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Abstract

To develop a better understanding of the origins of extreme-wave deposits and to help assess the potential risk of future overwash events, a field mapping survey was conducted in November 2006 on the northern coast of Bonaire, Netherlands Antilles. Deposits were mapped and analyzed to help develop a systematic sedimentological approach to distinguish the type of extreme-wave event (tsunamis or storms) or combination of events that formed and modified the deposits over time.

Extreme-wave deposits on the northern coast of Bonaire between Boka Onima and Boka Olivia have formed sand sheets, poly-modal ridge complexes, and boulder fields on a Pleistocene limestone platform 3-8 meters above sea level. The deposits exhibit characteristics that are consistent with both large storm and tsunami processes that often overlap one another. Sand sheets occur as low-relief features underlying and incorporated with boulder field deposits. The seaward edge of ridge complexes are deposited up to 70 m from the shoreline and can extend over 200 m inland. Over 600 clasts were measured in fields and range in size from coarse gravel to fine block, weigh up to 165 metric tons, and are placed over 280 m from the shoreline.

Our analyses indicate that the deposits may have been produced by a combination of hurricane and tsunami events spanning 10s to 1000s of years. Comparing the different deposit morphologies between study sites highlights the importance of shoreline orientation to the distribution of extreme-wave deposits onshore. However, further investigation is required to fully understand the processes that have produced and modified these deposits over time.

Introduction

In November 2006, a field mapping survey was conducted on the northern coast of Bonaire, Netherlands Antilles to help assess the potential risk from extreme-wave events such as tsunamis and hurricanes in the Caribbean Sea (fig. 1). Bonaire is the eastern most island of the ABC island group (Aruba, Bonaire, and Curacao) in the Netherlands Antilles just north of Venezuela. The purpose of the survey was to determine the spatial distribution and origin of sedimentary deposits occurring along the coast between Boka Onima and Boka Olivia in an area where extreme-wave deposits have been described previously (Scheffers, 2005; Morton and others, 2006 and 2008). The deposits range in size from mud to megagravel (Blaire and McPherson, 1999) and overlie an older Pleistocene reef platform that is now 3 to 8 m above sea level.

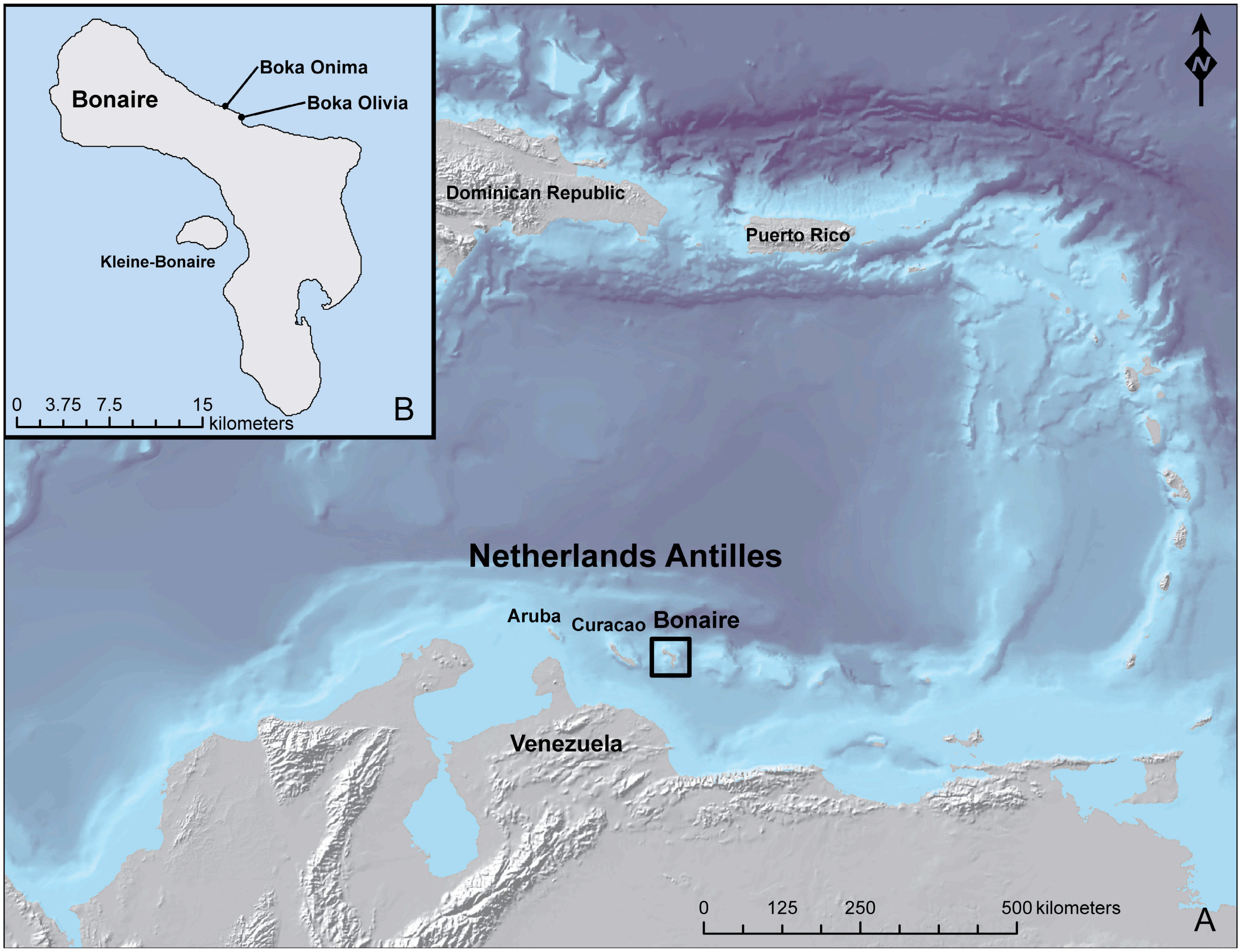


Figure 1. Location map showing Bonaire, Netherlands Antilles in the southern Caribbean Sea north of Venezuela (A). Boka Onima and Boka Olivia are located on the northern coast of Bonaire on the inset map in upper left corner (B).

The exposed limestone platform and boulders have been colonized by microbial endoliths that penetrate the rock surface and embed themselves into the limestone structure. Over time these bacteria cause bioerosion of the rock surface resulting in biokarstic features including flat-bottomed pools with overhanging walls, vertically oriented flutes, or intertidal notches (Folk and others, 1973; Glaub and others, 2007). Microbial endoliths stain rocks they have colonized in varying shades of grey that can be used to infer boulder transport. Stained rocks that are overturned or fractured reveal fresh white limestone faces that have not been colonized. An overturned boulder also will reveal a white uncolonized patch on the limestone platform where a boulder was formerly deposited. White chips, scrapes, or fractures on the grey platform also indicate that a boulder (or other material) has impacted and damaged the platform surface.

The coarse-clast ridge deposits on Bonaire were reported on previously by Scheffers (2002, 2005) who concluded that they were most likely the result of three tsunamis. Conversely, Morton and others (2006, 2008) concluded that the ridge deposits were more likely produced by multiple storm wave-events such as hurricanes. They concluded the ridge complexes spanned centuries to millennia after interpreting the origin of many sand and coarse clast extreme-wave deposits on the islands of Bonaire, Puerto Rico, Jamaica, and Guadeloupe. In addition, they summarized the geology, historical hurricanes and tsunamis, and discussed the origin of extreme-wave deposits in the Caribbean and Bonaire not covered in this report.

On Bonaire, Morton and others (2006, 2008) observed that coastal deposits formed two general distribution patterns: (1) ridge complexes and (2) boulder fields. Ridge complexes are composed of mixtures of modern and older coral reef and limestone cobbles, pebbles, boulders, and sand up to 4 m thick and 10s of meters wide. The deposits form wedges a few to 10s of meters from the shoreline and terminate abruptly in avalanche slopes on their landward sides. They concluded that ridges and ridge complexes are primarily storm and hurricane constructed features built up as a result of multiple storm wave-events.

A ridge complex at Boka Onima included in this study was described by Morton and others (2008) as a clast-supported framework of cobbles and boulders filled with sand. They hypothesized that the ridge complex may have been produced as a result of framework deposition by extreme-waves and subsequent framework infiltration of sand by less powerful waves. A shore normal cross section of the ridge complex was exposed by mining operations and revealed crude stratification, vertical textural sorting, bounding surfaces, internally imbricated clasts and steep seaward dipping beds. Four to five different stratigraphic units were identified and molluscs from each of the layers were dated by using AMS radiocarbon analyses. The molluscs range in age from 174 to 5669 calibrated years before present (cal yrs BP) and are distributed in a pattern consistent with ridge complex aggradation and progradation over thousands of years (Morton and others, 2008).

Boulder fields on Bonaire generally contain some clasts that are much larger than those found in ridge complexes. Clasts deposited in fields are spaced farther apart, form single layers, and have less influence on subsequent transport and deposition of one another than those in ridge complexes. Determining the origins of boulder fields is more difficult than ridge complexes because boulder fields can be deposited by storm waves and/or tsunamis (Morton and others, 2006).

While Morton and others (2006) postulated that the boulder fields are consistent with what would be expected by a tsunami, they concluded a systematic sedimentological approach would be required before the origin of the deposits could be determined with any certainty. This report takes the next step toward the development of a systematic sedimentological approach to identify the origins of boulder deposits on Bonaire.

Methods

Data sets collected in the field include aerial kite-camera images, topographic profile transects, trenching and sediment samples, single-beam bathymetric surveys, digital camera and digital cobble-camera photographs, and field measurements of boulder positions, dimensions and orientations. All data sets were integrated into a Geographic Information System (GIS) database for further analyses.

Kite-Camera Mosaics

A kite and digital camera system (fig. 2) was used to obtain high-resolution normal and oblique aerial images at three locations: Boka Onima, north of Boka Olivia, and Boka Olivia. A 9’x 4’7” Levitation Delta kite is equipped with a 7.1 megapixel Canon PowerShot S70 camera that was aimed and activated remotely from the ground by using a 3-channel Futaba radio control. Kite-camera images were collected along shore-normal transects extending from the shoreline approximately 300 m inland. The camera was flown at a height of about 75 m above ground.

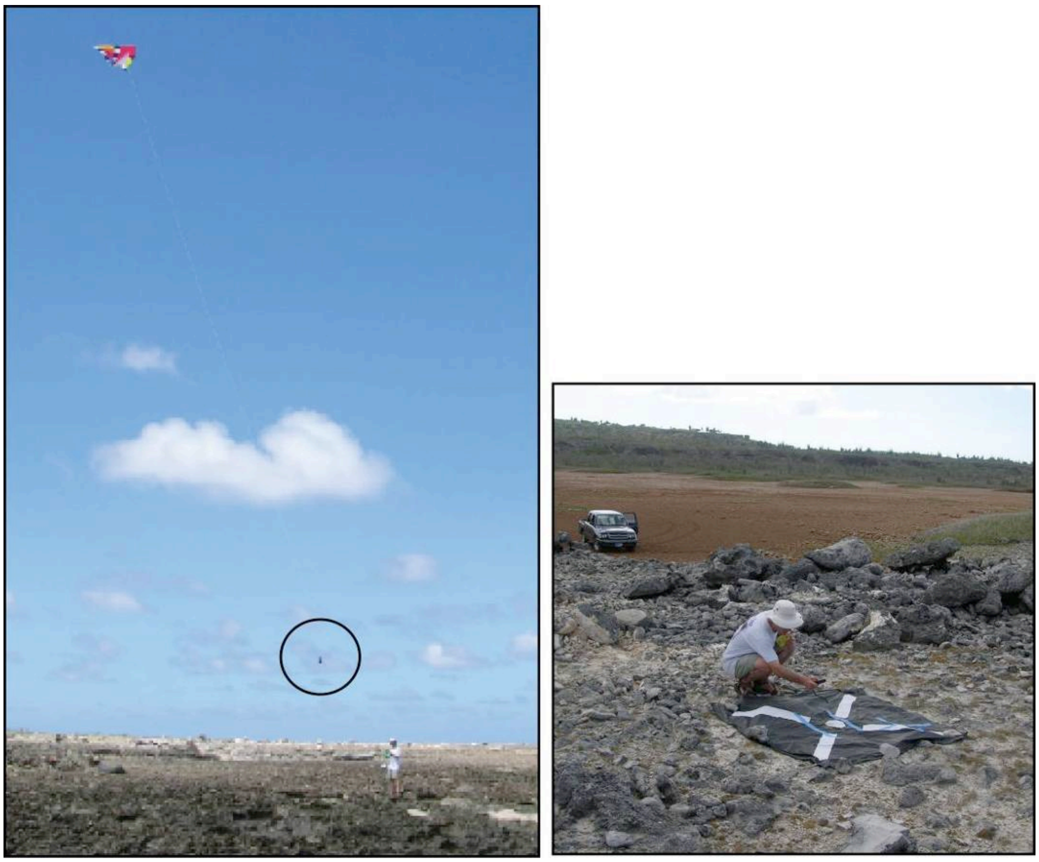


Figure 2. Photographs showing the digital kite-camera system during deployment. The black circle in the left panel indicates the position of the camera in relation to the kite while being deployed. Images are georeferenced by using 1.5 meter x 1.5 meter ground targets (right panel) located by using GPS.

Shoreline orientation and the prevailing west winds dictated whether or not the shoreline could be captured in kite-camera images. At Boka Onima, the shoreline is oriented to the north, allowing the kite-camera to image the shoreline. The shorelines north of Boka Olivia and Boka Olivia are oriented to the east. Westerly winds pushed the kite-camera inshore, making it impossible to image the shoreline.

Kite-camera images shot normal to the ground were georeferenced and mosaiced in GIS to form base maps at each location. Obliquely shot images were not georeferenced. To accurately georeference the kite-camera images, uniquely numbered 1.5 m x 1.5 m ground-control points were placed along the transects. The ground-control points were located by using time-averaged data from a Garmin GPSmap 76CS. Control points identified in the images were used to georeference each image in GIS. Additional georeferencing was performed between overlapping images to improve the overall quality of a mosaic by matching unique features found in common among the images and with other GPS located points of interest such as roads and easily identified boulders. Adobe Photoshop® was used to enhance the overall quality of each mosaic.

Control points used for georeferencing the images were located by time-averaging GPS signals (1 per second) over a few minutes. The control points provide horizontal accuracies of about ± 2.5 m. Areas in the mosaics within a few 10s of meters of control points have similar horizontal accuracies but accuracy decreases with increasing distance from the control points. Areas farthest from control points have an accuracy of ± 10 m. Positional errors are compounded along the outer edges of images where acute camera angles in relation to ground and horizontal and vertical accelerations of the kite have caused distortion. The pixel resolution for each mosaic is 4 x 4 centimeters (cm).

Bathymetric Survey

Water depths along the northern coast of Bonaire were measured November 7, 2006 by using a Garmin GPS MAP 420s depth sounder with an integrated GPS unit. The soundings were collected during rough sea conditions and generally have an error of ± 0.75 m. The accuracy of the soundings was estimated by comparing the depths of adjacent soundings between overlapping survey lines. An elevation surface of the bathymetric point data was interpolated by using an inverse distance weighted model in GIS to produce 10 m bathymetry contours. The data were not corrected for tide and local sea level was used as the vertical datum. Tides in Boniare are diurnal and the maximum annual tidal range is approximately 1 m, with an average range of 0.30 m during a lunar cycle (Bak, 1977).

Topography

Topographic profiles were surveyed by using an Impulse LR laser range finder and Garmin GPSmap 76CS. Local sea level was used as the vertical datum. GPS positions were recorded at the start and end of each transect. An elevation surface of the topographic point data was interpolated by using a triangular irregular network (TIN) model in GIS to produce 0.5 m elevation contours and for estimating the elevation of each boulder. The TIN model results were compared to measured topographic points and edited to minimize errors produced as a result of the interpolation.

Trenching and Sediment Samples

Trenches were excavated in the ridge complex and boulder field deposit along a topographic profile at Boka Olivia to measure the deposit thickness. Sediment samples were collected vertically at fixed intervals in trench walls and analyzed for grain-size statistics. In addition to individual sediment sample statistics, samples also were bulk averaged for each trench by adding the corresponding grain-size bins from each sample together as one single sample. A Beckman-Coulter Counter was used for grain-size analyses. Molluscs also were collected from a trench and two samples were used for AMS radiocarbon analyses.

Cobble-Camera Images

Digital images were taken along transects over ridge complexes and rectified in order to accurately count the number of clasts, measure axis lengths and long-axis (a-axis) orientations relative to the shoreline at Boka Onima and Boka Olivia. To capture the images, a high-resolution digital camera was mounted on a tripod above the sediment surface (fig. 3). The camera was aimed straight down at the sediment and leveled. A tape measure was placed horizontally along the length of the transect within the camera's field of view to provide a scale to measure individual cobble axes and shoreline orientations by using a computer. Accurate axis and orientation measurements can be made with coordinate geometry tools in GIS once the images have been oriented and georeferenced.

Figure 3. Photograph of the cobble camera set-up at Boka Onima. The black circle indicates camera position.

General shoreline orientations for Boka Onima and Boka Olivia were determined in GIS over several kilometers (km) of coastline. Clast long-axis orientations are grouped into categories relative to the shoreline orientations where they were deposited; shore normal, sub-normal, shore parallel, sub-parallel, and all other orientations. Preferences for clast orientations in a cobble-camera image or collected in the field were calculated by dividing the number of clasts in a particular orientation category by the number of degrees for that category. The orientation of the clasts may indicate the mode of transport, such as sliding or rolling and provide clues about the approach angle of an extreme-wave(s) (Inman, 1949; Collinson and Thompson, 1982; Williams and Hall, 2004).

Boulder Measurements

Boulder dimensions (a, b, and c axes) and the shoreline orientations of the long-axis (a-axis) were measured for each boulder in two ways: (1) in the field by using a tape measure and either a Brunton compass or an electronic compass on a Garmin GPSmap 76CS (± 5 degrees) or (2) on a computer by using georeferenced kite-camera images and coordinate geometry tools in GIS. Boulder locations also were mapped in two ways: (1) by using a Garmin GPSmap 76CS and (2) by marking boulders on printed kite-camera images in the field and plotting them later in GIS after the images were georeferenced.

Boulder volumes were estimated by multiplying the three orthogonal axis lengths. Due to the irregular shapes of boulders, this method often results in an over estimation of boulder volume (Spiske and others, 2008). To estimate individual boulder weights, rock and coral samples were collected for bulk density measurements. The density (g/cm^3) for each rock sample was calculated at the U.S.Geological Survey (USGS) sedimentology lab in Menlo Park, CA by using volume measurements from fluid displacement.

Bulk density was determined from five rock samples collected in Boka Olivia (table 1 and fig. 4). Most samples were composed of either the limestone platform or corals. Samples S1 and S2 were taken from different parts of the same boulder. When possible, different sample densities were used to calculate boulder weights. For example, five boulders were noted as being composed of coral. The densities of the coral rock samples S4 and S5 were averaged (1.85 g/cm^3) and used to calculate the coral-boulder weights. Unless otherwise noted, the average density of all five samples (2.24 g/cm^3) was used to calculate boulder weights.

Table 1. Sample weight, water displacement and bulk density of Boka Olivia rock samples collected in November 2006

Sample	Sample weight submerged (gram)	Water displacement (milliliter)	Bulk density (gram per cubic centimeter)
S1	449.69	187	2.40
S2	150.89	54	2.79
S3	135.73	59	2.30
S4	343.72	290	1.19
S5	72.73	29	2.51

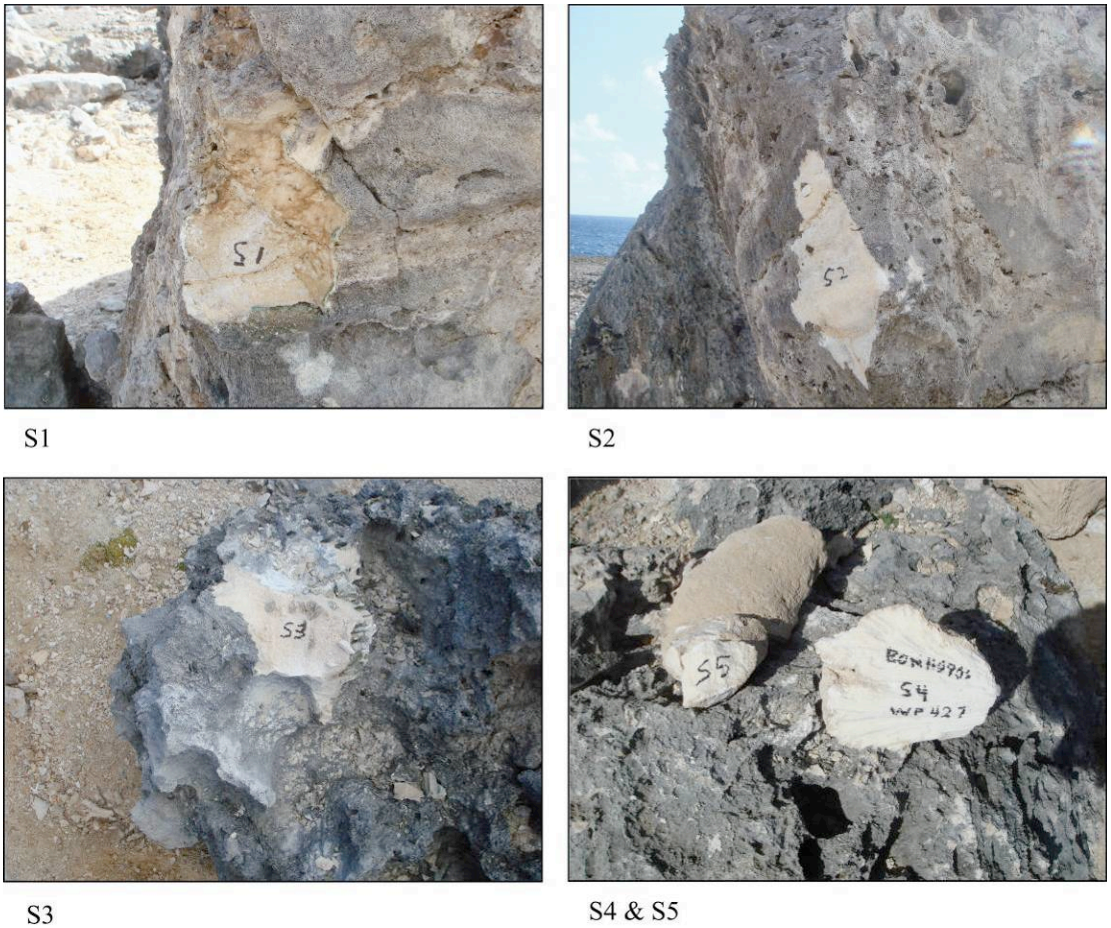


Figure 4. Photographs of limestone boulders (S1, S2, and S3) and corals (S4 and S5) sampled for bulk density measurements.

