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HURRICANE IRMA DEPOSITS ON A MODERN CARBONATE PLATFORM

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Abstract:
The study of modern hurricane deposits on a carbonate platform is useful both in identifying the fingerprint of ancient hurricane deposits in similar geological settings and gaining a deeper understanding of future depositional markers produced by major storm events. Little Ambergris Cay is a 6 km long uninhabited island on the Caicos platform in the Turks and Caicos Islands. Hurricane Irma passed directly over Little Ambergris Cay on Sept 7, 2017, making it an ideal location to study the deposits formed during the hurricane. Observations of hurricane deposition on Little Ambergris Cay were compared and contrasted to previous studies on washover fans and used to develop a framework for expected depositional trends in both modern and ancient carbonate platform settings. Samples and drone images were collected in March and July 2018 (6 and 10 months after Hurricane Irma, respectively). Samples were collected from multiple hurricane deposits, including washover fans in the interior of the island and lobes at the mouths of tidal channels. All samples were rinsed, dried, and analyzed using a Camsizer to examine variations in grain size, roundness, and sorting in relation to depth and location on the island. Aerial drone imaging of the island helped to establish the changes in position of the sediments associated with current and wind re-working. Examining internal structures and sediment trends of the washover fans allowed for the construction of a template for hurricane deposits in a high-energy storm event on a carbonate platform.
Introduction:

Deposits:

Washover fans are the product of near-instantaneous depositional events (Morton & Sallenger 2003) that represent the flow conditions during a major storm or hurricane and are unique depositional records that can be used to reconstruct those conditions post-hurricane. These sediment bodies form as the flow velocities associated with major storms or hurricanes ebb, resulting in net sediment deposition. The deposits typically form when a landward storm surge overreaches or breaches the height of the local topography.

Washover fans are a common depositional feature of areas exposed to extreme weather (Morton & Sallenger 2003), and a number of studies have reported expected dimensional and sedimentary trends involving grain size and sediment structures. The majority of studies previously conducted on hurricane deposits examined washover fans on barrier islands or continental coastal environments, where sediment bodies of this type are most commonly found after a storm event (Morton & Sallenger 2003, Leatherman & Williams 1983, Wanless et al. 1988, Spiske & Jaffe 2009, Schwartz 1982, Sedgwick & Davis 2003, Soria et al. 2018, Wang et al. 2007, Deery et al. 1977, Leatherman & Williams 1977). There are consistent observed sediment trends between the results of most of these studies.

Some expected sediment trends characteristic of washover fan deposits in continental coastal environments are: graded or inversely graded bedding (Leatherman & Williams 1983, Wanless et al. 1988, Spiske & Jaffe 2009, Schwartz 1982, Sedgwick &
Davis 2003, Soria et al. 2018, Wang et al. 2007), tabular landward-dipping beds (Wang et al. 2007, Deery et al. 1977, Schwartz 1982, Sedgwick & Davis 2003), and lateral as well as vertical grading (Leatherman & Williams 1977, Schwartz 1982). In some instances, ripples are observed between tabular beds (Deery et al. 1977, Wanless et al. 1988). By far the most common feature is graded bedding (both lateral and vertical), followed by the tabular landward-dipping beds that are often observed with large, non-ephemeral fans that survive multiple storm surge events.

Modern carbonate platforms in the Atlantic hurricane belt (subject to counterclockwise storm circulation) are frequently traversed by hurricanes, but are less often studied than coastal areas. There is reason to believe the conditions producing sedimentation are quite different on carbonate platforms; the bathymetry is shallow in the vicinity of a carbonate platform, with a steep gradient from deep marine to shallow marine environments at the edge of the platform, and storms are often stronger in these open-ocean areas than nearer to continental coasts. Carbonate platform deposits are common in the rock record, and using a modern analogy to understand their associated hurricane deposits in greater detail can potential help to identify their sedimentary signature in ancient carbonate settings.

The signature of hurricane deposition on a low-elevation island that is subjected to a direct hurricane hit has not been closely studied until now, and represents an end-member depositional environment that can be further understood by examination of the character of recent deposits from Hurricane Irma (September 2017) on a carbonate platform. The distinct type of washover fan specific to this depositional environment provides a framework for understanding past (in the rock record) and future deposits after
this description. This study aims to describe washover fans specific to the carbonate platform environment.

