 100 m from the surf zone. This degree of movement could not have occurred during a single event as indicated by the cross-shore velocities predicted by the XBeach 1D model ([Nandasena et al., 2011a, 2013; Cox et al., 2020](#)). Therefore, boulder transport must have occurred across multiple events as indicated by the chronological ranges obtained from the radiocarbon dating (Table 5). The initial displacement of coastal boulders could have occurred during the 4000 years BP scenario, during which the maximum cross-shore velocity

reached 12 m/s (Fig. 11). This velocity is consistent with other tsunamis that have caused the displacements of similar boulders, as observed during events such as the 2004 Indian Ocean Tsunami ([Paris et al., 2010; Nandasena et al., 2011a](#)).

Field evidence from Spain has shown that minimum flow velocities between 3.6 and 8 m/s can displace coastal boulders by a maximum distance of 40 m ([Lario et al., 2023](#)). Similarly, boulders weighing 60–90 tons were moved up to 32 m by wave flows of around 10 m/s in New South Wales, Australia ([Young et al., 1996](#)). Several instances of coastal

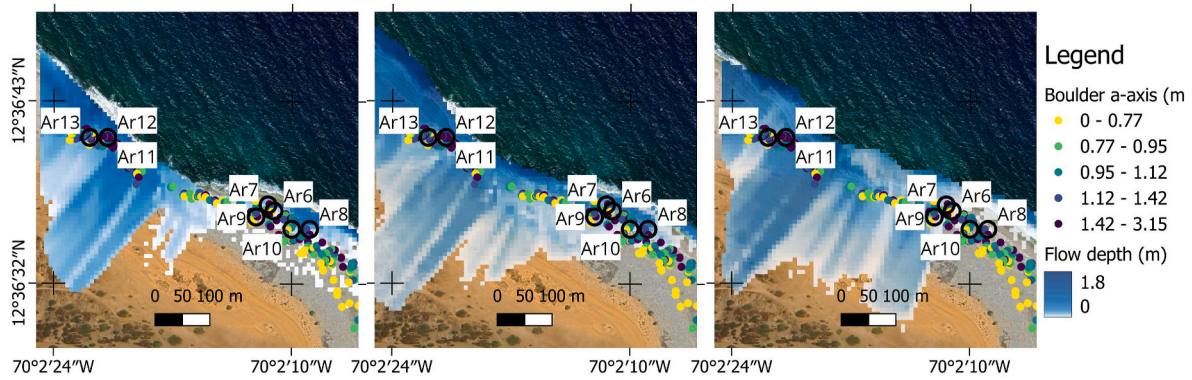


Fig. 16. Modeled inundation scenarios at the Tierra del Sol site, Aruba: a) inundation caused by Hurricane Ivan (2004) at present-day sea levels, b) inundation caused by the El Pilar tsunami based on relative sea-levels in the 500 years BP and c) 4000 years BP scenario. The empty black circles indicate the location of the mega-boulders surveyed at this site, while the colored dots represent smaller boulders that comprise the ridge, colored by their a-axis size as measured from field photos. Basemap source: Esri, Maxar, Earthstar Geographics, and the GIS User Community.