The distance of a boulder from the shoreline was measured in GIS to compare with platform elevation and boulder weight. The distance of a boulder from the shoreline does not necessarily imply a transport distance as boulders are likely derived from several locations including the shoreline, the nearshore, or outcrops inland of the shoreline. The shoreline was mapped by walking a GPS trackline parallel to shore approximately 30 m inland because the seaward edge of the platform is extremely sharp and corrugated. The trackline was shifted 30 m seaward to approximate the true shoreline position. Each boulder was measured to the nearest point on the adjusted shoreline. The corrected TIN model elevations were used to estimate an elevation in meters above sea level (m asl) for each mapped boulder.

Coordinate positions (latitude/longitude) for kite-camera image control points, topographic profile start and end points, trenches, sediment samples, boulders, and cobble-camera and other digital photos were collected by using Garmin GPSmap 76CS receivers. The unit has a horizontal accuracy of 2-10 m.

Deposit Descriptions

Boka Onima

The bathymetry offshore of Boka Onima rises steeply from 170 m water depth about 720 m from shore, to 60 m deep about 420 m from shore (figs. 5 and 6). A more gently-sloping shelf extends from 420 m to 300 m from shore, rising only 10 m. Depth decreases rapidly between 300 m to 160 m from shore, rising 50 m to about 16 m deep. Rough conditions at the time of survey prevented the vessel from working closer to shore.

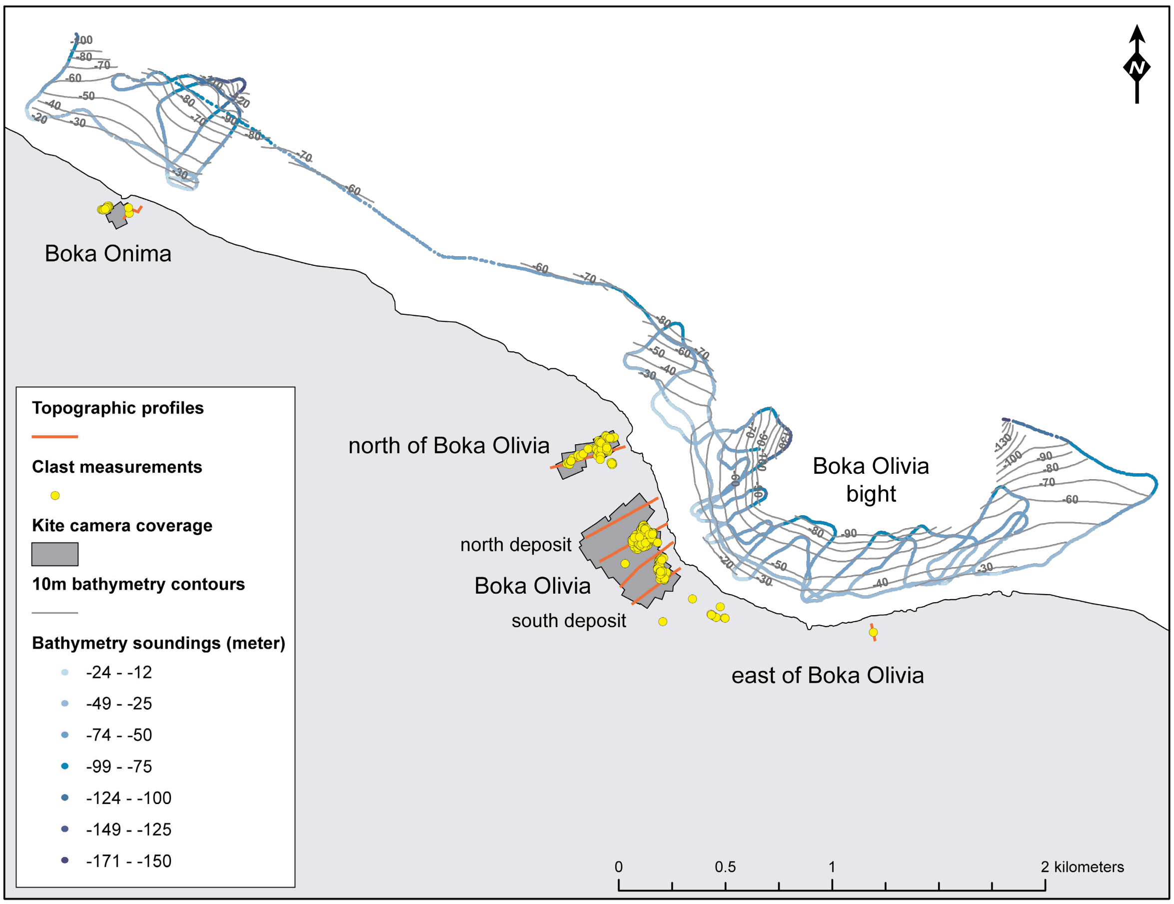


Figure 5. Map showing an overview of the study areas and data collection sites from Boka Onima to Boka Olivia, Bonaire.

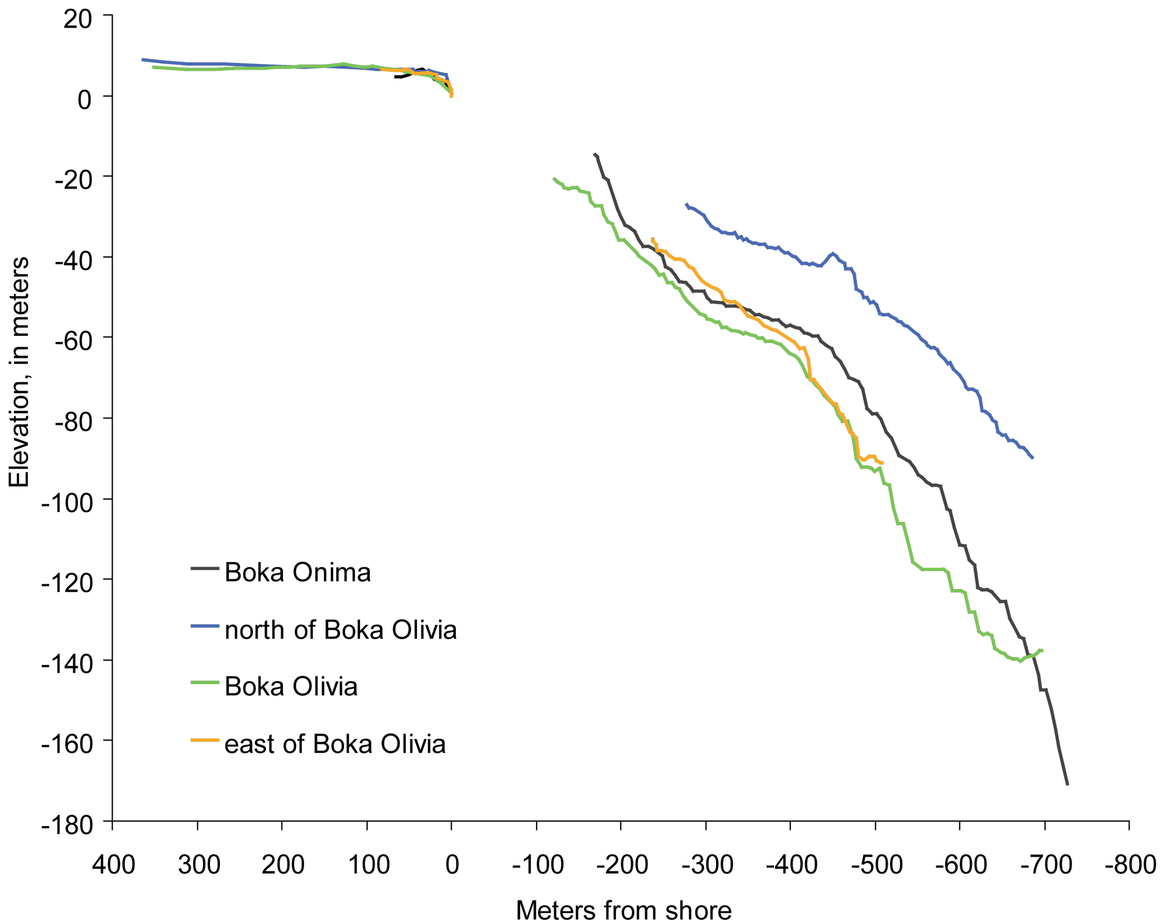


Figure 6. Topography and bathymetry profiles from Boka Onima to one kilometer east of Boka Olivia. Rough wave conditions at the time of survey prevented the vessel from getting closer than 125 meters from the shoreline.

A ridge complex and solitary boulders deposited on the platform were mapped in detail at Boka Onima (fig. 7). An extensive boulder field inland of the ridge complex was not deposited in this location. The deposit had been impacted by mining operations that continued during the 2006 field study (fig. 8). A small reentrant (small-scale indentation) in the coastline about 40 m long and 15 m wide is seaward of a section of the deposit (fig. 9 and table 2). The general shoreline orientation at Boka Onima is 120° (table 3) and the morphology at the shoreline is variable due to erosion caused by persistent wave action. At some locations a wave-cut notch undermines a steep shore cliff, while a few meters away the limestone exposure slopes up steeply to a flat or gently sloping platform about 3.5 to 4 masl.

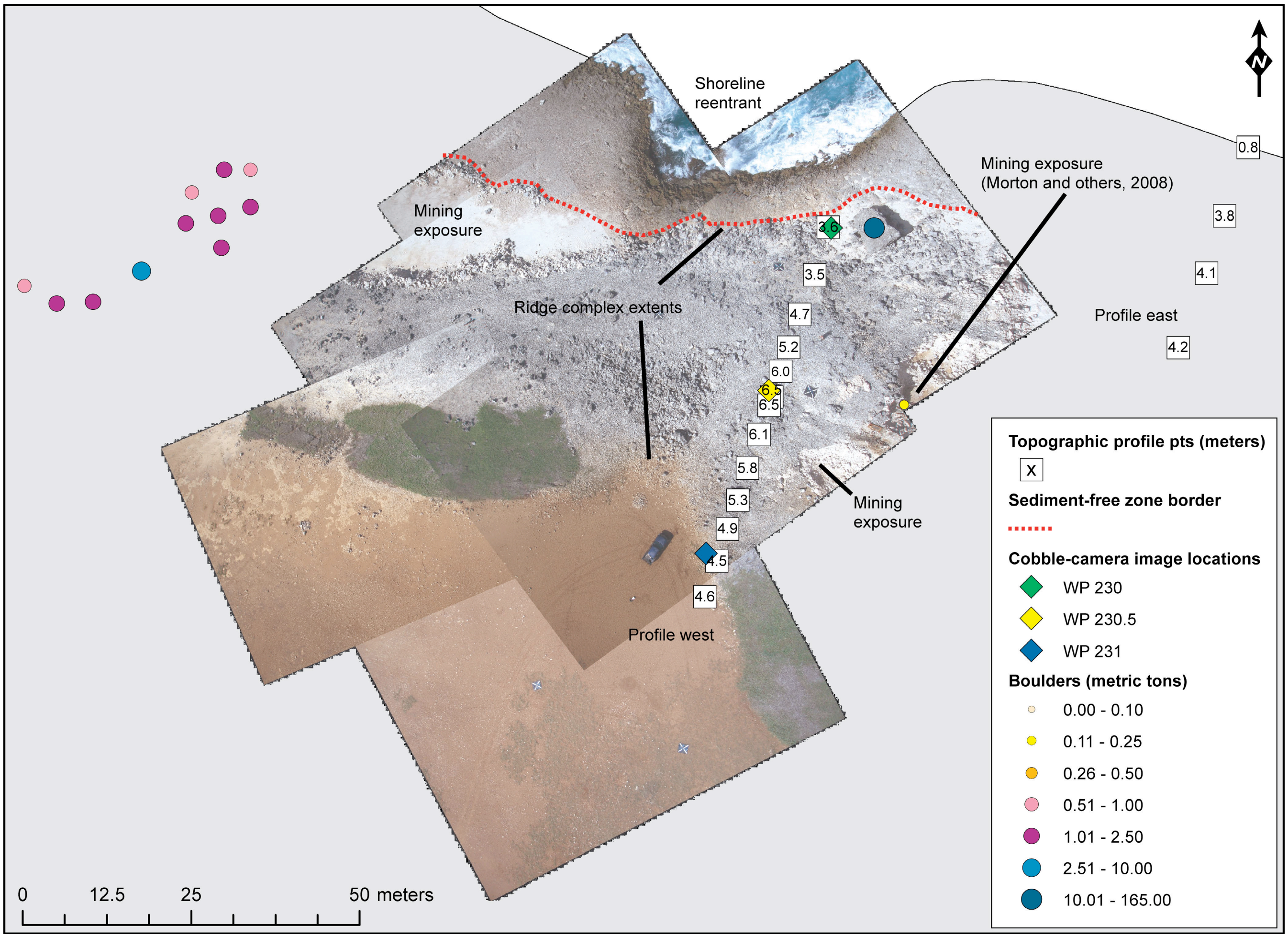


Figure 7. Boka Onima kite-camera mosaic with topographic profile elevations (in meters above sea level), cobble-camera locations and boulder weights in metric tons.

A

B

Figure 8. Photographs showing impacts from (A) ongoing mining operations on the ridge complex at Boka Onima. (B) The gray surface coating caused by microbial endoliths and the underlying natural color of the carbonate clasts is well illustrated.

Figure 9. Photograph showing the shoreline reentrant, limestone surface and karst features developed on the seaward edge of the platform at Boka Onima.

Table 2. Deposit descriptions in the study areas on Bonaire

	Boka Onima	north of Boka Olivia	Boka Olivia north deposit	Boka Olivia south deposit	east of Boka Olivia
Deposit types	ridge complex/ boulder field	boulder field and accumulation/ sand sheet	ridge complex/ boulder field	ridge complex/ boulder field	mined ridge/ boulder field
shoreline indentation (X x Ym)	40x15 (600 m^2)	115x50 (5750 m^2)	60x20 (1200 m^2)	125x20 (2500 m^2)	none
minimum sediment free zone width (m)	20 (5 at reentrant)	80 (35 at reentrant)	70 (50 at reentrant)	60 (46 at reetnrant)	45
seaward platform elevation (m)	3.4	6.1	6.5	5.5	5
ridge crest elevation (m asl)	6.4	7.2 (boulder accumulation)	7.3 and 7.9	7.2	mined
crest height above platform (m)	3.0	1.1 (boulder accumulation)	0.8 and 1.4	1.7	mined
seaward edge (m)	20 (7 at reentrant)	85 (boulder accumulation)	70	55	mined
landward edge (m)	60	250 (sand sheet)	225	120 (truncated by racetrack)	mined
ridge width (m)	44	45 (boulder accumulation)	155	75	mined

Table 3. General shoreline orientations, shoreline orientation categories (for cobbles and boulders), and degrees per category for Boka Onima, north of Boka Olivia, and Boka Olivia, November 2006.

	Boka Onima	north of Boka Olivia and Boka Olivia	Degrees per category
shoreline orientation	120°	160°	
shore normal	20°-40°	60°-80°	20
sub-normal	0°-20°/40°-60°	40°-60°/80°-100°	40
shore parallel	110°-130°	150°-170°	20
sub-parallel	90° -110°/130°-150°	0°-10°/130° -150°/170°-180°	40
others	60°-90°/150°-180°	10°-40°/100°-130°	60

The platform near the shoreline is free of loose sediment (including boulders), presumably swept away by over topping waves. The sediment-free zone is about 20 m wide to the east and west and about 5 m wide at the shoreline reentrant. The seaward edge of the ridge complex and large boulders mark the end of the sediment-free zone. The ridge complex is deposited parallel to the general orientation of the shoreline and does not shift inland at the shoreline reentrant. It is wedge shaped and roughly 45 m wide from seaward to landward edge (fig. 10). The ridge crest is about 33 m from shore at the reentrant and has an elevation of 6.5 m asl, 3 m higher than the underlying platform on the seaward side. Landward of the crest, the ridge elevation decreases over the next 25 m and the ridge complex terminates abruptly in avalanche slopes approximately 60 m inland from the shoreline. Landward of the ridge complex is hard-packed mud with loose and buried pebbles, cobbles and coral fragments, but no boulders (figs. 3 and 11).

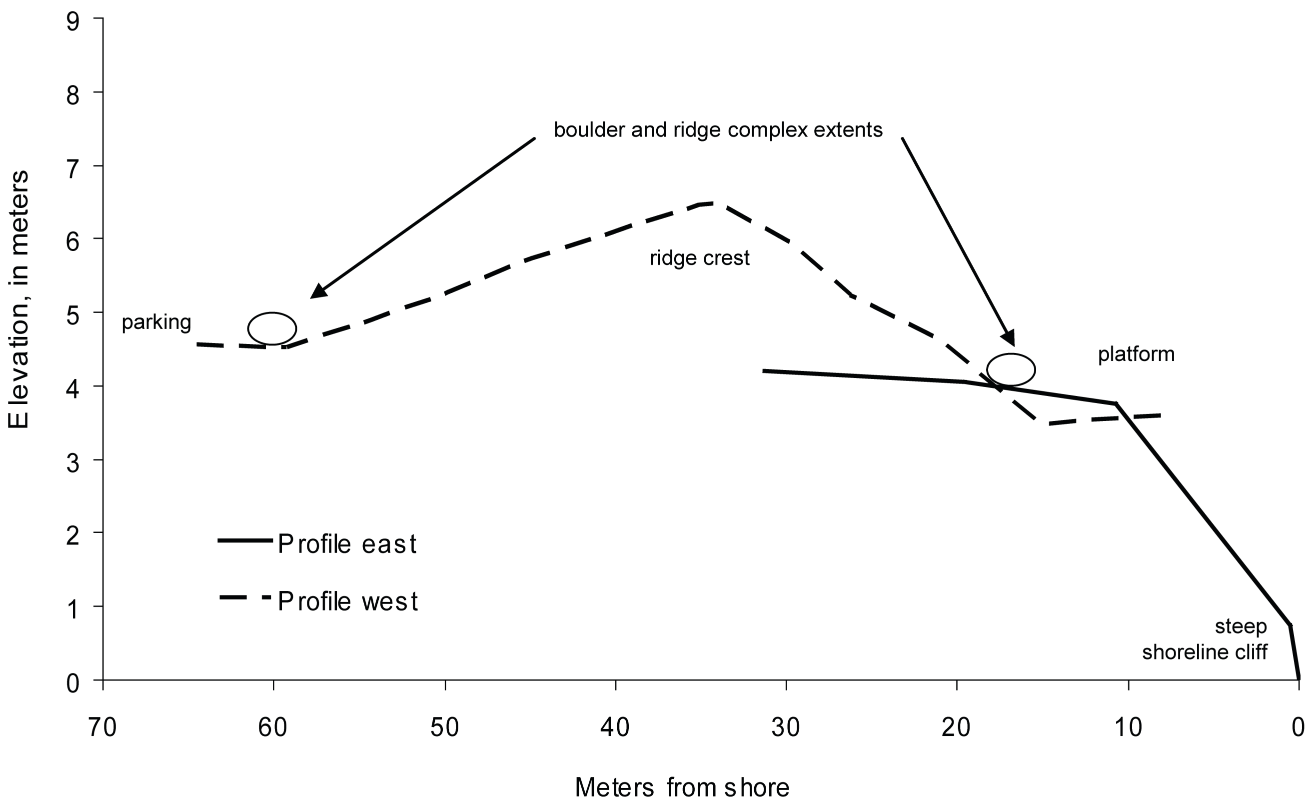


Figure 10. Topographic profiles of the ridge complex at Boka Onima.

Figure 11. Photograph of the landward avalanche face of the ridge complex at Boka Onima and the underlying hard-packed orange brown mud which rests on the older limestone surface.

Cobble-camera images collected from the seaward edge of the ridge, the ridge crest, and the landward edge of the ridge were processed in GIS (figs. 12, 13, and 14). The number of clasts in the images increases with increasing distance inland at Boka Onima; the most dramatic increase occurs between the ridge crest and the landward edge of the ridge about 60 m inland (table 4). The range of clast long-axis lengths is fairly consistent at all three locations, but the mean length decreases sharply landward of the ridge crest. At the seaward edge and the ridge crest, clasts are tightly packed and support one another. They are angular to sub-rounded and no significant amount of sand or mud is present at the surface. Clasts on the landward edge of the ridge are scattered, generally smaller in size and unsupportive of other clasts. The landward edge clasts range from angular to rounded and many are buried in hard-packed mud. There is a slight preference for shore normal and sub-normal long-axis orientations for clasts on the surface of the ridge complex in Boka Onima (fig. 15). At the ridge crest, the preference for shore normal and sub-normal shoreline clast long-axis orientations is strongest. While more clasts on the landward edge of the ridge are oriented normal to shore than parallel to shore, no strong preference for any particular orientation is evident.