*Study Site:*

This study focuses on Little Ambergris Cay, a 6 km long, 1.6 km wide uninhabited island on the Caicos platform in the Turks and Caicos Islands (Figure 1). Hurricane Irma passed directly over the island on September 7, 2017, making it an ideal location to study the deposits formed during the hurricane. Little Ambergris Cay was located directly in the path of the hurricane, with the eye of Hurricane Irma traversing the island roughly east to west during the passage of the storm (Figure 2). Counterclockwise circulation as the storm passed over the island subjected Little Ambergris Cay first to a southward storm surge associated with the leading arm of the storm, and then to a northward storm surge associated with the trailing arm of the hurricane. The average depth of the storm surge at the height of the hurricane was about 3.5 m according to measurements at the neighboring island of Big Ambergris Cay; the highest elevation point on Little Ambergris Cay is about 4 m. The submersion of the island was thereby nearly complete during the height of the storm surge.

The low-level topography of little Ambergris Cay consists of beach ridges from tidal and storm influence at the exterior of the island and a tidal lagoon in the interior of the island that is shallowly submerged and subject to gentle reworking by tides as water flows in and out of the lagoon. The island is situated on the Caicos platform, a shallow-marine carbonate shelf with a collection of low-level islands of Pleistocene origin which are composed of lithified carbonate rock (Kerans et al. 2019) and unconsolidated oolitic
sand made up of rounded grains of calcium carbonate that form through precipitation in warm, shallow marine waters. The sediment on Little Ambergris Cay is almost exclusively composed of these ooids, with intermixing of small skeletal clasts. The island is dominated biologically by microbial mats, with some zones of mangroves.

In previously studied cases of hurricane washover, the storm surge was often not quite so high as it was at Little Ambergris Cay, due to the reduction in strength of a hurricane making landfall in a coastal setting. Additionally, storm trajectories approaching a coastline are often less direct. Lower offshore bathymetry and topography combine in a carbonate platform to allow for a uniform surge with high flow velocities, and a direct rather than oblique storm trajectory focuses the energy of the storm over a smaller area. Vegetation on Little Ambergris Cay also differs in major ways from a continental coastal environment, being generally sparse and not particularly obstructive to flow.

The deposits formed during the storm consist mainly of washover fans on the southern side of the island interior and channel lobes extending offshore on the northern side of the island. The northward-directed storm surge of the trailing arm of the storm likely created both of these sets of deposits. The washover fans and channel lobes formed during the hurricane are composed of the prevalent oolitic sand. Any sand bodies formed during the passage of the leading arm of the storm would likely have been subsequently remobilized and erased by the passage of the trailing arm of the hurricane; the primary record of Hurricane Irma conditions is therefore that gleaned from deposits formed during the second, northward-flowing storm surge.
The lobes situated at the mouths of tidal channels suggest that these channels served as an outlet for the storm surge and accompanying sediment. These deposits are analogous to the formation of a washover fan, only with the sediment movement originating from the direction of the interior of the island rather than from the open ocean. Both types of sediment bodies are formed as a result of the ebb in flow velocity following the passage of the storm surge, which allowed grains to be deposited from suspension. The channel lobes were subjected to significant potential for reworking by westward-directed longshore currents and tidal currents. The washover fans were less likely to be affected by reworking, as they are perched on the edge of the southern side of the island and subjected only to the tidal flow in the interior lagoon.

The opportunity to study hurricane-associated deposits directly in the aftermath of the storm allows for a unique chance to achieve a deeper understanding of these types of deposits and the conditions behind their formation.

**Methods:**

Sediment samples from the hurricane deposits were collected in March and July of 2018 (6 and 10 months after Hurricane Irma, respectively). Samples were collected from multiple hurricane deposits at several depths, in order to observe any lateral or vertical grading that might be present. Changes in sediment sorting were also examined to determine if there were fluctuations in flow energy over the course of the storm event.

The sediment bodies sampled included the washover fans in the interior of the island (Figure 3) and the lobes at the mouths of the tidal channels (Figure 4). 71 sediment samples were collected in March 2018 and 33 in July 2018. The washover fans were sampled only in March, and samples were collected from the channel lobes on both
occasions in order to determine the role of current reworking. All samples were rinsed, dried, and analyzed using a Retsch Camsizer P4 to document grain size, roundness, and sorting. Drone imaging was conducted on both occasions to visually observe any reworking that may have occurred between the first and second sampling.