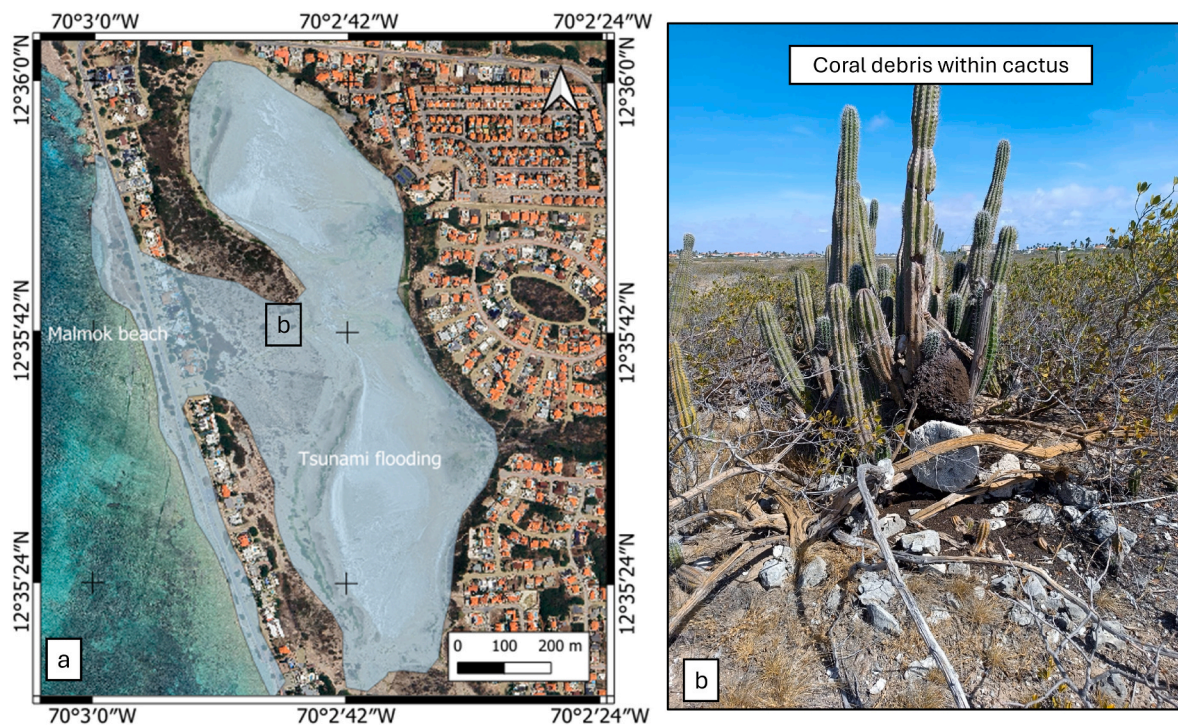


Fig. 17. Modeled El Pilar fault-generated tsunami effects at Malmok beach (Aruba). a) Flooding map at Malmok beach obtained using the Celeris software (DEM derived from TanDEM X). b) Coral debris within cactus plants observed in Malmok lagoon.

boulders being displaced multiple times due to different tsunami events have been studied in Australia; in these cases, top-cliff boulders weighing 20–100 tons were moved up to 100 m inland by two Holocene tsunami events (Scheffers et al., 2008). In this study, the location of the coastal boulders of the ABC Islands may be the culmination of different tsunami events that drove boulder transport as indicated by the paleo-landscape reconstruction of the 500 years BP scenario.

5.3. Inundation surfaces and boulder accumulations

The impact of tsunamis and storm waves can result in the severe inundation of the three studied islands. Pignatelli et al. (2010) showed that the inundation limit was located further inland than the positions of the tsunami-transported boulders. Using paleo-landscape reconstructions at Tierra del Sol on Aruba, which was hit by relatively small waves compared to Bonaire and Curaçao (Fig. 14), we simulated

the paleo-landscape inundation caused by the impact of tsunamis that occurred 500 and 4000 years BP and compared them to the flooding caused by Hurricane Ivan (September 2004) under present sea-level conditions (Fig. 15a). In general, the inundation extent was similar for all events, extending a maximum of 200 m inland. This similarity between these events makes determining the scenario responsible for the observed boulder displacement more challenging. For example, the impact of hurricanes has occasionally led to the displacement of some boulders, such as was observed during Hurricane Ivan in Bonaire (Scheffers and Scheffers, 2006; Engel and May 2012).