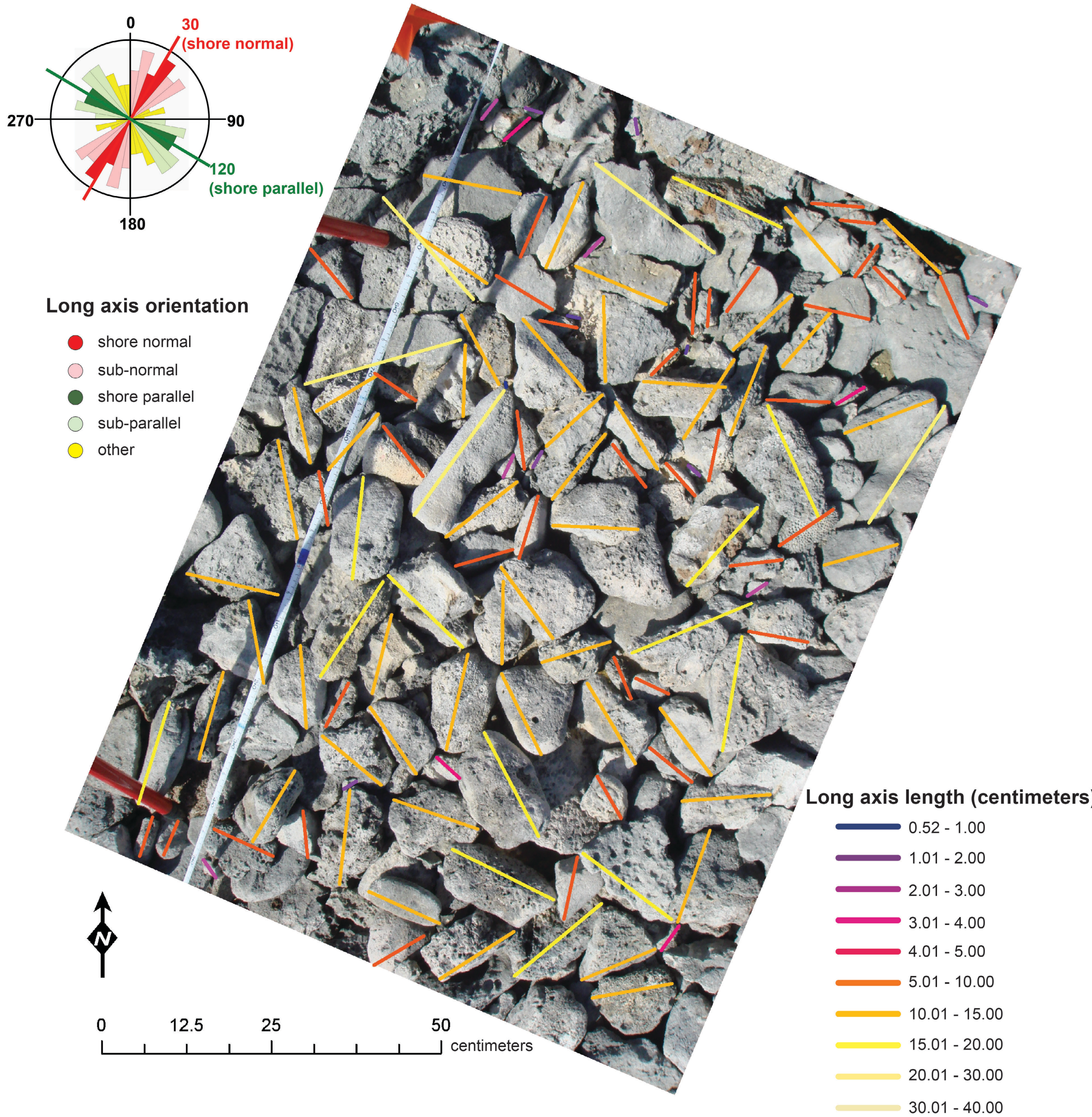


Figure 12. Boka Onima cobble camera image WP 230 taken on the seaward edge of a ridge complex approximately 15 meters from the shoreline. Colored lines in the image indicate long-axis lengths and clast orientations to north. The rose diagram in the upper corner organizes the clast shoreline orientations into the categories listed in table 3.

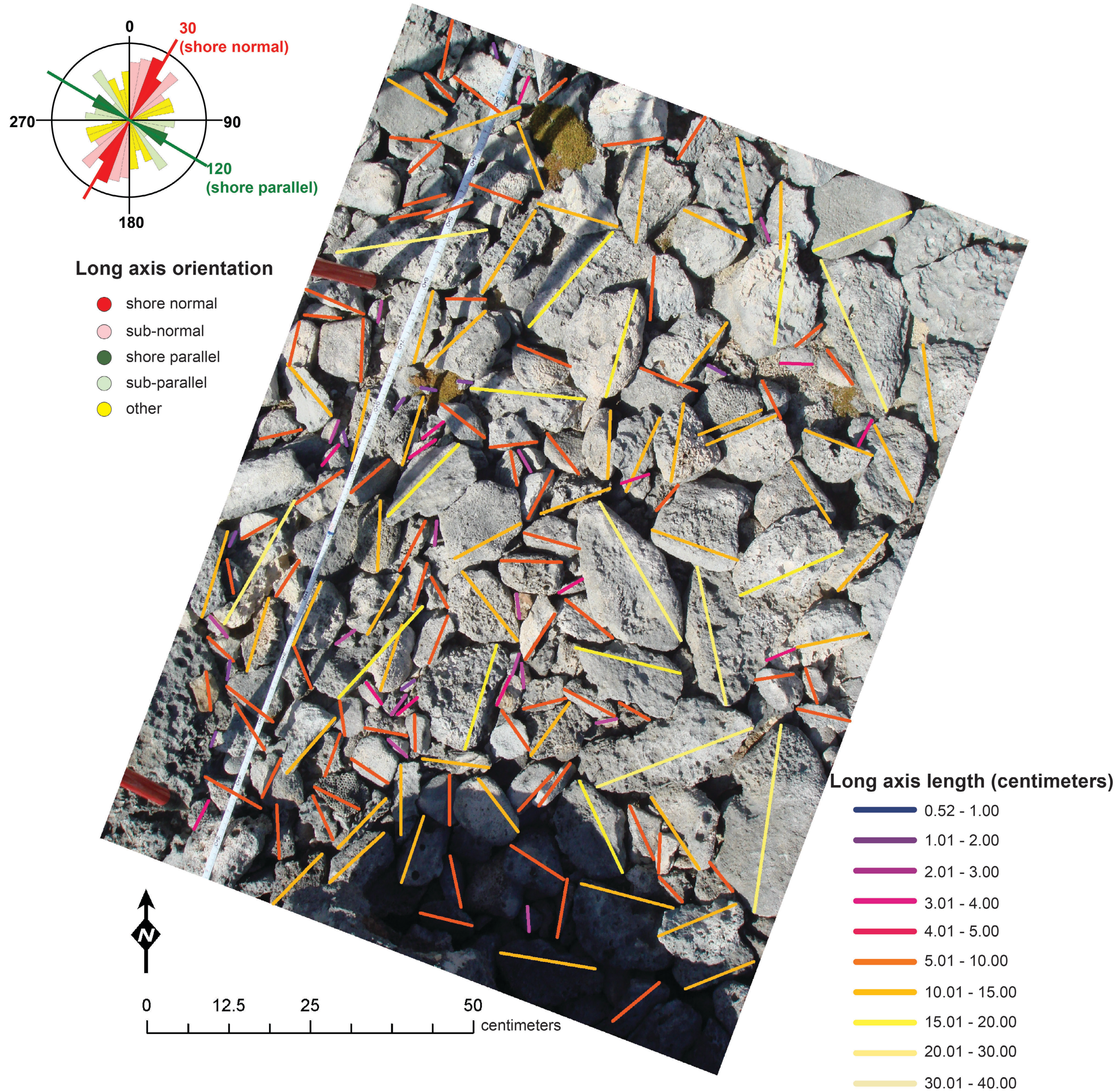


Figure 13. Boka Onima cobble-camera image WP 230.5 taken at the ridge crest approximately 35 meters from the shoreline. Colored lines in the image indicate long-axis lengths and clast orientations to north. The rose diagram in the upper corner organizes the clast shoreline orientations into the categories listed in table 3.

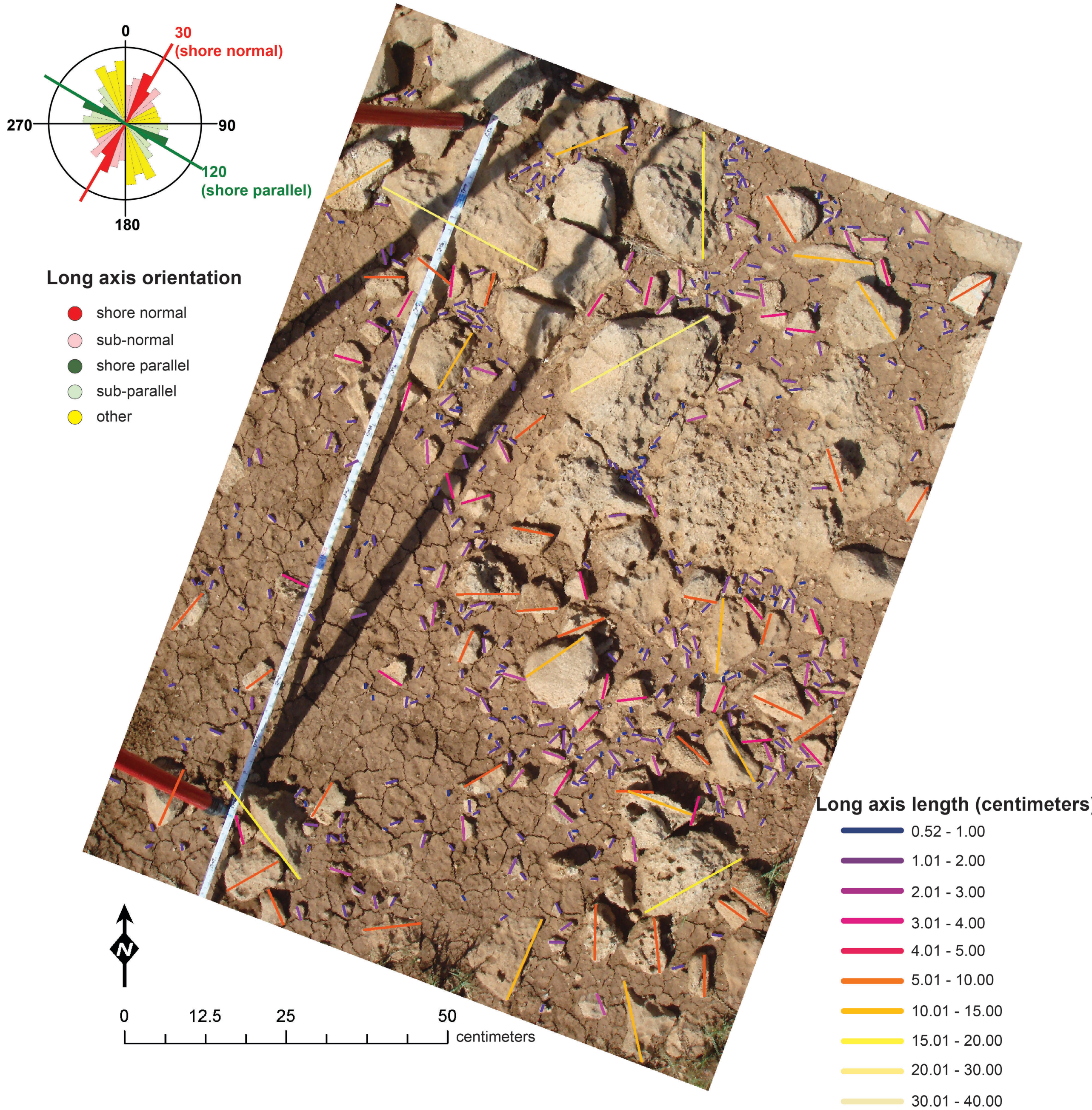


Figure 14. Boka Onima cobble camera image WP 231 taken at the landward edge of the ridge complex approximately 60 meters from the shoreline. Colored lines in the image indicate long-axis lengths and clast orientations to north. The rose diagram in the upper corner organizes the clast shoreline orientations into the categories listed in table 3.

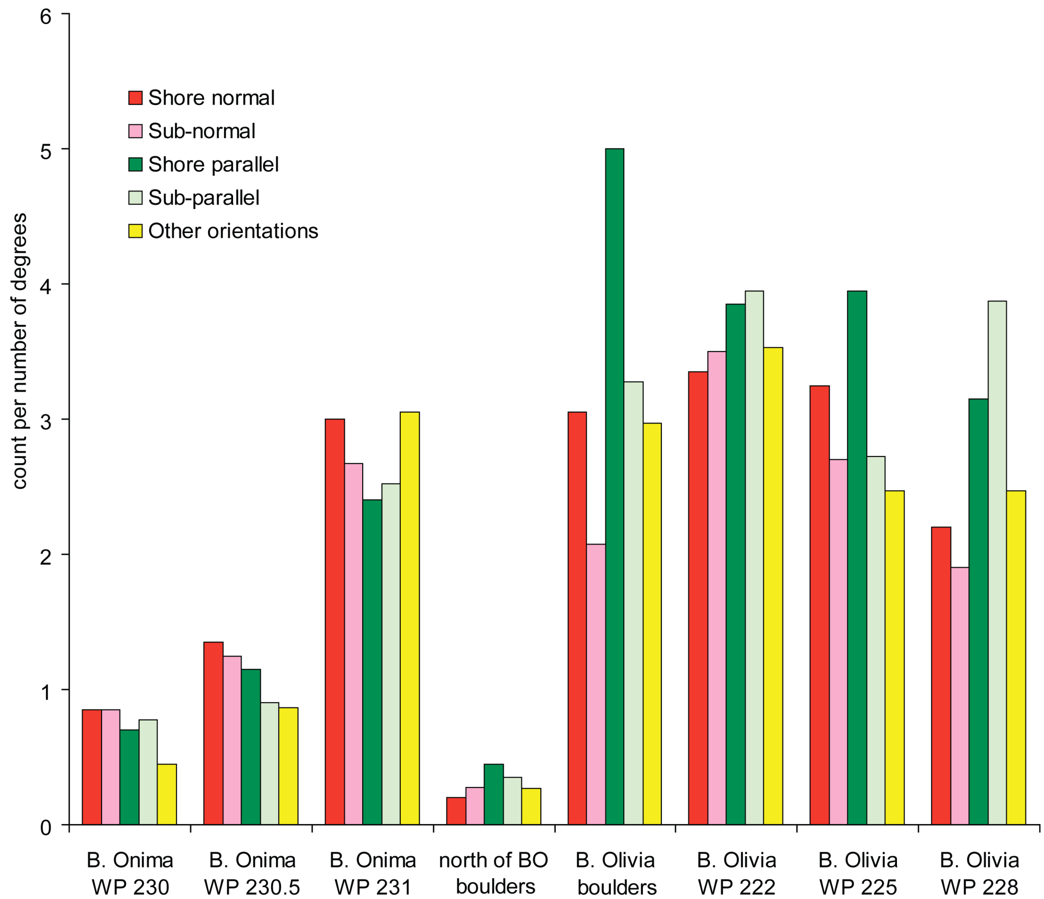


Figure 15. Clast long-axis orientations are normalized by the number of degrees per category for cobble-camera images at Boka Onima, boulders at north of Boka Olivia, and cobble-camera images and boulders at Boka Olivia. See table 3 for details regarding shoreline orientation categories.

Table 4. Clast long-axis length statistics of cobble-camera images for Boka Onima and Boka Olivia, November 2006.

Location	Way Point	Comments	meters from shore	Count	Maximum (centimeter)	Minimum (centimeter)	Mean (centimeter)	Standard Deviation
Boka Onima	230	seaward edge	10	123	23.9	0.7	10.5	4.8
Boka Onima	230.5	ridge crest	35	182	28.9	2	9	4.9
Boka Onima	231	landward edge	60	507	27.2	0.5	2.5	2.9
Boka Olivia	222	seaward of crest	75	654	40.1	0.5	1.9	2.6
Boka Olivia	225	ridge crest	120	510	40.3	0.5	3.4	3.9
Boka Olivia	228	landward of crest	190	486	18.2	0.5	2.7	2.8

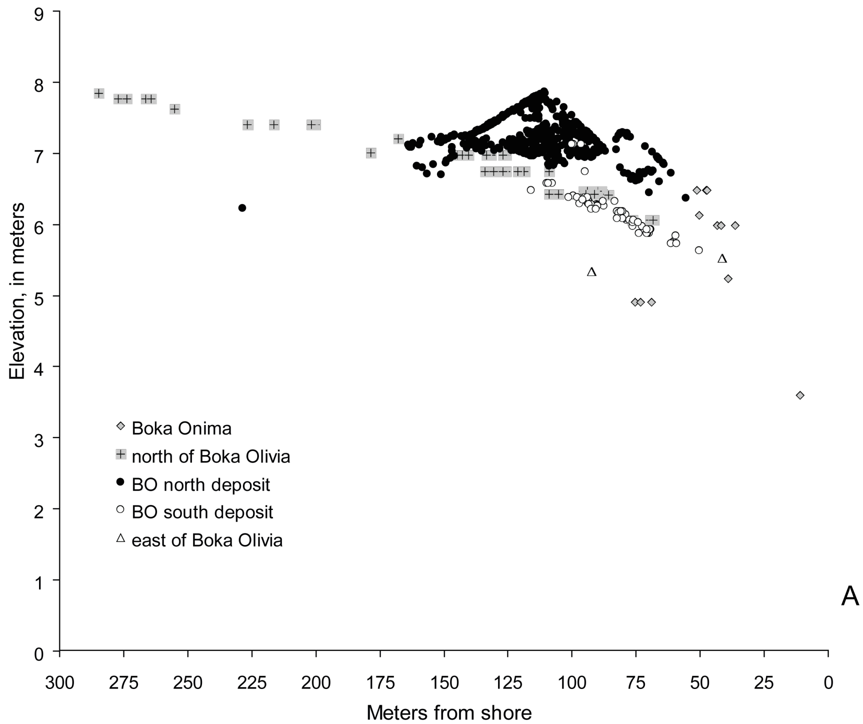
Many boulders have been deposited on the exposed platform and on top of the ridge complex surface at Boka Onima. Boulders are not deposited landward of the ridge complex. The largest boulder weighs over 100 metric tons and rests on the exposed platform at the seaward edge of the ridge complex 3.6 m asl (table 5 and figs. 16 and 17). The long-axis of the boulder is oriented parallel to shore. Boulders were measured as far as 75 m inland and 6.5 m asl.

Table 5. Statistics for 636 clasts measured from Boka Onima to Boka Olivia. Size category from Blair and McPherson (1999).

Boka Onima (13 boulders)	Minimum	Maximum	Average	STD DEV
A-axis (centimeter)	75	670	177	144
B-axis (centimeter)	60	380	119	78
C-axis (centimeter)	15	180	57	38
Size category	medium boulder	very coarse boulder	coarse boulder	
Volume (cubic meter)	0.07	45.83	4.13	12.04
Weight (metric tons)	0.15	102.65	9.26	26.97
Distance from shore (meter)	11	60	50	17
Elevation (meters above sea level)	3.6	6.5	5.6	0.8
north of Boka Olivia (58 boulders)	**Minimum**	**Maximum**	**Average**	**STD DEV**
A-axis (centimeter)	45	750	175	104
B-axis (centimeter)	30	270	107	53
C-axis (centimeter)	10	180	61	36
Size category	fine boulder	very coarse boulder	coarse boulder	
Volume (cubic meter)	0.01	22.43	1.94	3.69
Weight (metric tons)	0.03	50.23	4.36	8.28
Distance from shore (meter)	68	285	137	59
Elevation (meters above sea level)	6.1	7.8	6.3	0.49
Boka Olivia north deposit (486 boulders)	**Minimum**	**Maximum**	**Average**	**STD DEV**
A-axis (centimeter)	25	800	114	81
B-axis (centimeter)	15	440	79	54
C-axis (centimeter)	10	280	45	34
Size category	coarse cobble	fine block	medium boulder	
Volume (cubic meter)	0.01	73.60	1.27	5.69
Weight (metric tons)	0.01	164.86	2.86	12.75
Distance from shore (meter)	56	228	113	21
Elevation (meters above sea level)	6.2	7.9	7.2	0.3
Boka Olivia south deposit (67 boulders)	**Minimum**	**Maximum**	**Average**	**STD DEV**
A-axis (centimeter)	70	410	158	63
B-axis (centimeter)	55	280	110	48
C-axis (centimeter)	20	180	57	26
Size category	fine boulder	very coarse boulder	coarse boulder	
Volume (cubic meter)	0.18	17.22	1.49	2.88
Weight (metric tons)	0.40	38.57	3.35	6.45
Distance from shore (meter)	50	116	85	13
Elevation (meters above sea level)	5.6	7.1	6.2	0.3

east of Boka Olivia (12 boulders)	Minimum	Maximum	Average	STD DEV
A-axis (centimeter)	140	350	232	62
B-axis (centimeter)	85	270	160	46
C-axis (centimeter)	30	185	86	50
Size category	medium boulder	very coarse boulder	coarse boulder	
Volume (cubic meter)	0.88	9.14	3.59	2.93
Weight (metric tons)	1.98	20.47	8.04	6.57
Distance from shore (meter)	33	93	70	22
Elevation (meters above sea level)	5.5	5.5	5.5	0

Figure 16. Photograph of the largest boulder measured at Boka Onima (view to the north).