Our observations were compared and contrasted with previous studies (Morton & Sallenger 2003, Leatherman & Williams 1983, Wanless et al. 1988, Spiske & Jaffe 2009, Schwartz 1982, Sedgwick & Davis 2003, Soria et al. 2018, Wang et al. 2007, Deery et al. 1977, Leatherman & Williams 1977) dealing with similar sediments in similar environments. These previous studies served as a guideline for expected dimensions and sediment trends to contrast with what we observed on Little Ambergris Cay. We used a digital elevation model (Figure 5), which was created through aerial drone imaging, to examine how the topography of beach ridges on the island may have affected patterns of sediment deposition during the storm event, as well as a previously compiled facies map (Figure 6) to note where differences in the types of microbial mat growth affected the size or sediment trends of the washover fans (Stein et al. 2016).

Measurements were taken of small boulders transported into the interior of the island during the storm in order to calculate flow velocities into the island interior at the height of the hurricane. These flow velocities were compared to those that would be required for transport of oolitic sand in bedload, suspended load, and washload, to identify the transport regime of sand during peak hurricane intensity. Ooid sand transport regimes were calculated using the Rouse number $P$, a dimensionless number that describes different modes of transport:
\[ P = \frac{w_s}{k u_*} \]

where \( w_s \) is settling velocity, \( k = 0.41 \) is Von Karman’s constant, and \( u_* \) is the bed shear velocity. The Rouse number \( P = 7.5 \) corresponds to the threshold for motion, \( P = 2.5 \) to bedload transport, \( P = 1.2 \) to 50% of sediment suspended, and \( P = 0.8 \) to sediment in washload. We used Camsizer measurements of median grain size \( (D_{50}) \) of washover fan sediment to calculate \( w_s \), following Dietrich (1982). We then solved for \( u_* \) at each Rouse threshold using the above equation rearranged. Finally, we used flow velocity equations to solve for depth-averaged flow velocity for each \( u_* \):

\[ u = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) \]

yields flow velocity as a function of depth where \( u, u_* \), and Von Karman’s constant are defined as above, and \( z \) is the height above the bed, \( z_0 \) being the basal flow height. Integrating this equation and dividing by the depth of flow

\[ < u > = \frac{1}{H} \int_0^H \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) dz \]

where all other variables are as previously defined and \( H \) is the flow depth, yields depth-averaged flow velocities \( (< u >) \) for the oolitic sand.

Using boulder average axes of intermediate axis length 29cm and short axis length 13cm, flow velocities required to transport the boulders were calculated using the following equations from Soria et al. (2018):

\[ \text{Sliding: } u^2 \geq \frac{2 \left( \frac{L}{D_w} - 1 \right) g c (\mu_s \cos \theta + \sin \theta)}{C_d \left( \frac{L}{D} \right) + \mu_s C_l} \]
Rolling: \( u^2 \geq \frac{2(\frac{\rho_s}{\rho_w} - 1)gc \left( (\frac{c}{b}) \cos \theta + (\frac{c}{b}) \sin \theta \right)}{c \left( \frac{c}{b} \right)^2 + C_l} \)

Lifting: \( u^2 \geq \frac{2(\frac{\rho_s}{\rho_w} - 1)gc \cos \theta}{C_l} \)

where \( \rho_s \) is the boulder density (2.85 g/cm\(^3\)), \( \rho_w \) is the density of seawater (1.025 g/cm\(^3\)), \( g \) is the acceleration due to gravity (9.81 m/s\(^2\)), \( c \) is the length of the shortest axis of the boulder, \( b \) is the length of the intermediate axis of the boulder, \( u_s \) is the coefficient of static friction (0.5), \( \theta \) is the angle of the bedslope (0\(^\circ\)), \( C_d \) is the coefficient of drag (1.95), and \( C_l \) is the coefficient of lift (0.178).

Flow velocities required to transport the oolitic sand grains and boulders were then compared.