Small boulders were observed to be sorted along the ridge deposits, with their a-axis values decreasing in length landward (Fig. 16). The presence of ridge deposits resulting from hurricane impacts on the ABC Islands has been discussed in previous studies (Morton et al., 2008; Spiske et al., 2008). Nevertheless, there are boulders weighing over 50 tons that have not been displaced by hurricanes (Scheffers and Scheffers,

2006; Engel and May 2012). Some coral debris and overwash deposits were observed in the back lagoon located at Malmok Beach (Aruba; Fig. 17). This may be related to the El Pilar earthquake-generated tsunami, which produced water levels of ~ 3 m, resulting in a maximum inundation surface that extended across the lagoon. A similar pattern was observed in Salina Tam (leeward Bonaire; Engel et al., 2012b), where high-energy deposits were observed in sedimentary cores and attributed to episodic tsunami events.

6. Conclusions

The coastal boulders of the ABC islands represent out-of-size deposits that may be related to tsunami or storm events. The dimensional features and distributions of these deposits are important factors that can be used to constrain the type of event that was responsible for their displacement. Here, SfM/MVS methods allowed us to obtain high-resolution dimensional data of the studied coastal boulders as well as reconstruct paleo-landscapes in the ABC islands. Radiocarbon dating allowed for the identification of three key event horizons associated with multiple extreme wave occurrences: 500, 2000, and 4000 years BP. Given the distance of the boulders from the surf zone (more than 100 m in some cases), these displacements are likely to have occurred at different times. The onset of boulder displacement is most likely to be associated with the oldest key horizon (4000 years BP), corresponding to a sea-level position of -1.65 m and a paleo shoreline located about 60 m seaward. An analysis of the incipient motion of the boulders combined with numerical models and chronological constraints revealed that the events responsible for boulder displacement would have resulted in high flow velocities in Bonaire and slightly lower velocities in Curaçao and Aruba. The overall displacement of the coastal boulders is likely to have been caused by multiple events across the three key event horizons.

Based on hydrodynamic simulations and the calculated wave flow velocities required to move the boulders, the most likely tsunamigenic scenario is associated with slip along the El Pilar fault system (a Venezuelan structure); this hypothesis is supported by water level models of tsunami propagation. Furthermore, the cross-shore velocities of the modeled El Pilar fault-generated tsunami resulted in higher values than the required flows as indicated by incipient motion formulas. The El Pilar fault-generated tsunami models were also consistent with other geomorphological evidence of coastal flooding detected in Aruba. While hurricanes can result in the deposition of imbricated ridges and may have influenced the current positions of the coastal boulders across the islands, we show that the initial and main factors that drive coastal boulder transport are likely related to the impacts of different tsunamis across multiple event horizons.

Author contributions

Conceptualization: Giovanni Scardino, Giovanni Scicchitano; Data Curation: Giovanni Scardino, Denovan Chauveau, Patrick Boyden, Alessio Rovere; Formal analysis: Giovanni Scicchitano, Alessio Rovere, N.A.K. Nandasena; Funding acquisition: Giovanni Scicchitano, Alessio Rovere, Giovanni Scardino, Patrick Boyden; Investigation: Giovanni Scardino, Malena Dahm, Sonia Bejarano, Giovanni Scicchitano, Alessio Rovere, Eric Mijts, Harold Kelly. Methodology: Giovanni Scardino, N.A.K. Nandasena, Elisa Casella, Alessio Rovere, Patrick Boyden, Denovan Chauveau, Chiara Barile. Project administration: Alessio Rovere, Patrick Boyden, Giovanni Scicchitano. Resources: Alessio Rovere, Patrick Boyden, Giovanni Scicchitano, Giovanni Scardino. Software: Giovanni Scardino, Chiara Barile, Alessio Rovere. Supervision: Alessio Rovere, Giovanni Scicchitano, Eric Mijts, Harold Kelly. Validation: Alessio Rovere, Elisa Casella, Patrick Boyden, Denovan Chauveau. Visualization: Eric Mijts, Harold Kelly, Sonia Bejarano. Roles/Writing - original draft: Giovanni Scardino, Giovanni Scicchitano and Writing - review & editing: Alessio Rovere, Patrick Boyden, Denovan Chauveau.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2024.109136>.

Data availability

Data will be made available on request.

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