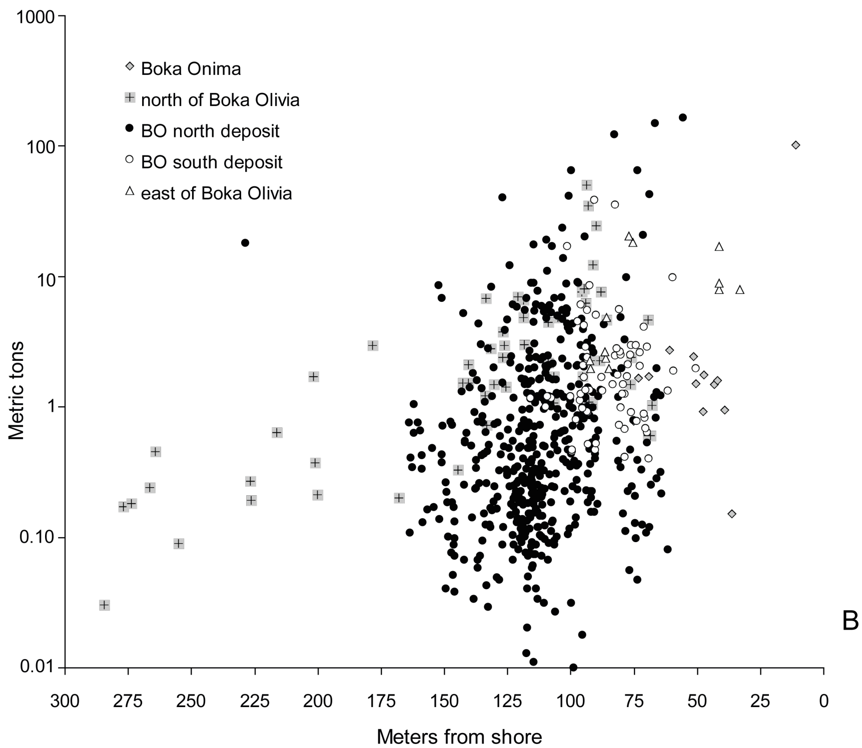


Figure 17. The top graph (A) plots boulder elevation above sea level compared to the distance from shore. The bottom graph (B) plots boulder weight in metric tons compared to the distance from shore for clasts measured from Boka Onima to Boka Olivia.

North of Boka Olivia

Approximately 2.5 km southeast of Boka Onima the shoreline curves to a more east facing direction (160°) and forms the western end of a small coastal bight (table 3 and fig. 5). A deposit was mapped and analyzed at this location informally called north of Boka Olivia.

The bathymetry offshore north of Boka Olivia does not slope as steeply and is roughly 20-30 m shallower than Boka Onima at similar distances offshore (fig. 6). From roughly 680 m offshore, the bathymetry rises from 90 m water depth to 50 m water depth over the span of 200 m. At about 480 m from shore a unique bathymetric high roughly 50-60 m wide and about 5-10 m higher than the seafloor on either the landward or seaward side. Landward of the bathymetric high, about 420 m from shore, the seafloor gradually rises from 45 m deep to 28 m deep 275 m from the shoreline. The bathymetry contours outline a 30 m deep shelf extending over 400 m offshore of the deposit north of Boka Olivia.

The shoreline seaward of the deposit north of Boka Olivia has a reentrant 115 m long and 50 m wide. The seaward edge of the deposit curves inland at the shoreline reentrant (table 2 and fig. 18). A topographic profile collected on the northern end of the reentrant starts with a steep eroded cliff that quickly ascends to a limestone shore platform that is pitted with rounded-bottom karst pools about 5-6 m asl (figs. 19 and 20). The cliff edge and shore platform are about 2 m higher above sea level at north of Boka Olivia than at Boka Onima.

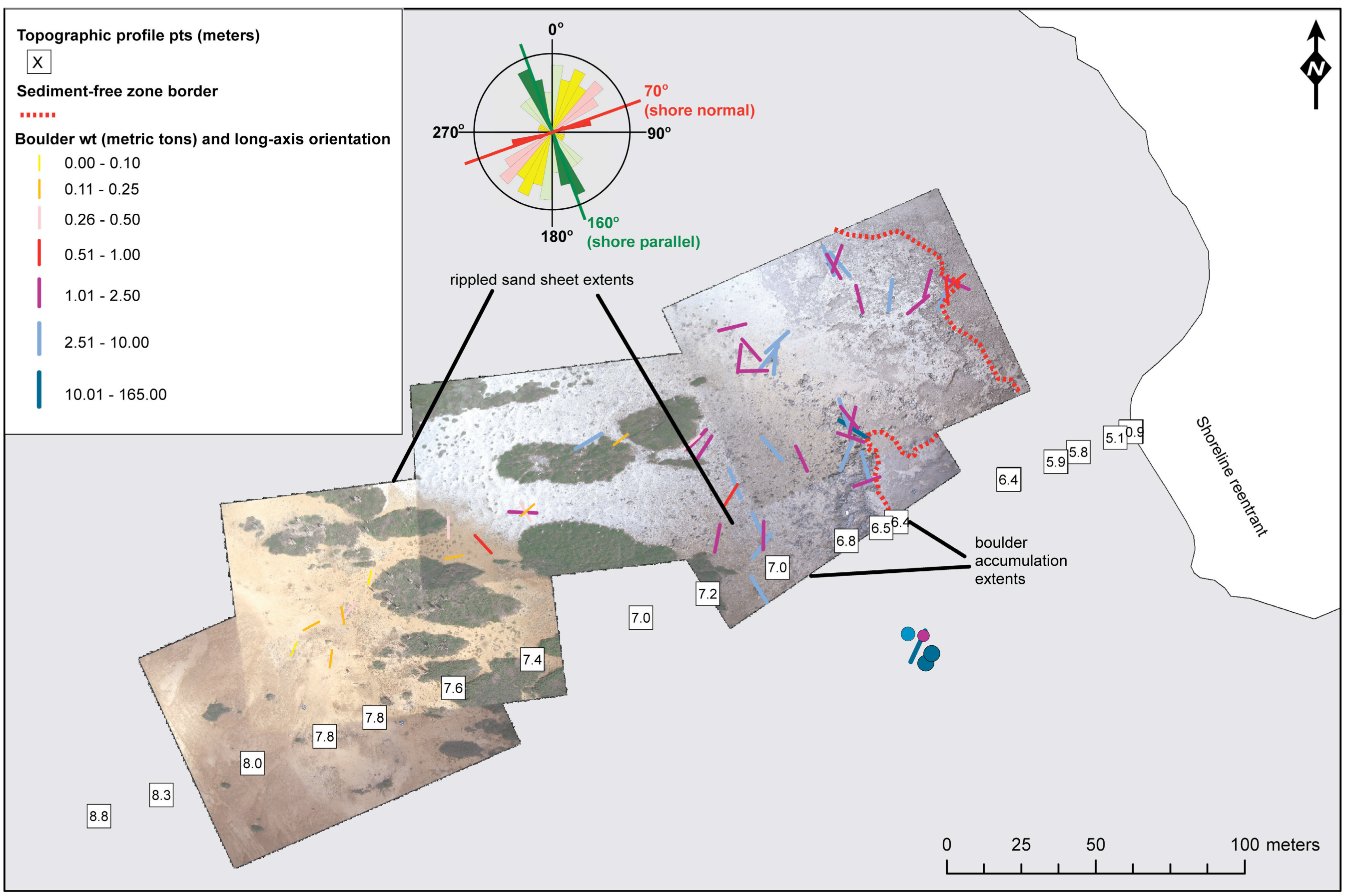


Figure 18. Kite-camera mosaic north of Boka Olivia, including topographic profile elevations (in meters above sea level), and boulder weights in metric tons.

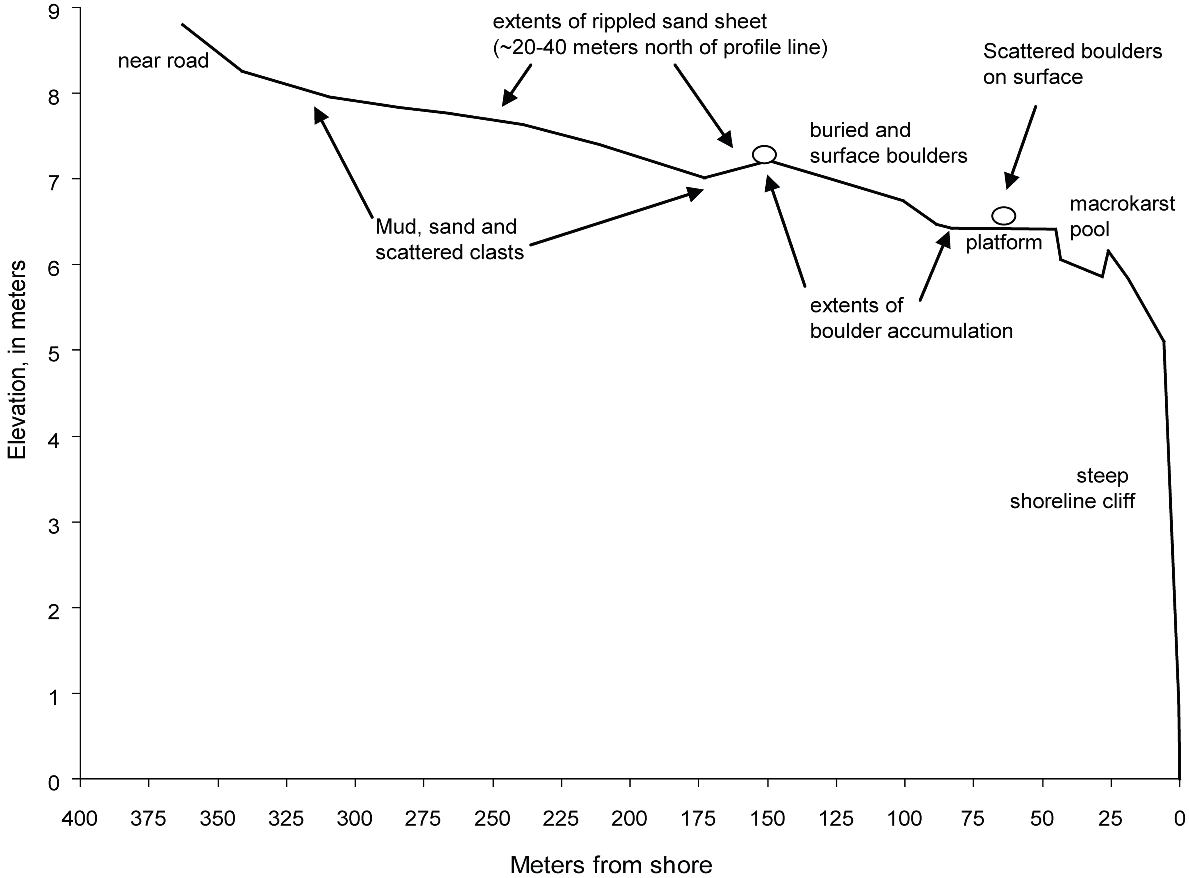


Figure 19. Topographic profile and associated features north of Boka Olivia.

A

B

Figure 20. Photographs of the shoreline showing (A) the shoreline and wave splash-zone karst features and (B) a rounded-bottom karst pool north of Boka Olivia.

The wave swept sediment-free zone terminates about 80 m from the shoreline where scattered boulders are deposited on the surface of the platform. The sediment-free zone also includes areas where the platform surface has been excavated by wave processes. One isolated boulder a few 10s of meters north of the concentrated boulder deposit has been overturned and transported in a landward direction, revealing a white limestone patch on the dark grey platform where the boulder was formerly deposited (fig. 21). Approximately 85 m from shore is a dense concentration of boulders that mark the seaward margin of an accumulation of boulders mixed with sand. Ridge-like characteristics of the deposits north of Boka Olivia are subdued compared to those at Boka Onima and the south deposit at Boka Olivia. Many boulders in the deposit are slab shaped and imbricated against one another (fig. 22A) and some are deposited with the long-axis vertically oriented (fig. 22B). Many of the boulder slabs appear to have been excavated from the platform surface and exhibit surficial or internal features that serve as tracers to their original positions and distances of transport. For example, the degree and style of weathering of the boulder faces (fig. 22A) and the boulder compositions match well with seaward zones of karstification and the limestone facies (breccia, finger corals) on the platform. The same surficial features also provide a basis for determining the original *in situ* up direction (fig. 22B) before the slab was transported.

Figure 21. Photograph of a boulder north of Boka Olivia that has been overturned and transported landward revealing a white exposure in the platform and the white bottom (now top) of the boulder not yet colonized and turned gray by microbial endoliths.

A

B

Figure 22. Photographs of boulder accumulations north of Boka Olivia showing (A) imbricated boulders and (B) a boulder deposited with the long-axis vertically oriented. Both views are seaward.

The concentrated boulder accumulation north of Boka Olivia, which is approximately 45 m wide and about 1 m asl higher than the seaward platform, does not have a well-defined peak or landward avalanche faces. The accumulation is not tightly packed like the ridge complex at Boka Onima and is built from larger clasts mostly in the boulder size category. The position and low accumulation of imbricated boulders north of Boka Olivia may indicate it is in the initial stages of ridge/ridge-complex development.

Axis measurements were made for 58 boulders on the platform surface, in the boulder accumulation and scattered landward of the accumulation. Measured boulders north of Boka Olivia weigh up to 50 metric tons and are deposited a maximum of 285 m from the shoreline at a peak elevation of 7.8 m asl (table 5 and figs. 17 and 18). Of the boulders measured north of Boka Olivia, long-axis orientations have a slight preference for shore normal or sub-normal shoreline orientations (table 3 and figs. 15 and 18).

Sand deposited on the landward side of the boulder accumulation has buried some boulders. Of the boulders measured, 36% (21) are partially buried in sand and 64% (37) are on the limestone or sand deposit surface. Scattered boulders and cobbles are mixed with a sheet-like rippled sand deposit that begins about 150 m from the shoreline and extends to about approximately 250 m landward (figs. 18 and 23). Ripple features in the sand sheet are parallel to shore and have wave lengths up to 1.5 m. The white marine sand is distinctly different in color and texture than the underlying hard-packed orange brown terrestrial sandy mud.

Figure 23. Photograph of the sand sheet with ripple features about 1.5 meters in wave length north of Boka Olivia.

Boka Olivia

The deposits studied at Boka Olivia are approximately 3 km southeast of Boka Onima and 0.5 km south of the deposit north of Boka Olivia on the western end of a small coastal bight (fig. 5). The bathymetry survey offshore of Boka Olivia covers about 1.5 square kilometers (km^2). Approximately 725 m offshore of Boka Olivia the water is 140 m deep (fig. 6). The seafloor rises in a series of steps, the widest (40 m) at about 118 m deep and another about 90 m deep that is about 30 m wide. A gently sloping shelf has developed 300-400 m offshore and is 55-65 m deep. Closer to the shore the shelf depths decrease to approximately 20 m about 120 m from the shoreline.

The shoreline at Boka Olivia is oriented 160°, the same direction as the shoreline north of Boka Olivia (table 3). Two adjacent deposits referred to as the north and south deposits were studied in Boka

Olivia and are covered by the same kite-camera mosaic (fig. 24). Seaward of both deposits are two reentrants in the coastline similar to the ones at Boka Onima and north of Boka Olivia (table 2). The reentrant seaward of the north deposit is about 60 m wide and extends 20 m landward. At the south deposit the reentrant is approximately 125 m wide and extends 20 m inland. Between the reentrants a slight promontory about 50 m wide that matches the general curve of the shoreline north and south of the reentrants. The seaward edge of the north deposit does not appear to be influenced by the seaward reentrant, while the south deposit arcs inland landward of the larger reentrant. Inland of the road (370 m from the shore) behind the deposits is a paleo-seacliff 3-8 m higher than the present (2006) platform (fig. 25A). Landward of the south deposit is a sail car racetrack that may have altered the deposit (fig. 25B). As a result, only boulders on the seaward side of the track were measured in the south deposit.

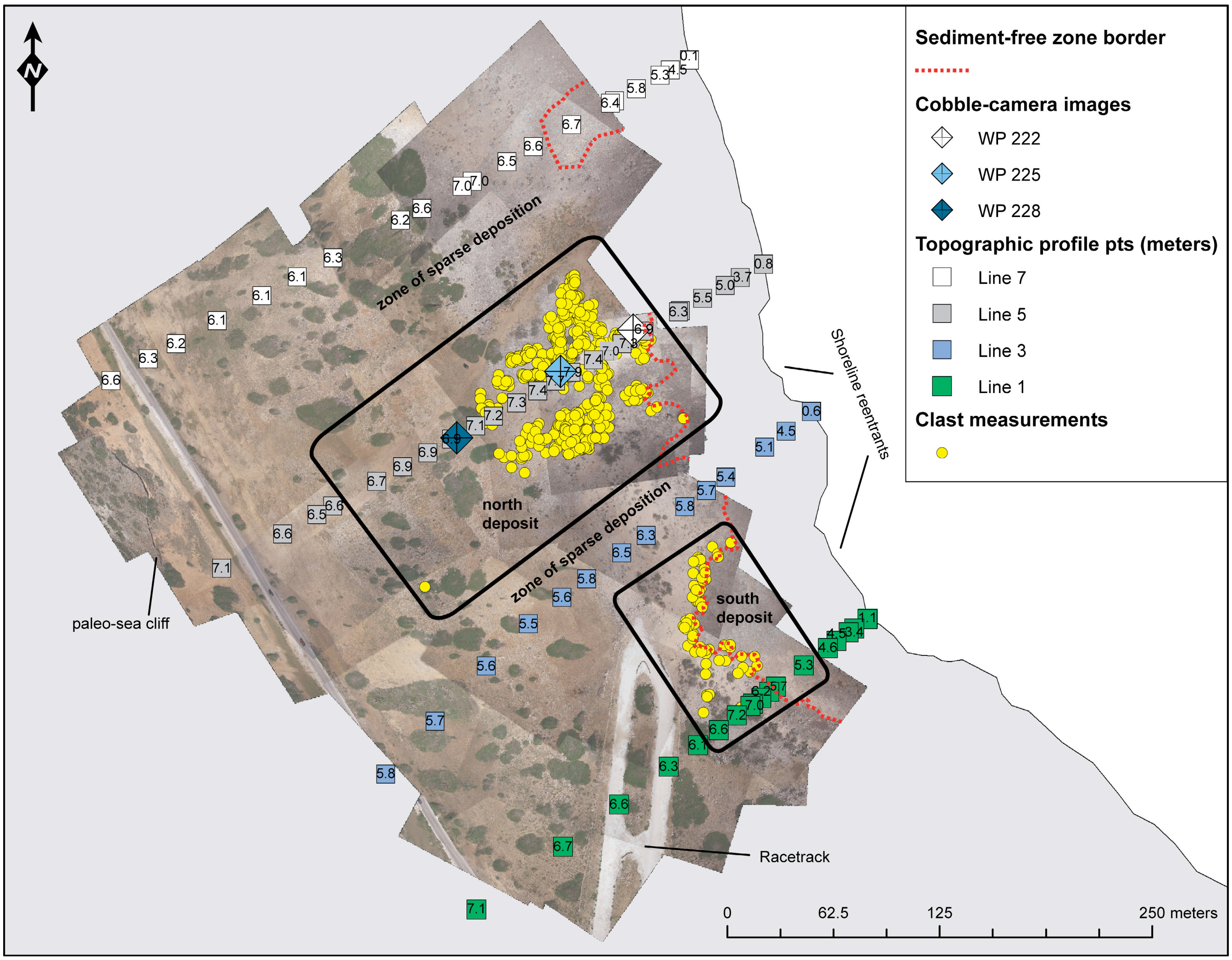


Figure 24. Boka Olivia kite-camera mosaic, topographic profiles (in meters above sea level), cobble-camera image locations, and clast measurement locations in the north and south deposits.

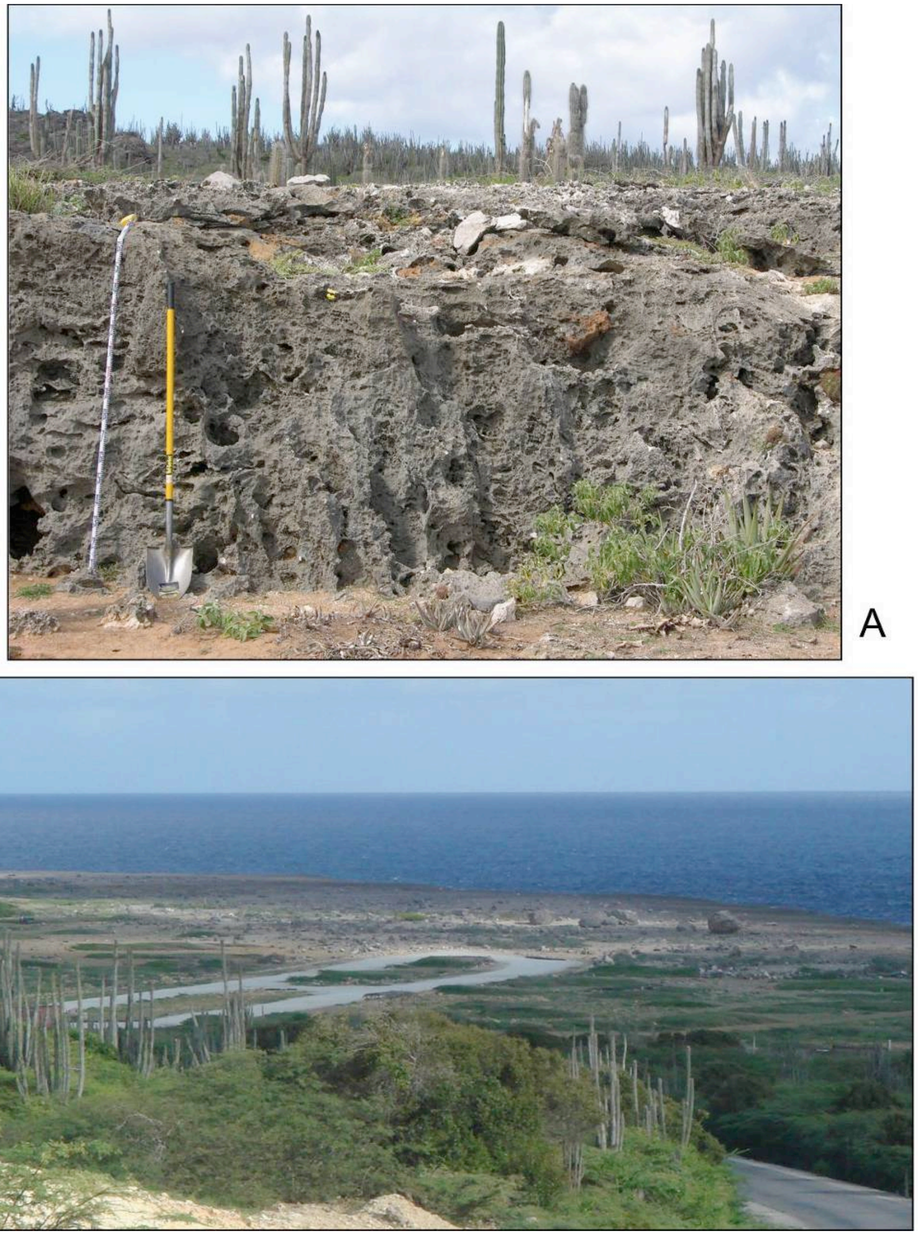

A
B

Figure 25. Photographs showing (A) a paleo-seacliff exposed approximately 375 meters inland from the shoreline that ranges from about 3 to 8 meters above sea level higher than the present platform and (B) a sail car racetrack built near the south deposit.