**Results:**

Washover fans on Little Ambergris Cay are on the small end of the range of those that have been observed in previous studies, and they lack the sedimentary structures that are common to washover fans on continental coasts and barrier islands (Figure 7). In fact, they lack any internal sediment trends whatsoever. The maximum storm strength and the height of the storm surge on Little Ambergris Cay were unique to the direct passage of a storm over a low-lying island on a carbonate platform, and most likely played a significant role in the unique features (or lack thereof) of these sediment deposits.

The washover fans on Little Ambergris Cay follow the morphological pattern of those in other localities, overtopping the shoreline ridges and creating a scalloped pattern along the edge of the island (Bourouilh-Le 1998). This pattern of deposition is familiar to studies of post-storm barrier islands, and Little Ambergris Cay fans are consistent with
the perched fan type described by Morton & Sallenger (2003). The washover fans occur in an area of the island where topography is consistent along the beach, and there are not many mangroves to interrupt flow patterns. The channel lobes on the northern shore may have been subjected to more complex flow patterns that could have affected the rates of sediment reworking between deposits.

Although washover fans examined in a variety of locations share similar sedimentary structures, washover fan lengths vary from 10s to 100s of meters (Morton & Sallenger 2003, Deery et al. 1977). Little Ambergris Cay washover fans are unusually small, with even the largest fans falling on the lowest end of the length spectrum gleaned from other studies (Figure 8). They range from a few tens of meters to a hundred meters, while most previously studied washover fans are hundreds of meters long on average. The thickness of typical washover fans ranges from 10 cm (Deery et al. 1977) to 1.5 m (Morton & Sallenger 2003.) The Little Ambergris Cay washover fans do not exceed a thickness of about 12 cm, again placing them on the lower end of the size scale. In environments with similar sediment sizes and types to the Caicos platform, storm deposits tend to be composed completely of well-sorted sand (see Major’s 1996 study of a Bahamian ooid shoal), which is consistent with the washover fans and channel lobes we address here.

The only observable sediment trend in the washover fans is that median grain size increases moving east to west over the washover fan area (Figure 9). This is a trend that exists between fans, but there are no trends within individual fans. On an individual basis, the fans exhibit no observable sedimentary structures, showing only massive bedding for each deposit, with sorting and grain size consistent both laterally and horizontally
throughout each individual washover fan. The fans are composed entirely of oolitic sand (Figure 10) that is well sorted (with occasional skeletal fragments and tiny clasts of bacterial mat) and is neither bedded nor graded in any observable way.

There were no spatial trends in sediment size, shape, or sorting in the channel lobes from both the March and July sample sets, but there was evidence of significant reworking between March and July. Drone imagery showed a migration of about 10 m westward during this time, and the fan tips curved westward (Figure 11). This indicates substantial reworking by westward longshore transport (Trower et al. 2018) that was not observable (or possible) in the location of the washover fans. Of the five channel lobes sampled, the fifth and most eastern was completely washed out by the longshore currents, so that it could no longer be sampled at the second data collection. Differences in sorting and median grain size in the remaining four channel lobes (Figure 12) show that the sediments were shifted over time, each lobe affected differently by tidal currents through each associated channel. The significance of the reworking over such a short time scale suggests that even the earliest (March) sampling was reflective of sediments that had already been altered from their original depositional state. The extent of channel lobe reworking also suggests that these deposits are somewhat ephemeral and may not be preserved in the rock record.

**Discussion:**

The samples from the channel lobes showed changes in sorting and median grain size distribution that suggested they had been reworked by longshore currents. Therefore, the following analysis focuses on the washover fan samples in order to obtain the most accurate representation of Hurricane Irma storm conditions. The washover fans were not
subjected to any migration due to currents, and showed minimal disturbance beyond the regrowth of microbial mat cover; they provide a better opportunity for analysis of the storm conditions affecting the island in September 2017. The channel lobes serve the purpose of analogous flow regimes and indicators of sediment transport and bypass.