The topography at Boka Olivia was measured with four profiles spaced from 100 m to 120 m apart from north to south. Line 7 runs approximately 100 m north of the north deposit and starts at the waters edge of a non-indented section of shoreline. (figs. 24, 26 and 27A). Along Line 7 a shoreline cliff rises steeply to approximately 6 m asl and then levels out to a flat to gently-sloping limestone platform within 20-30 m from the shoreline. The surface of the platform is irregular and pitted with microkarst solution cavities. A scarp about 0.5 m in relief is present approximately 50 m inland and 6 m asl. Similar to Boka Onima and north of Boka Olivia, the seaward margin of the platform near the shoreline is swept clean of any debris, including sand and boulder deposits. The sediment-free zone terminates with scattered boulders deposited on top of the limestone platform surface 60 m inland. The seaward edge of a poorly developed low-relief sand and boulder ridge sits approximately 120 m inland. The ridge crests at 7 m asl, just 0.5 m higher than the seaward platform elevation. The sandy portion of the ridge terminates about 175 m inland while scattered boulders persist to about 230 m inland. Hard-packed mud and scattered pebbles and cobbles are noted along the rest of the profile that ends near the road.

A

B

Figure 26. Photographs of (A) a wave-cut notch and (B) a flat to gently sloping limestone terrace and phytokarst development at Boka Olivia.

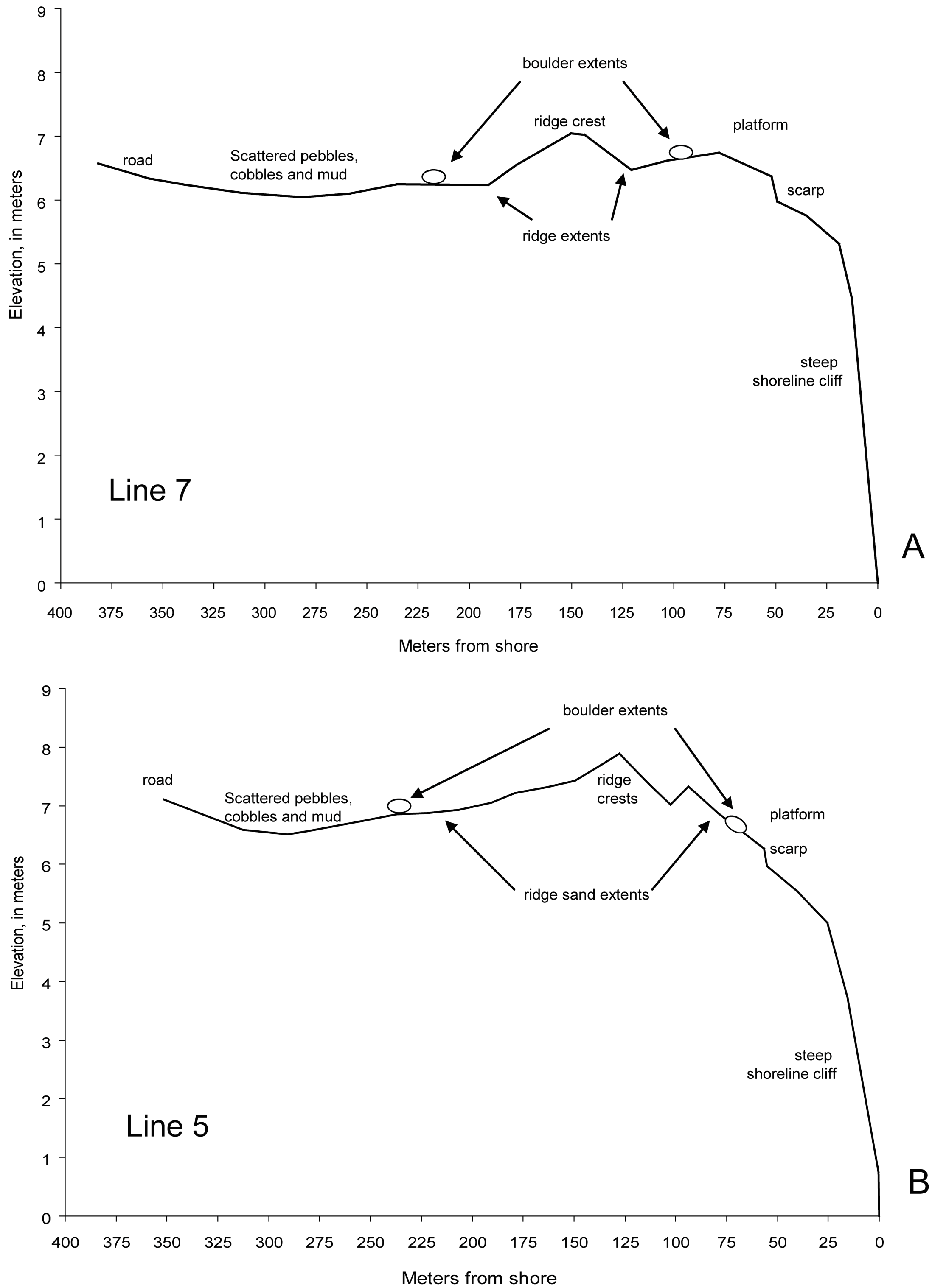


Figure 27. Topographic profile at (A) Line 7 100 meters north of the north deposit and (B) Line 5 that runs through the middle of north deposit at Boka Olivia.

Profile Line 5 runs down the center of the north deposit (figs. 24 and 27B). As a result, other data sets were collected along this profile including trenches, sediment samples and cobble-camera images. The shoreline has variable morphology either in the form of marine notches or steeply ascending cliffs. The shore cliff is ~ 5 m asl and levels out to a flat to gently sloping limestone platform. The surface of the platform is irregular and corrugated with microkarst solution cavities. A similar scarp about 0.5 m high is present 50 m inland and 6 m asl. The sediment-free zone is roughly 70 m inland where large boulders have been placed on the platform surface. At about the same distance inland a poly-modal mixture of sand, pebbles, cobbles and scattered boulders have formed a low ridge complex with two crests. The first crest reaches a height of 7.3 m asl 78 m inland and the second reaches a height of 7.9 m asl 110 m inland. The second crest is about 1 m asl higher than the ridges at Boka Onima and north of Boka Olivia. The landward limit of the sandy part of the ridge complex is about 210 m inland from the shore, while the landward extent of the main boulder concentration is about 170 m. Some scattered boulders were measured farther inland, the farthest at 230 m from shore and about 6.2 m asl. It is unknown whether this boulder was deposited by an overwash event or some other process.

Six trenches were excavated along Line 5 to estimate the thickness of the deposit overlying the limestone platform (table 6 and figs. 28 and 29). The trenches were excavated between 80 and 125 m from the waters edge in the densest depositional zone. Three of the trenches penetrated to the platform and were used to estimate the deposit thickness along the profile. Three trenches did not reach the platform due to a lack of space and sediment collapsing into the trench. The thickest deposit measurements were recorded at trenches H5 and H6. Both trenches were excavated to 65 cm, however neither penetrated to the underlying platform. The locations and depths of the trenches suggest that the deposit overlies a shallow scarp at least 1m high (fig. 29). It is possible that the trenches were excavated into microkarst cavities, leading to an over estimation of the depth of the overall platform elevation.

The ridge complex at Boka Olivia is composed of sand and isolated clasts ranging from pebble to boulder. There is little evidence of stratification, bounding surfaces, or imbricated clasts found in the trench exposures. Twenty-seven sediment samples were collected at vertical intervals in five of six trenches (all but trench H4) to analyze grain-size trends. Figures 30 and 31 display vertical grain-size statistics and percent composition of sediment samples within each trench in relation to the profile cross-section of the deposit.

Table 6. Trenches characteristics along Line 5 at the north deposit at Boka Olivia

Trench	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**
meters from shoreline	125	110	103	100	90	80
trench depth (centimeters)	22	36	35	65	65	55
elevation at top of trench (meters)	7.55	7.90	7.62	7.5	7.18	7.25
elevation at bottom of trench (meters)	7.33	7.54	7.27	6.85	6.53	6.7
reached platform	yes	yes	no	no	no	yes
sediment samples	7	4	0	4	6	5

H2

H3

H7

Figure 28. Photographs of three of six trenches excavated in Boka Olivia.

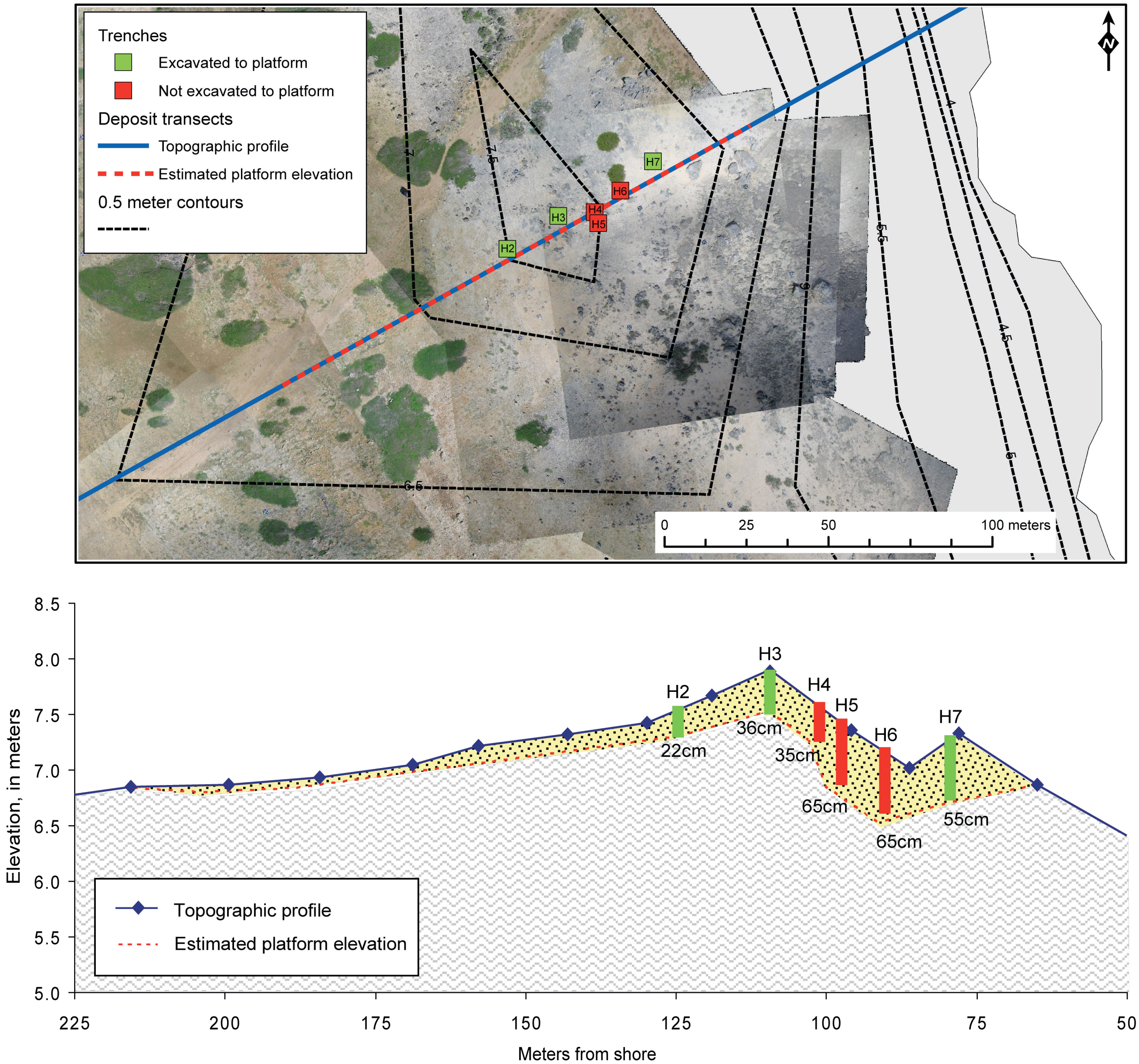


Figure 29. Kite-camera mosaic and diagrammatic cross-section showing the location of six trenches along Line 5. Trenches shown in green were excavated until reaching the platform, red trenches did not reach the platform. The depth of each trench is noted in centimeters (cm). The seaward and landward limits of the deposit were determined by the exposure of the underlying platform.

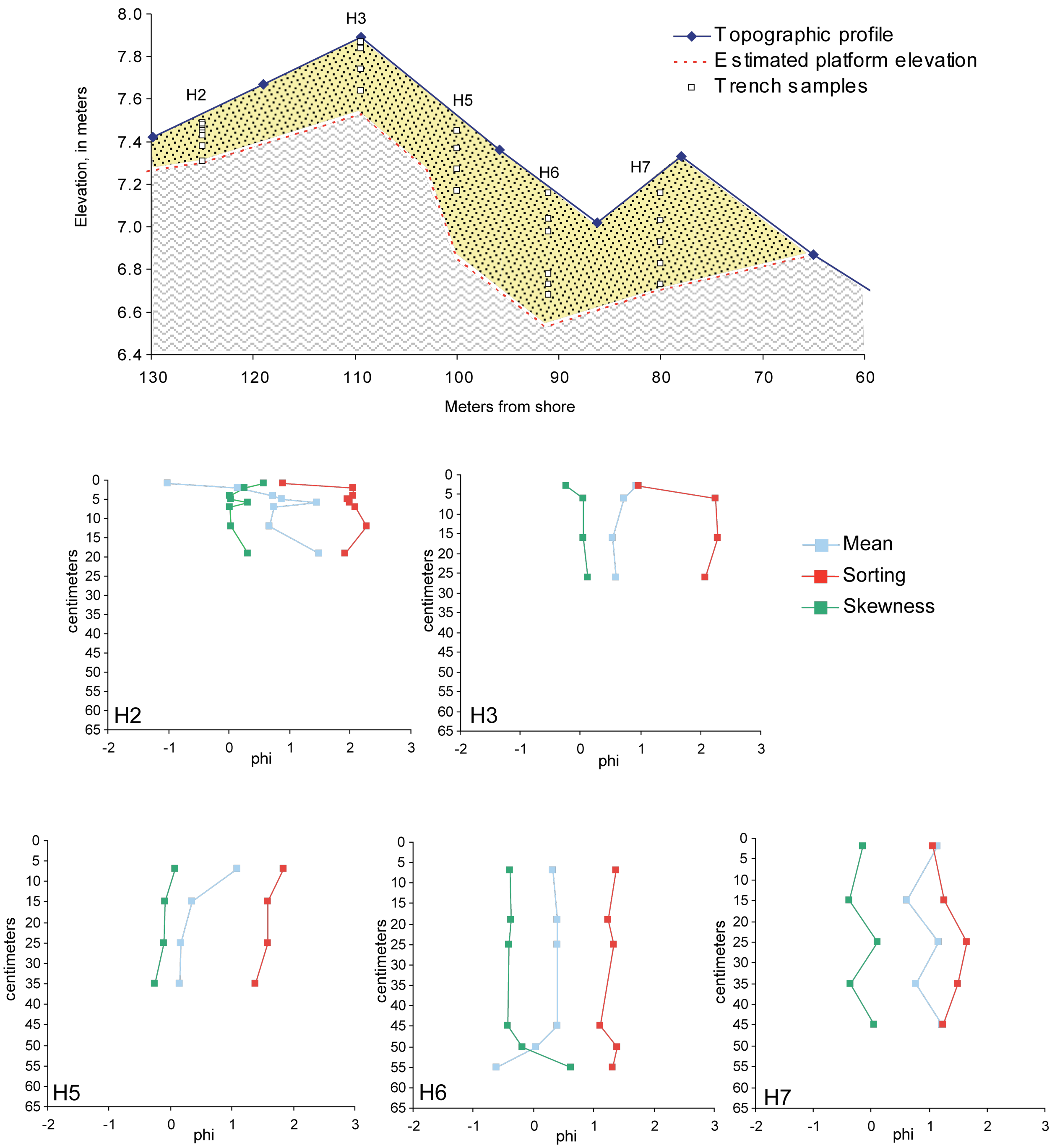


Figure 30. Plots showing mean grain-size, sorting, and skewness phi values are displayed for each sediment sample collected in trenches along Line 5 at Boka Olivia. Zero equals the surface of the deposit.

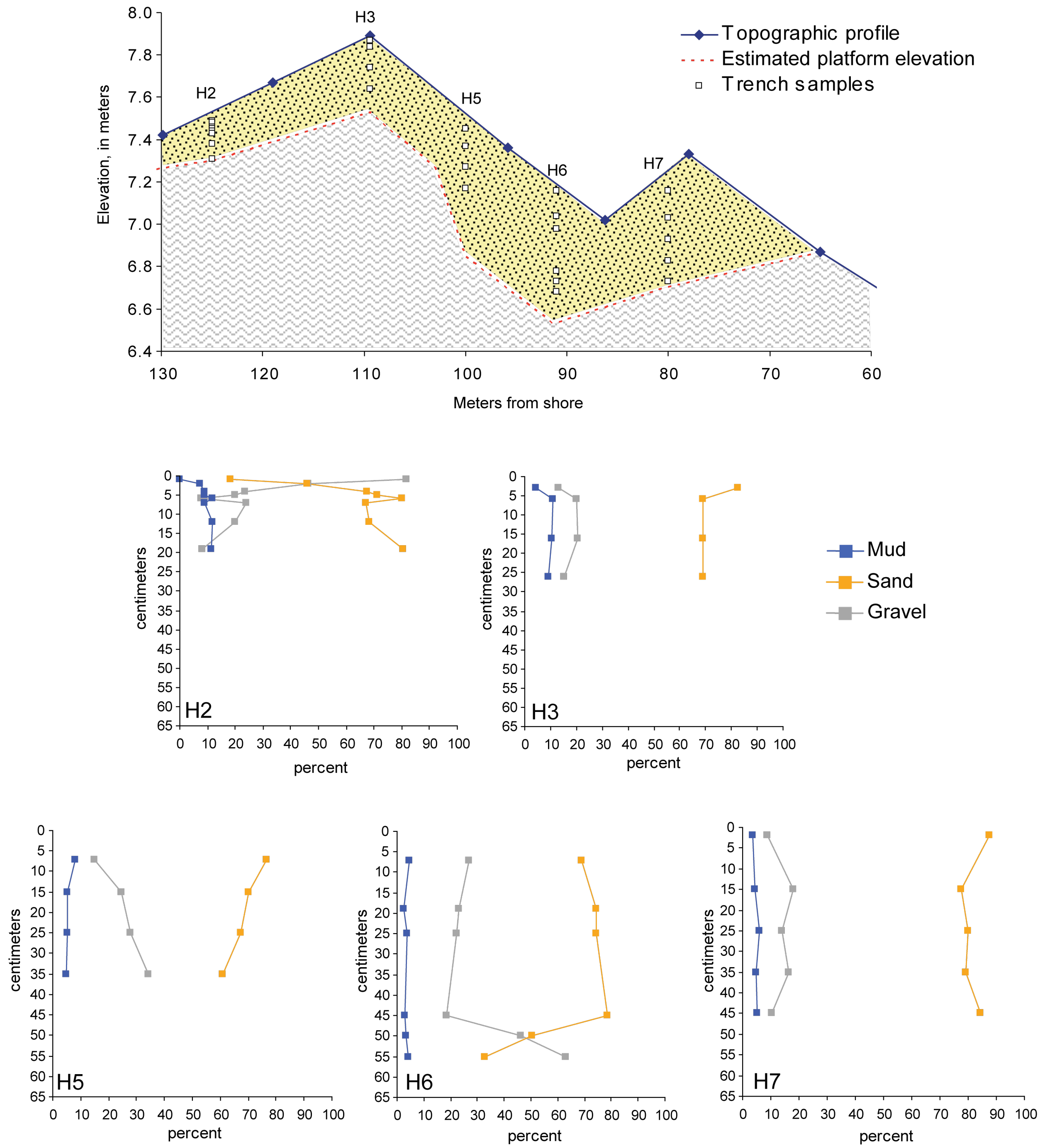


Figure 31. Plots showing the percentage of mud, sand, and gravel are shown for each sediment sample collected in trenches along Line 5 at Boka Olivia. Zero is the surface of the deposit.

Trench H7, located 80 m inland from the shoreline on the landward side of the first ridge, exposed the underlying limestone platform 55 cm beneath the deposit surface. An alternating pattern of normal and inversely graded sequences of poorly sorted medium and poorly sorted coarse sand are present from 45 to 3 cm deep. The grain-size distribution skewness follows a similar pattern, alternating from symmetrical to very negatively skewed. The percent mud, sand and gravel composition is fairly consistent in trench H7 from 45 to 15 cm deep. At 15 cm from the surface, the sand concentration increases and gravel decreases towards the top of the trench.

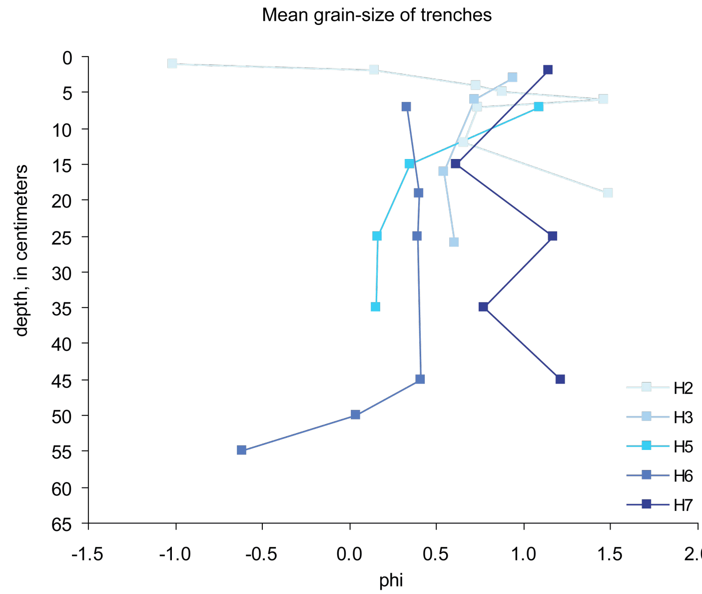
Ten meters farther inland, trench H6 was excavated on the seaward slope of the second ridge. An abrupt fining-upward sequence of poorly sorted granule to poorly sorted coarse sand is present from 55 to 45 cm deep. This sequence is overlain by a massively bedded, poorly sorted coarse sand from 45 cm to 6 cm deep. At 55 cm the sediment is very positively skewed and becomes very negatively skewed at 45 cm. After 45 cm the sediment becomes negatively skewed until 6 cm from the surface. Gravel percentage is high (63%) at 55 cm deep and decreases (19%) to 45 cm while the sand percentage increases over the same depth interval. Between 45 and 6 cm from the surface, sand and gravel percentages remain consistent. Percent mud percent composition is fairly consistent throughout trench H6 (2-4%).

Trench H5 is located about 100 m inland on the seaward slope of the second ridge. A normally graded sequence from coarse to medium sand is present from 35 to 6 cm. All samples in this trench are poorly sorted. From 36 to 25 cm, samples are negatively skewed then become symmetrical up to 6 cm. The percent sand composition increases from 35 to 6 cm, while gravel percentage decreases over the same depth interval. The percent mud composition is consistently low throughout the trench.

At the peak elevation of the second ridge (7.9 m asl), trench H3 was excavated 36 cm to the limestone platform. A weak fining-upward trend in mean grain-size is present from 25 cm to the surface of the trench. All samples in this trench are classified as coarse sand. Samples are very poorly sorted at the base of the trench to 6 cm and become moderately sorted near the surface. At the bottom of the trench, sediment is positively skewed at 26 cm. Above 26 cm, the skewness is symmetrical to 6 cm, then negatively skewed at 3 cm. Percent mud, sand, and gravel compositions are consistent from 26 to 6 cm deep. At a depth of 6 cm, the sand percentage increases to 3 cm, while mud and gravel percentages decrease. Vertical trends in mean grain size are similar in trenches H5 and H3.

H2 is the farthest trench inland (about 125 m) and located on the landward side of the second peak in the ridge complex. H2 was excavated 22 cm to the limestone platform. Grain-size trends within this trench are more variable than those found in the other trenches. Starting near the base of the trench (19 cm), poorly sorted medium sand inversely grades to very poorly sorted coarse sand at 12 cm. From 12 to 6 cm, very poorly sorted coarse sand normally grades to poorly sorted medium sand. From 6 cm to the top of the trench, poorly sorted medium sand inversely grades to moderately sorted granule sized sediment. Near the base of H2 (19 cm), the sediment is very positively skewed and becomes symmetrical from 12 to 7 cm. The sedimentary skewness becomes very positive at 6 cm and symmetrical again between 5 and 4 cm. At 4 cm deep, the sediment becomes positively skewed and then very positively skewed near the surface of the trench. Trench H2 has the highest and lowest mud percent compositions (12% at 6 cm deep, and 0.1% at 1 cm) and the highest gravel percentage (82% at 1 cm) sampled in Boka Olivia trenches. As percent sand composition decreases upward from 19 to 7 cm, gravel percentages increases. A spike in sand (and mud) percentages at 6 cm occurs with a corresponding decrease in gravel percentage. Percent sand and gravel compositions are roughly equal at 2 cm deep and diverge near the surface of the trench (gravel 82 %, sand 17.9 %.)

Normally graded sequences are present between 5 and 15 cm from the surface of trenches H2, H3, H5, and H7 (fig. 32). The exception is trench H6, where a massively bedded sequence is present at that depth interval. Percent mud compositions peak in trenches H2, H3, H5, and H6 around 5 to 6 cm deep from the top of the trenches.



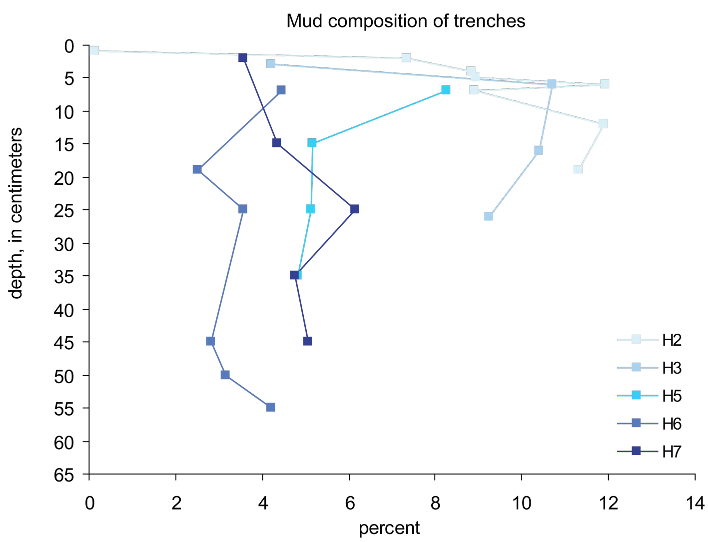


Figure 32. Plots of mean grain-size (top graph) and mud percentages (bottom graph) of all trenches.

To evaluate grain-size trends with increasing distance inland, sediment sample data for each trench were bulk averaged together (fig. 33). The bulk mean is smallest at trench H7 (medium sand) on the landward side of the first ridge and coarsens at trench H6 (coarse sand), just up the seaward slope of the second ridge. From trench H6 up to the peak of the second ridge (H3), average mean grain-size fines then coarsens slightly to trench H2. Bulk average sorting generally becomes poorer with increasing distance inland. Average sorting is poor at trenches H7 and H6 and becomes very poorly sorted to trench H3 at the top of the second ridge. Average sorting continues to be very poor to trench H2. Average skewness becomes increasingly positive with distance inland. Skewness values for trenches H7 and H6 are symmetrical. From trench H6 average skewness increases slightly to positively skewed at trench H3 and remains positively skewed to trench H2.

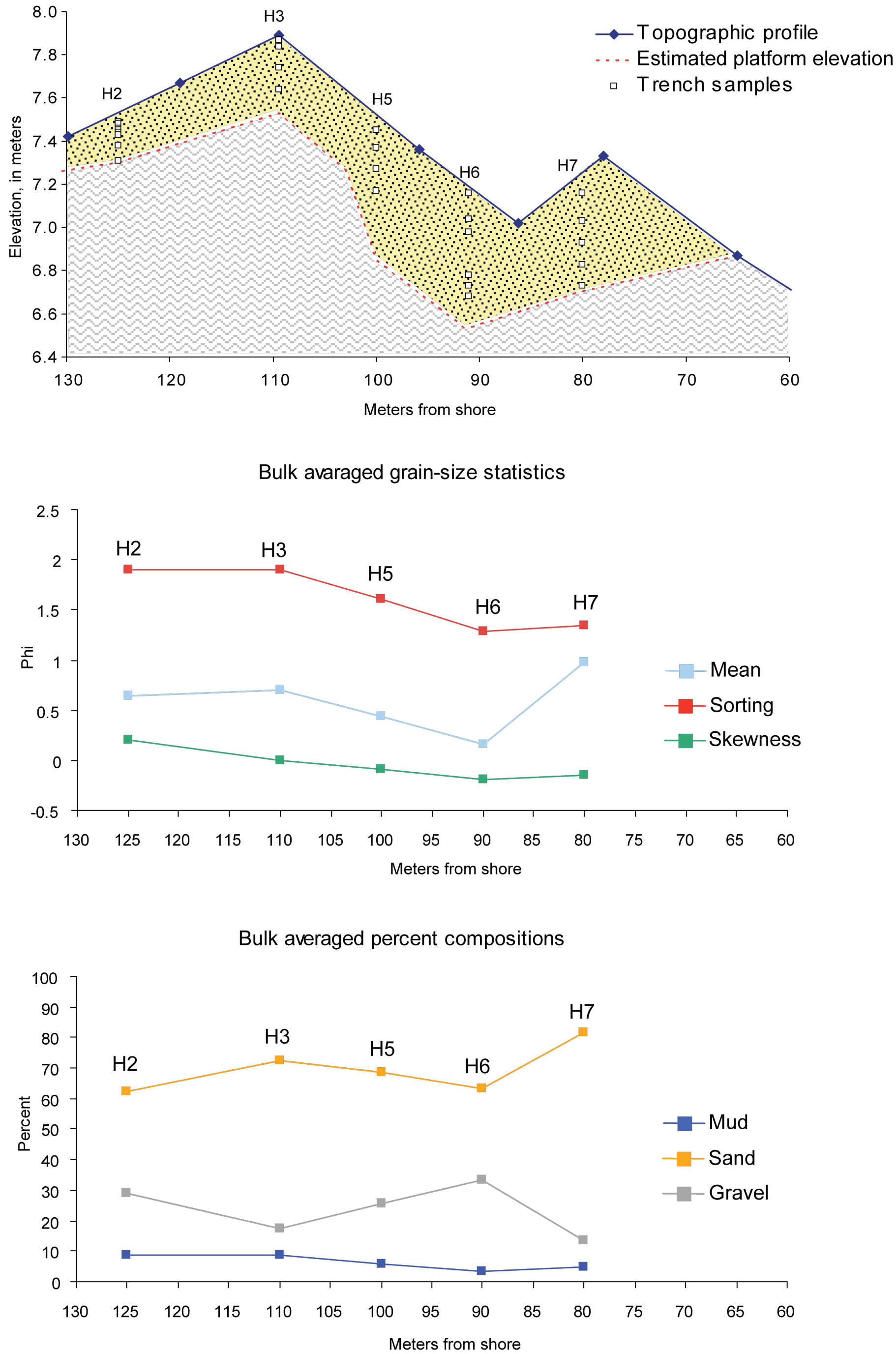


Figure 33. Graphs of bulk grain-size statistics and sediment texture for all trenches.

Average sand percentage is highest near the peaks of the ridges (fig. 33). Percent sand is highest at trench H7 and decreases at H6. Sand percentage increases to the peak of the second ridge (H3) and decreases to trench H2. Average gravel percentage trends at each trench are the opposite of the sand percentages. Average gravel percentages are lowest (17% and 14%) where sand percentages are highest (H3 and H7 respectively). The highest average gravel percentage (34%) was sampled behind the first ridge at trench H6. Average mud percentages increase slightly with increasing distance inland. The highest average mud percentages per sample are located at H3 and H2 (both 8.5%).

Mollusc samples were collected from two locations in trench H5 for AMS radiocarbon age analyses (fig. 34 and table 7). The oldest molluscs are found deepest in the trench. Mollusc samples from the bottom of the trench between 50-60 cm (BOL-C1) are about 4,500 years old; whereas, samples collected between 40-50 cm (BOL-C2) are 1,715 years old. The large disparity in ages (2,785 years) and proximity of samples in the ridge complex may suggest a record of at least two extreme-wave events.

Figure 34. Photographs of mollusc samples collected in trench H5 for AMS radiocarbon age analysis.

Table 7. AMS radiocarbon ages of mollusc samples collected in trench H5 in Boka Olivia, November 2006

Sample ID	^{14}C age (years)	Depth from surface
BOl-C1	4500	50-60cm
BOl-C2	1715	40-50cm

A series of cobble-camera images recorded clasts on the surface of the ridge complex along Line 5 through the north deposit (fig. 24). Three images were analyzed, 75 m from the shoreline on the seaward side of the ridge, 120 m inland near the second crest of the ridge complex, and 190 m from the shoreline on the landward side of the ridge (figs 35, 36, and 37).

The number of clasts in each image decreases with increasing distance inland, with the greatest decline between the seaward image (WP 222) and the image at the ridge crest (WP 225) (table 4). The range of clast lengths is consistent between the seaward edge image and ridge crest image but the mean of the long-axes is greatest at the ridge crest. The long-axis lengths range decreases on the landward side, however the mean axis is longer on the landward side than the seaward side of the ridge.

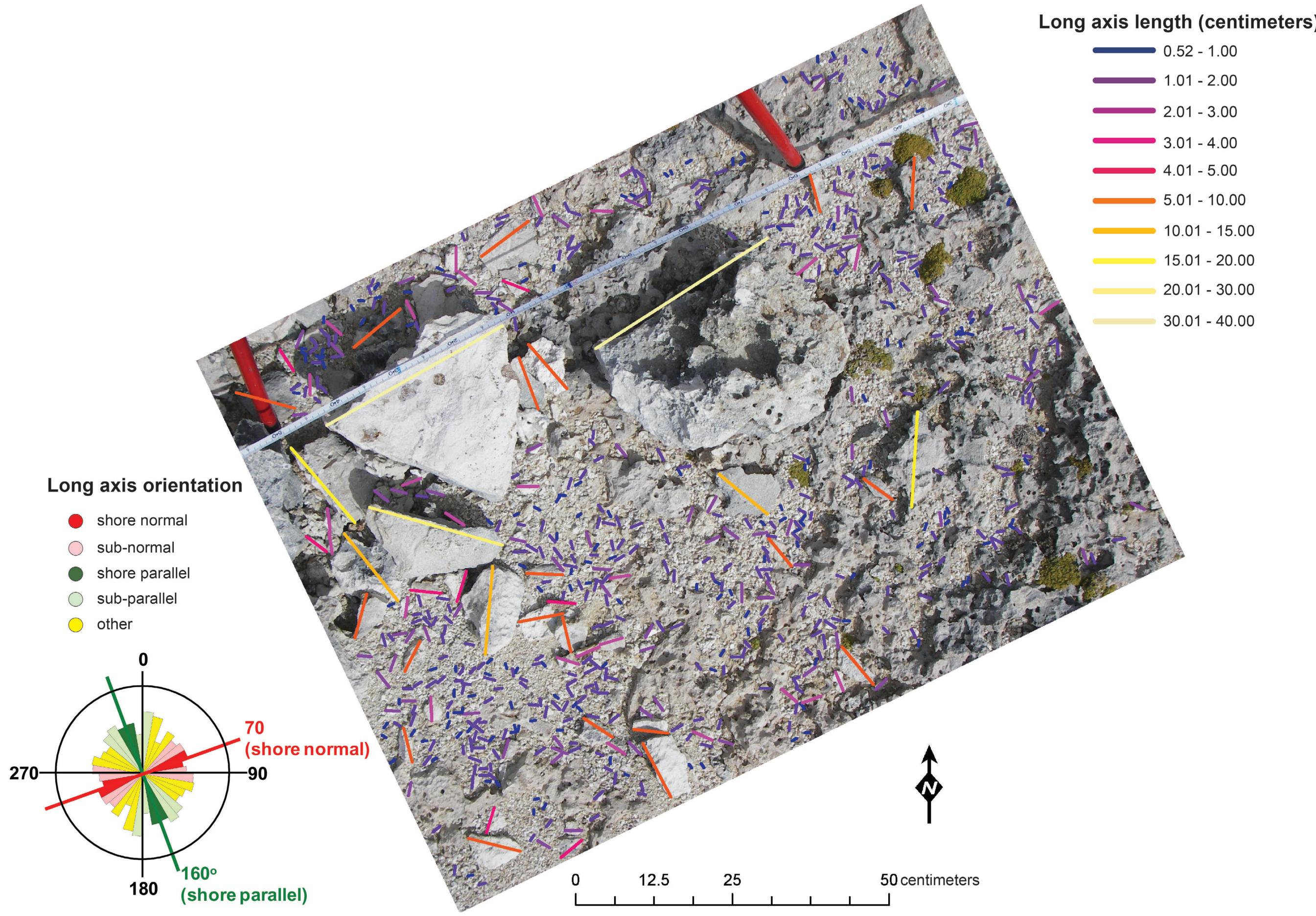


Figure 35. Boka Olivia cobble-camera image WP 222 taken on the seaward side of a ridge complex approximately 75 meters from the shoreline. Colored lines in the image indicate long-axis lengths and clast orientations to north. The rose diagram in the lower corner organizes the clast shoreline orientations into the categories listed in table 3.

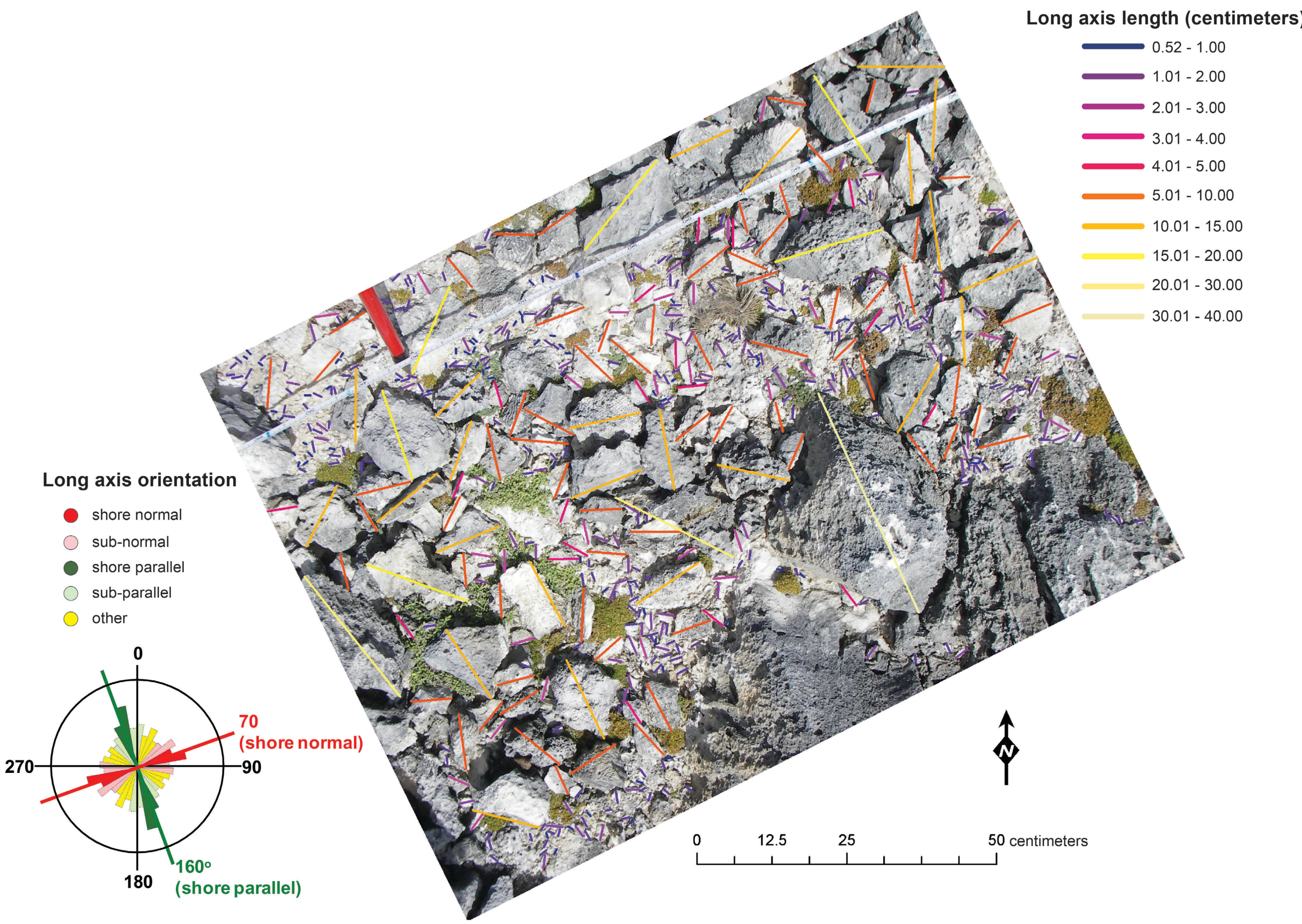


Figure 36. Boka Olivia cobble-camera image WP 225 taken on the seaward side of a ridge complex approximately 120 meters from the shoreline. Colored lines in the image indicate long-axis lengths and clast orientations to north. The rose diagram in the lower corner organizes the clast shoreline orientations into the categories listed in table 3.

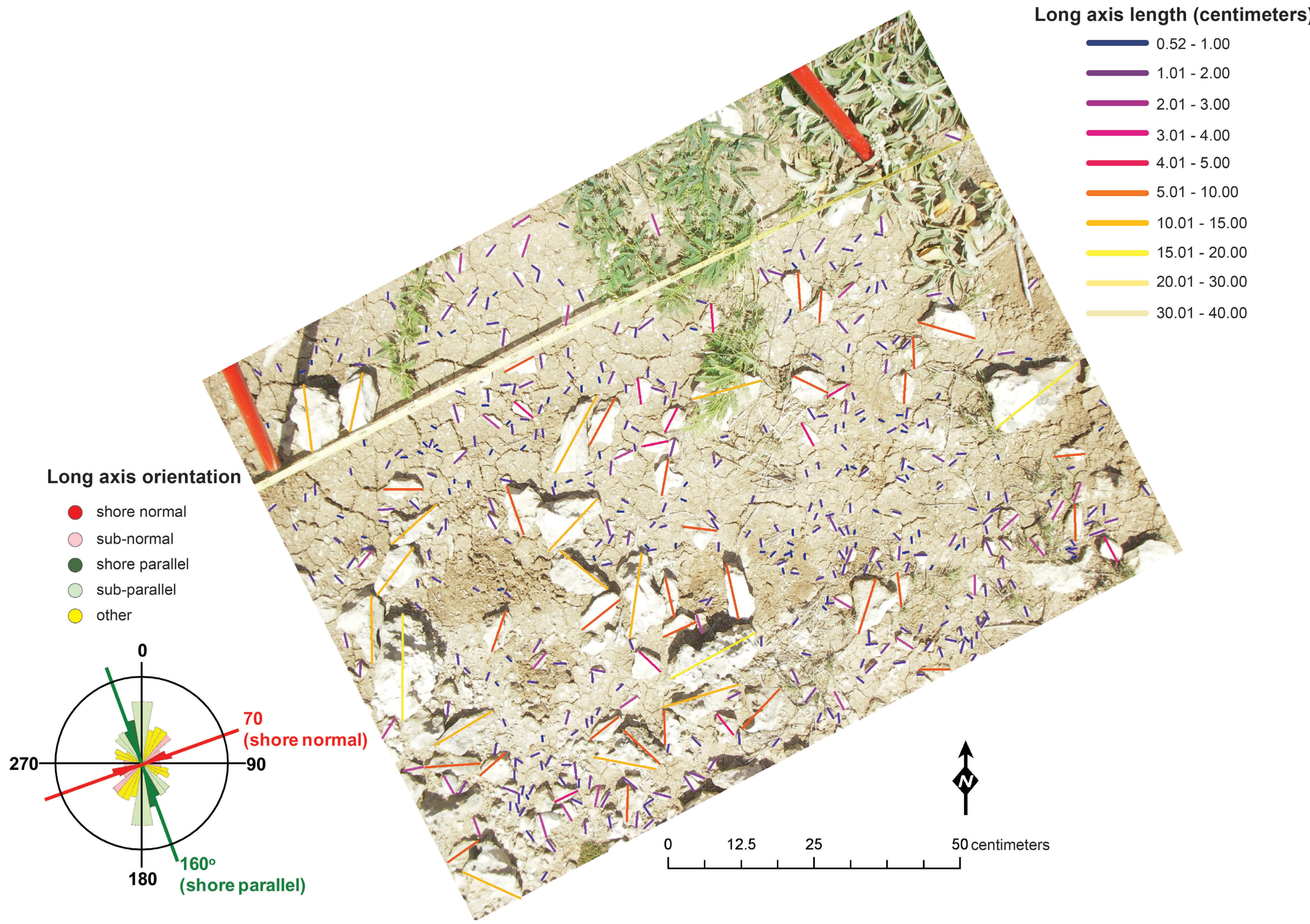


Figure 37. Boka Olivia cobble-camera image WP 228 taken on the seaward side of a ridge complex approximately 190 meters from the shoreline. Colored lines in the image indicate long-axis lengths and clast orientations to north. The rose diagram in the lower corner organizes the clast shoreline orientations into the categories listed in table 3.

The larger clasts on the seaward side of the Boka Olivia ridge are angular to sub-rounded while the smaller clasts are angular to rounded (fig. 35). Clasts are scattered, mixed with sand and many are partially buried. At the ridge crest clasts are angular to sub-rounded and more supportive of one another than in the other locations along transect (fig. 36). Sand has buried many clasts and filled many of the gaps between clasts. A moss-like plant has taken root in the areas of sand accumulation. Landward of the ridge crest clasts are smaller in axis length, scattered and angular to sub-rounded (fig. 37). Many clasts are embedded in hard-packed cracked mud. Clast long-axis orientations have a slight preference for shore parallel and sub-parallel orientations in Boka Olivia (table 3 and fig. 15). The shore parallel/sub-parallel preference is weak on the seaward side of the ridge. At the crest and along the landward side of the ridge, shore parallel and sub-parallel orientations are favored over shore normal orientations.

Line 3 runs between the north and south deposits in a section of non-indented shoreline between two reentrants in Boka Olivia (figs. 24 and 38A). The shoreline morphology is generally similar to the other profiles in Boka Olivia, an eroded steep shoreline cliff followed by a shallow (0.5 m) scarp 50 m from the shoreline at about 6 m asl and a microkarst pitted sediment-free platform. The platform (4.5-5.8 m asl) is about 1 m lower in elevation than Line 5 or 7 (5-6.8 m asl and 5.5-6.5 m asl, respectively). The sediment-free zone terminates in a sand deposit approximately 70 m from the waters edge. Ridge and boulder deposits along Line 3 are less extensive than at the other observation sites. There is less sand accumulated and boulders are smaller in size and scattered farther apart than either north or south of Line 3. Sand mixes with scattered boulders about 75 m inland to 170 m inland. The sand and boulders build a poorly developed peak 0.5 m above the seaward platform 140 m from the shoreline. The sand deposit continues 10-20 m farther inland than scattered boulders. Hard-packed mud, scattered pebbles, and cobbles are deposited landward of the ridge and inland to the road.

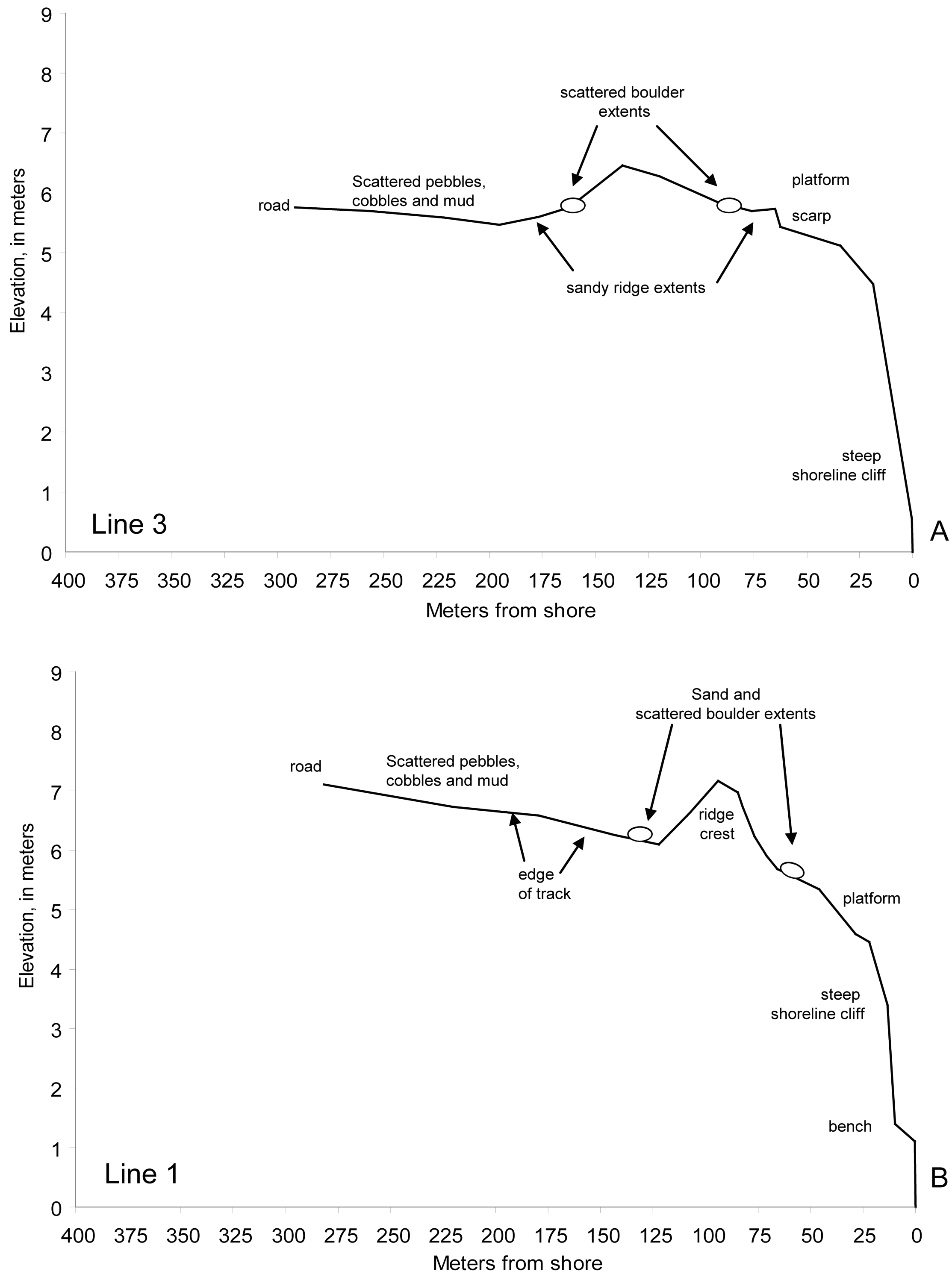


Figure 38. Topographic profile (A) Line 3 extends between the north and south deposits and (B) Line 1 extends along the southern edge of the south deposit at Boka Olivia.

Line 1 runs along the southern side of the south deposit and crosses through a sail car racetrack (figs. 24, 25B and 38B). Line 1 begins within the southern shoreline reentrant at the waters edge with a small 1 m wide bench not present along the other Boka Olivia profile lines. The bench may indicate a particularly wave resistant part of the limestone. Landward of the bench, Line 1 exhibits a typical steep shoreline cliff and a 60 m wide sediment free microkarst pitted platform. No topographic scarp was measured along this profile. The sediment-free zone ends with a sandy deposit that mixes with scattered and accumulated boulders at about 65 m inland. Sand and accumulated boulders build a pronounced ridge that peaks about 1.5 m higher than the seaward platform (7.2 m asl) about 95 m from the waters edge. Beyond the ridge crest, scattered boulders and sand are deposited to the edge of the sail car racetrack. On the inland side of the track, scattered cobbles, pebbles and mud are present (fig. 39).

Figure 39. Scattered cobbles and pebbles landward of the sail car racetrack and landward of the south deposit at Boka Olivia.

The deposits at Boka Olivia were mapped in more detail due to the high concentration and large size of the boulders (table 5 and fig. 40). Boulders were measured over 228 m inland from the shoreline and up to 7.9 m asl (fig. 17). In Figure 41 the distribution of boulders on the landscape are shown categorized by weight and long-axis orientation. Sixty three percent of the boulders (350) weigh less than 1 metric ton. The largest boulder is the closest to shore (56 m), approximately 6.5 m asl and weighs about 165 metric tons.

Figure 40. Measuring the largest boulder (about 165 metric tons) at the north deposit in Boka Olivia, Bonaire.

Boulder long-axes are grouped into categories based on their relation to the shoreline such as shore parallel or shore normal (table 3). Long-axes of boulders at Boka Olivia exhibit a preferential shore parallel orientation over the other possible orientations (figs. 15 and 41). Boulders that are oriented normal to shore weigh less than 5.2 metric tons with the exception of one boulder in the southern deposit that weighs 35 metric tons. The long-axes of the two heaviest boulders (about 165 and 148 metric tons) are sub-parallel and parallel to shore, respectively.

About 50% of the boulders are partly buried in the ridge-complex deposits (fig. 42) and 50% are on the deposit surface or exposed limestone platform (fig. 43). There are no boulders buried within 65 m of the shoreline. Boulders resting on the surface are found as far inland as buried boulders.

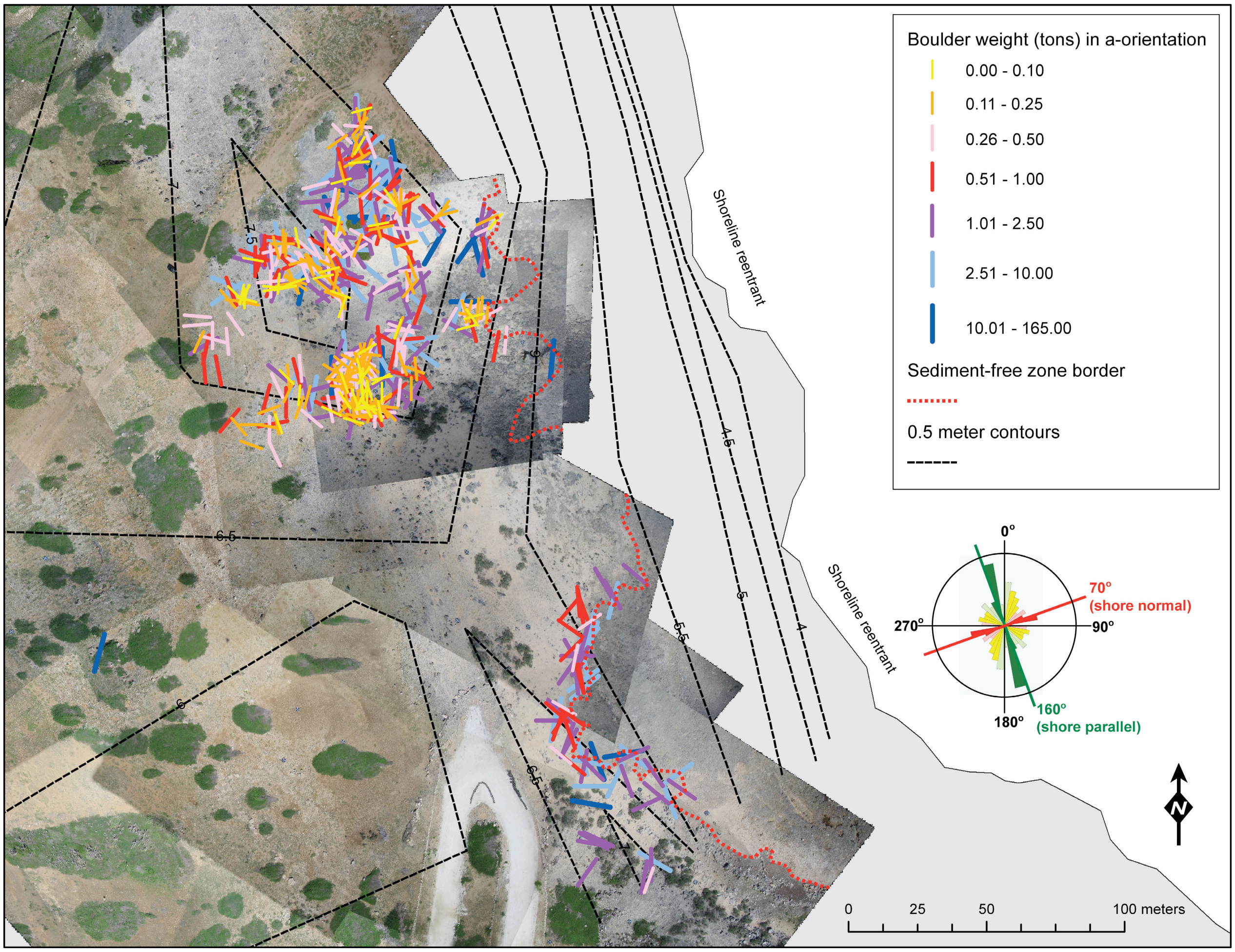


Figure 41. Map showing the weight of boulders (metric tons) and long-axis orientation for the north and south Boka Olivia deposits. The rose diagram depicts the clast shoreline orientations into the categories listed in table 3.

Figure 42. Photograph of a boulder partially buried in sand at Boka Olivia. The buried portion of the boulder was not colonized by microbial endoliths and remained white while the exposed portion was stained grey.

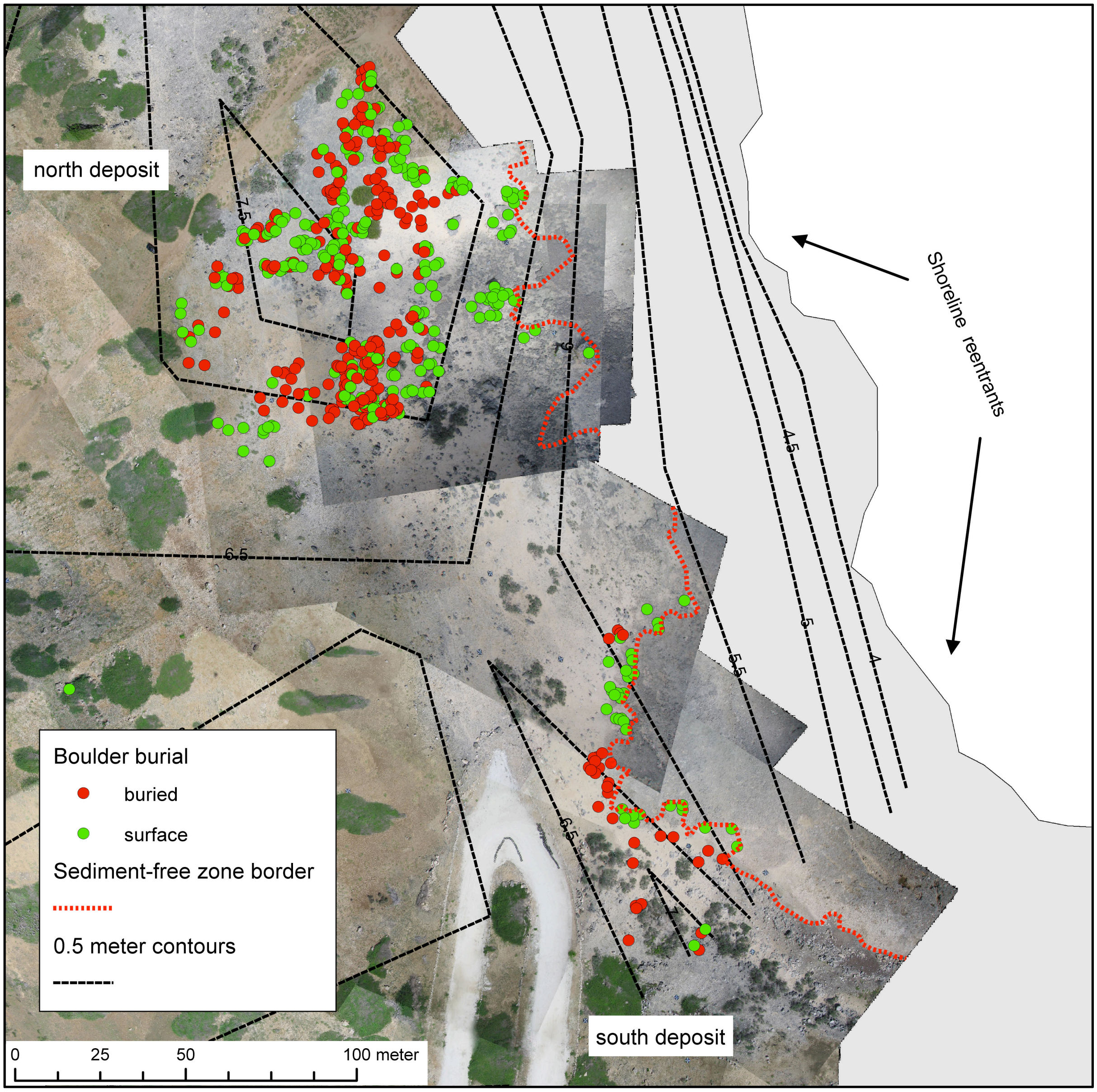


Figure 43. Map showing the distribution of buried boulders (red) and those on surface (green) at the north and south deposits at Boka Olivia, about 50% of boulders are buried.

East of Boka Olivia

East of Boka Olivia the shoreline curves to form the eastern side of a coastal bight (fig. 5). On the eastern end the shoreline orientation is 80°. The offshore bathymetry east of Boka Olivia is similar to Boka Olivia (fig. 6). A profile begins roughly 90 m deep and 510 m offshore. The seafloor is similar in slope and depth to the profile at Boka Olivia. Where the seafloor flattens into a gently sloping shelf in the other profiles (about 400 m offshore and 50-60 m deep) the depth of the seafloor east of Boka Olivia continues to decrease at the same slope. The profile ends about 240 m from shore in 35 m of water.

Mapping and data collection efforts east of Boka Olivia (fig. 44) were less comprehensive than at the other locations due to the impact of mining operations in this area. Thirteen boulders were measured east of Boka Olivia but no orientations were recorded. Boulders were measured as far as 93 m inland. Elevations for 10 of the boulders could not be estimated because topographic profiles were not collected nearby. A cluster of 4 boulders deposited with sand, cobbles and other boulders were artificially pushed into a ridge by mining operations 90 m inland (fig. 45A). The 2 largest boulders south of Boka Olivia were measured 30 m away and do not appear to have been impacted by mining (fig. 45B). The boulders weigh 18 and 20 metric tons and rest 75 m from the shoreline.

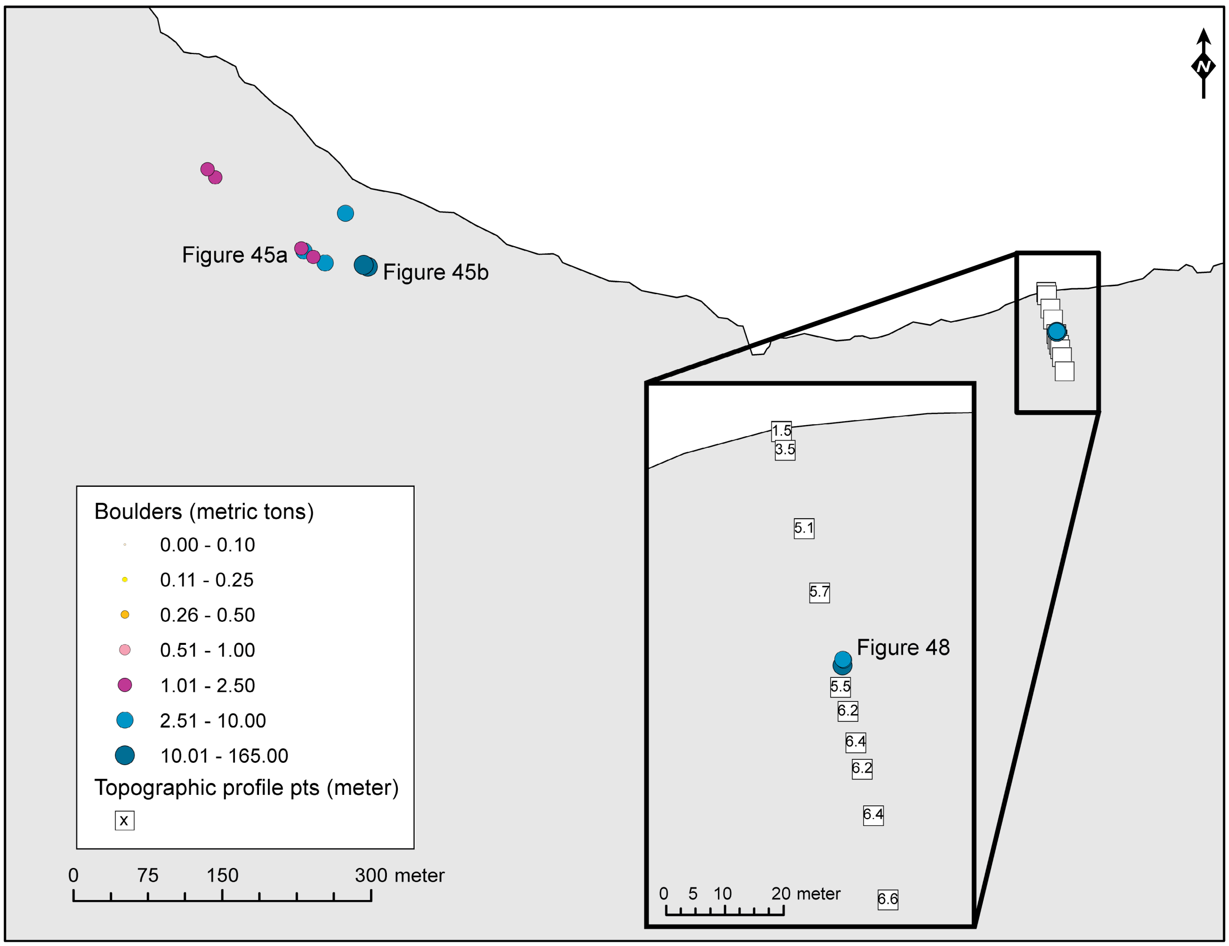


Figure 44. Surface elevations in meters above sea level, clast measurements and photograph locations (figs. 45 and 48) east of Boka Olivia.

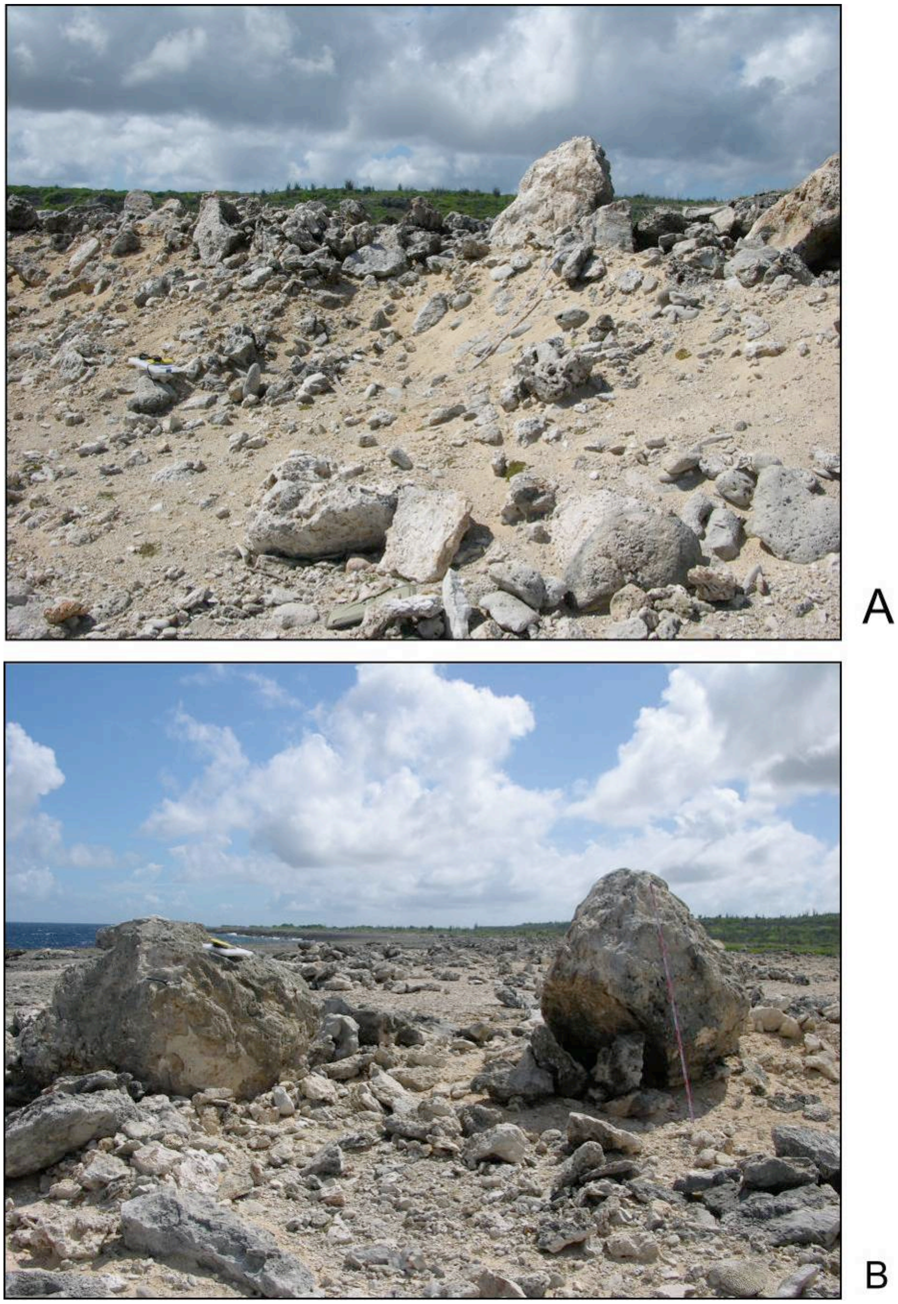


Figure 45. Photographs showing (A) a sand, cobble and boulder ridge produced artificially by mining operations and (B) the two largest boulders measured south of Boka Olivia. See figure 44 for photograph locations.

A topographic profile was measured about 1 km east of Boka Olivia (fig. 46 and table 2). At the shoreline there is an eroded cliff that ascends to a flat to gently sloping pitted limestone platform about 3.5 to 5 m asl (fig. 47). The profile is similar to the others collected on Bonaire, however, the normally sharp karst edges have been worn smoother than those observed elsewhere. There is a sediment-free zone roughly 45 m wide that includes a low-relief 0.5 m scarp about 20 m from the shoreline and 4.5-5 m asl. At 45 m inland three large boulders are deposited. The white underside of one of the boulders is exposed and was presumably overturned during transport by a recent extreme-wave event, possibly Hurricane Ivan in 2004 (fig. 48A). Impact marks on the platform observed as white exposures trace a path between the shoreline and boulders, further evidence of boulder transport during an extreme-wave event (fig. 48B). The largest boulder is 16 metric tons and the other two are about 8 metric tons each. Further inland along the profile a ridge complex has been severely impacted by mining.

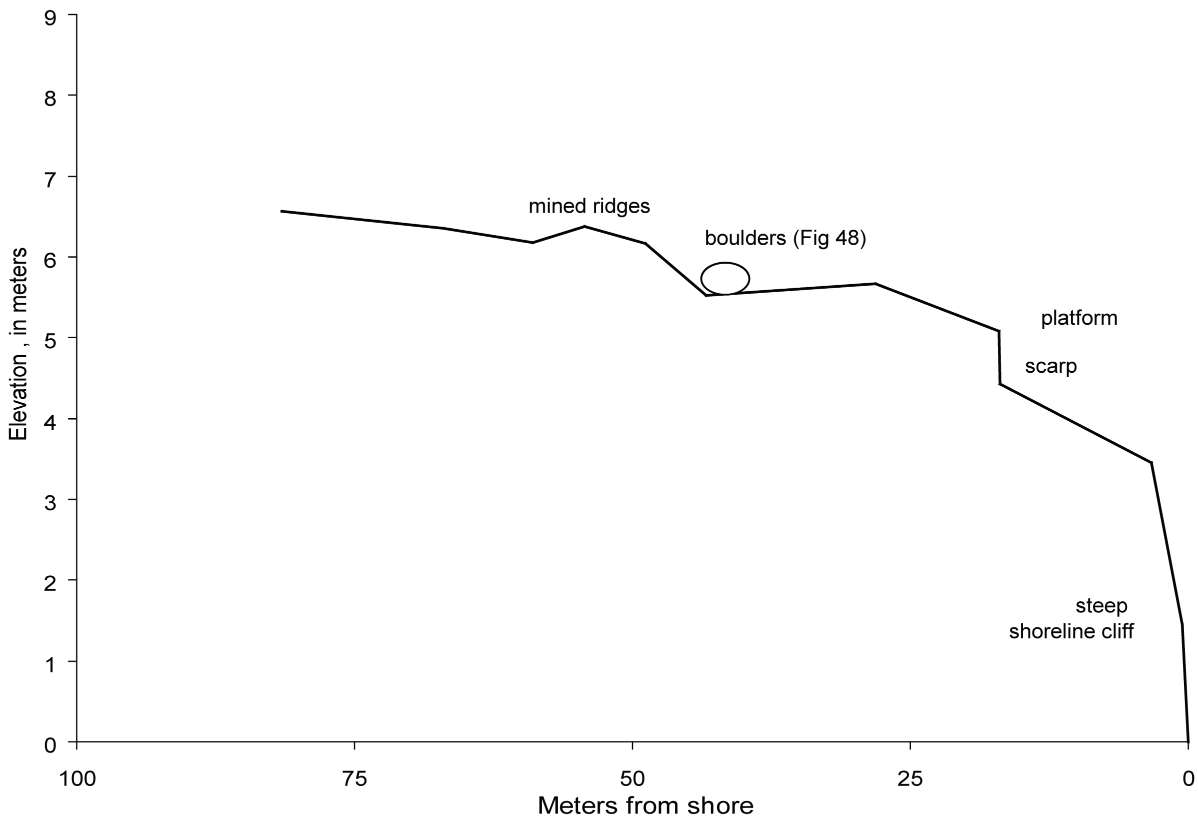


Figure 46. Topographic profile 1 kilometer east of Boka Olivia.

Figure 47. Photograph showing the seaward margin of the limestone platform east of Boka Olivia.

A

B

Figure 48. Photograph showing three boulders measured along the profile including one that was flipped over revealing the white underside not yet colonized by microbial endoliths (A). Researchers pointing out impact marks where the platform was chipped during boulder transport (B). See figures 44 and 46.

Comparison of Deposit Characteristics

Assuming that each of the deposits were produced and reworked by the same extreme-wave events, similarities and differences in deposit characteristics should provide insight into the processes that developed these deposits over time. The deposits exhibit characteristics consistent with both storm/hurricane deposits (ridge complexes) and tsunami deposits (scattered clast fields) implying that the deposits may have been produced and reworked by multiple wave events. Differences include the degree of storm versus tsunami deposit characteristics, the sediment-free zone width, deposit dispersal distance inland, platform elevation, shoreline orientation, the presence/absence and size of shoreline reentrants seaward of the deposits and bathymetry. In addition important factors remain unknown including the nearshore bathymetry and the availability of offshore sediment sources (sand and boulders).

Degree of Storm vs Tsunami Deposit Characteristics

The morphology of the deposit at Boka Onima more closely resembles an intact hurricane ridge complex than the other deposits. It is a well-defined 3 m high, tightly packed, shore parallel wedge that terminates abruptly with landward avalanche faces. Morton and others (2008) identified internal structural features and dated clasts consistent with ridge complex aggradation and progradation over 10s' to 1000s' of years. Large solitary boulders (up to 100 metric tons) consistent with tsunami deposits have been placed on the platform at the foot and on top of the ridge complex, but the ridge complex structure does not appear to have been severely altered by other extreme-wave events. No large clasts or marine sand deposits are found landward of the ridge complex and the deposit does not curve inland landward of a small shoreline reentrant.

The deposit north of Boka Olivia consists of three mixed morphologies: (1) a scattered clast field, (2) an arc-shaped, imbricated boulder accumulation and (3) a rippled sand sheet. The clasts in the scattered field are consistent with tsunami deposition, but are not as large (up to 50 metric tons) as those in Boka Onima or Boka Olivia. However, the clasts deposited north of Boka Olivia were mapped the farthest distance inland (up to 285 m). Landward of a large shoreline reentrant boulders have accumulated in a landward bending arc-shape and are imbricated against one another in a seaward dipping direction. The rudimentary structure may indicate that the deposit is in the initial stages of ridge complex development. Recent marine sand (likely from Hurricane Ivan) buries some of the boulders on the landward side of the accumulation and spreads well inland (250 m) into a unique (for Bonaire) sand sheet with 1.5 m wave length ripple features. It is unknown if the arc-shaped boulder accumulation formed in response to Hurricane Ivan or was a pre-existing feature.

The north deposit at Boka Olivia is perhaps the best example of a multiple extreme-wave deposit consistent with both storm (ridge complex) and tsunami (scattered boulder field) depositional patterns. The scattered boulder field is the most extensive of the deposits mapped in Boka Olivia that may indicate that more sediment was available for transport and that overwash events were more intense in this location. The deposit contains the largest boulders (up to 165 metric tons) and the greatest number of clasts (486 measured), which are densely clustered and dispersed over 225 m inland from the shoreline. The ridge complex at Boka Olivia is the most wide-spread and the only one mapped with two low peaks. It is the greatest in width (155 m), deposited farthest from the shoreline (70 m), and extends the greatest distance inland (225 m). However, it is not formed into well-defined wedge-shaped peaks terminating in abrupt landward avalanche faces. Six trenches excavated along the ridge complex revealed poor internal clast structure and a higher percentage of sand than the Boka Onima ridge complex. The sand extends 225 m inland burying many boulders in the scattered clast field. These observations indicate that the ridge complex at Boka Olivia has been reworked and possibly overtopped by multiple extreme-wave events.

The morphology of the south deposit consists of mixed scattered boulders and a ridge complex that is difficult to interpret due to the sail car racetrack. Scattered boulders are not as large (up to 39 metric tons) as the north deposit and an inland scattered field has been truncated by the racetrack approximately 120 m from the shoreline. Boulders deposited near the shoreline are positioned in a landward bending arc-shape landward of a large shoreline reentrant but the clasts are generally not in contact or imbricated. A ridge complex at the south deposit is slightly more well-defined than the north deposit with a higher elevation single peak but the peak is close to the edge of the racetrack and may have been impacted when the track was built.

Deposits east of Boka Olivia have been heavily mined making interpretation difficult. Evidence of recent boulder transport was observed where boulders were overturned and where chips and scrapes on the platform traced paths to transported boulders. These clasts may have been transported by Hurricane Ivan.

Sediment- Free Zone Width, Inland Dispersal Distance, Platform Elevation and Shoreline Orientation

Different shoreline orientations along the northern coast of Bonaire may have influenced the impact of storm and tsunami overwash events and the deposits they produced. Deposits placed on shorelines oriented in a more easterly direction in the western Boka Olivia bight are placed over 3 times as far from shore and over 4 times farther inland than the deposit on the more north facing shoreline at Boka Onima. The shorelines of the deposits at north of Boka Olivia and the north deposit at Boka Olivia face 160° to north and have the widest sediment-free zones (80 and 70 m respectively), greatest dispersal distances inland (285 and 225 m, farthest inland measured clasts) and have similar platform elevations (6.1 and 6.5 masl). Conversely, the deposit at Boka Onima is oriented 120° to north, 40° more north facing than the shoreline in the western Boka Olivia bight. The deposit has the narrowest sediment-free-zone (20 m), is dispersed the least distance inland (60 m) and rests on the lowest platform elevation (3.4 masl). Our observations suggest that the intensity of overwash events were greater along the more east facing shorelines in the Boka Olivia bight than along the more north facing shoreline at Boka Onima.

Shoreline Reentrants

Shoreline reentrants may have been produced when extreme-waves quarried cobbles and boulders from the seacliff and platform edge. Some boulders were placed on the platform and others may have fallen back to the sea and deposited at the base of the cliff. Besides the observation that shoreline reentrants exist seaward of many extreme-wave deposits, it is not clear how they contribute to the distribution of the deposits on Bonaire.

The largest reentrants exist north of Boka Olivia (115 m x 50 m) and at the south deposit at Boka Olivia (125 m x 20m). In both cases the deposits follow the curve of the indented shoreline, reflecting the influence of local topography on waves and the location and distribution of sediments. In contrast the shoreline reentrant at the north deposit at Boka Olivia (60 m x 20 m) and at Boka Onima (40 m x 20 m) appear to have had little effect on the shape of the seaward edge of the deposits there. In addition, deposits placed landward of non-indented shorelines such as along Line 7 near the north deposit at Boka Olivia and along Line 3 between the north and south deposits at Boka Olivia exhibit relatively sparser deposition of boulders and sand. Once a shoreline reentrant has developed it may facilitate platform inundation during other extreme-wave events allowing existing deposits to be more easily reworked.

The age relation between the formation of shoreline reentrants and deposits need to be analyzed to fully understand how shoreline reentrants influence extreme-wave deposits.

Bathymetry

Bathymetric features also could alter the impact of overwash events onshore. A 30 m deep shelf extends over 400 m offshore of the deposit north of Boka Olivia while the 30 m depth contour is only 170 m offshore of Boka Olivia. The water is deeper closer to shore at Boka Olivia. Approaching storm or tsunami waves may be altered or impacted by the shelf or other bathymetric features inshore of our bathymetric mapping. Hall and others (2006) found that offshore bathymetry was very important to the placement of boulders on cliff tops in Scotland and Ireland. Shoreline cliffs fronted by nearshore islands, offshore reefs and/or wide shore platforms did not have cliff top boulder deposits due to wave attenuation over these features. Mapping the nearshore bathymetry in detail could reveal additional features such as reefs, ledges and other outcrops that could influence overwash events. Images from high-resolution bathymetry surveys also could identify potential sediment sources such as clusters of boulders or sand deposits offshore.

Deposit Details at Boka Olivia

Vertical grain-size trends in the sandy ridge complex in the north deposit at Boka Olivia are variable within each trench and between the trenches along transect. Percent mud composition in the trenches remains fairly consistent but increases near the surface in 4 of 5 trenches between 5 and 6 cm deep. Four of 5 trenches exhibit a normally graded sequence approximately 5 to 15 cm from the sediment surface that may be consistent with deposition from suspension during tsunami inundation (Jaffe and Gelfenbuam, 2007).

The distribution of cobbles on the surface of the ridge complexes at Boka Onima and Boka Olivia show different trends. At the well-formed ridge complex at Boka Onima the long-axes of cobbles show a preference for shore normal to sub-normal alignment and there is a sharp increase in the number of clasts landward of the ridge crest along the avalanche face. Sand fills the fabric of the ridge complex at Boka Onima, but a substantial sand deposit does not extend inland. At the poorly developed Boka Olivia ridge complex cobble long-axes slightly favor shore parallel to sub-parallel alignment and there is a decrease in the number of clasts landward of the crests. Many small clasts are likely completely buried in sand. The deposit at Boka Olivia is composed of a higher percentage of sand that extends well inland. These observations may indicate that multiple extreme-events have more severely impacted the deposit at Boka Olivia than the deposit at Boka Onima. Only 6 of 46 cobble-camera images were processed due to the time required to analyze each image. While the images are useful in comparing different deposits, more images may need to be processed to evaluate the usefulness of cobble camera in future field mapping studies.

There is a slight preference for boulders and cobbles at Boka Olivia to be oriented either shore parallel or sub-parallel. At the Boka Olivia north deposit, boulders that were oriented normal to shore were smaller, 5.2 metric tons or less. The two largest boulders were oriented parallel and sub-parallel to shore. Assuming the flow of extreme-waves are normal to shore, boulders and cobbles with long-axes normal to flow (parallel to shore) implies the particles were rolling or sliding whereas boulder and cobbles with long-axes parallel to flow (normal to shore) implies turbulent suspension or saltation (Inman, 1949; Collinson and Thompson, 1982; Williams and Hall, 2004). It is not surprising that boulder long-axis shoreline orientation preferences are weak as many factors that affect transport, such as irregular boulder shape, uneven platform surfaces, and interference from other boulders or sand influence the final orientation of a boulder relative to the shoreline. Boulders may at different points roll, slide, and spin during a transport event. Some boulders may collide with one another and others may not be transported at all. The boulder orientations measured in Bonaire capture the final position of what may have been multiple wave-events involving both hurricanes and/or tsunamis.

Roughly half of the boulders in the north deposit at Boka Olivia are buried and half are resting on the surface of the sandy ridge complex and limestone platform indicating multiple extreme-wave events. Only boulders landward of the first ridge crest are buried. While the largest boulders in Boka Olivia are the closest to shore, a systematic landward-fining trend is not apparent. A landward-fining envelope may be a more appropriate description of boulder distribution with respect to the shoreline in Boka Olivia.

Summary

Detailed mapping and sedimentary analyses on northeastern Bonaire provide new information for the development of a systematic approach to determine the origin of extreme-wave deposits. Further investigation is required to fully understand the process or processes that produced and modified these deposits over time.

The presence of deposit morphologies consistent with both storm (hurricane) and tsunami processes plus a wide range of age dates from material within the deposits indicate that the deposits were probably formed by a series of storm/hurricane events superimposed by at least one tsunami over 10s' to 1000s' of years. Differences and similarities between the deposits highlight either storm or tsunami deposition while retaining properties consistent with both types of extreme-wave events. Comparisons of the degree of storm versus tsunami deposit characteristics, deposit dispersal, and shoreline orientation indicate that overwash events were probably more intense in the more east-facing Boka Olivia bight than at the more north-facing Boka Onima. More research is needed to understand the relation between shoreline reentrants and extreme-wave deposits.

The north deposit at Boka Olivia is the best example of a mixed multiple extreme-wave event deposit due to the large two-peaked ridge-complex and the widely distributed and immense boulder field deposit. The expansive area covered, wide-ranging clast sizes and extensive sand deposit may indicate that more material was available for transport here than at the other locations. Landward-fining trends in boulder deposition are better described as a landward-fining envelope and while boulder shoreline orientation preferences are not strong, the fact that they are measurable is noteworthy considering all the variables that influence boulder deposition and orientation. More analysis is needed to understand grain-size trends within the ridge complex and the distribution of clasts along the surface. The further collection of high-resolution nearshore bathymetry could image bathymetric features capable of influencing overwash events and reveal potential sediment sources.

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