The sediment deposits on Little Ambergris Cay associated with Hurricane Irma differ in several ways from other examples of hurricane deposits. The lack of internal structures in the washover fan deposits could be due to a number of factors that differentiate these deposits from those that have been addressed in previous studies. The allowance is often made for some variability among hurricane deposits, dependent on flow depth and topography (Morton & Sallenger 2003), and there are some accounts of washover deposits that do not show internal structures (Sedgwick & Davis 2003) but there is still commonly consistency between the deposits created by storm events in coastal settings. Washover fans lacking internal structures are rare and often occur adjacent to washover fans with graded bedding. Grading is commonly caused by a gradual decrease or increase in flow velocities over the course of a surge event. Loss of transportability over time will grade the sands that are left behind as flow velocities ebb, while on Little Ambergris Cay the deposition of sand was near-instantaneous. Massive bedding can occur when the time of deposition is not sufficient for internal structures to form (Leatherman & Williams 1977, Leatherman & Williams 1983). Many of the sedimentation patterns in other examples of washover fans are caused by repeated overwash events in a non-submerged setting (Schwartz 1982), while on Little Ambergris Cay the entire island was submerged at a depth of about 3.5m throughout the storm.
Features such as mangroves and beach ridges play a more significant role in other geological settings (Bourouilh-Le 1998, Suter et al. 1982, Wang et al. 2007), probably due to the more significant mangrove growth and ridge topography in continental coastal settings. Little Ambergris Cay has scattered mangrove growth, but mangroves are primarily located on the northern side of the island, down-current from where the washover fans penetrated, and the beach ridges are of a low elevation, with a maximum average elevation of 1.8 m (Figure 13) that is consistent along the shore where the fans are situated, so that the morphology of the island may not have substantially altered or interrupted flow. The channel lobes may have been subjected to more complex flow due to a higher rate of mangrove growth on the northern side of the island, but flow was concentrated in channels, minimizing the effect of mangrove growth between channels. It is possible that the mangroves provided necessary cohesion for flow concentration in channels, but they are not consistent throughout the channel lobe area and there are no specific correlations between mangrove growth and deposit dimensions. The dimensions are relatively consistent and the effects of current re-working show the highest influence on their morphology. Bioturbation also plays a significant role in reworking the deposits in most instances (Deery et al. 1977), while on Little Ambergris Cay there was a lack of burrowing and other reworking of the sediments; the only biological influence observed was the gradual re-growth of microbial mats over the months following the hurricane, which did not substantially alter any sedimentary structures within the fans. Near-shore bathymetry and the depth of an interior lagoon can also affect the force and depth of the storm surges that form these deposits (Pierce 1970). The bathymetry off the coast of Little Ambergris Cay is characteristic of a shallow-marine carbonate shelf, with no near-
shore reefs to redirect the storm surge or break the strength of the surge. Flow depth is acknowledged as a factor that can significantly affect the type of washover deposits formed and their characteristics (Spiske & Jaffe 2009, Suter et al. 1982). The flow depth during Hurricane Irma was significant, submerging the island nearly completely and allowing for extensive sediment transport.

The most striking morphological feature of the fans is that they are significantly larger (about a hundred meters long) to the East of the penetration area. Beach ridge topography seems to have played very little role in the larger size of the more eastern washover fans, as beach ridge topography is low and consistent over the washover fan area (Figure 13). Subtle changes in water depth as correlated with the different microbial mat facies (Figures 5, 6) might have influenced washover sand size. Prior to Hurricane Irma, two types of microbial mats occurred in the region where the washover fans were deposited. The eastern area is characterized by polygonal mat facies, which typically occur in a slightly shallower water depth than EPS mat facies, which characterized the western washover area (Figure 14). The larger, eastern fans were in the polygonal mat facies area while the smaller, western fans correlated with the EPS mats. Flow velocities in the eastern washover fan area, characterized by slightly less accommodation space, may have started depositing sediment sooner as the hurricane ebbed, resulting in larger washover fans with larger grain sizes (Figures 8, 9). There are no topographical or vegetative features constraining flow along this area of the shore.

The flow velocities required to transport cobbles into the interior of the island were far beyond those that would be required to transport all of the grain sizes that compose the washover fans and channel lobes in washload (Figure 15). Much of the
sand-sized sediment was likely carried across the island in suspension, precluding net deposition during peak hurricane intensity. The channel lobes on the northern side of the island support the interpretation of a high level of sediment bypass; their presence shows that enough sand was transported to the far side of the island during the northward storm surge to create large deposits on the northern side when flow velocities dropped. Deep channel scours in the tidal channels associated with the lobe deposits also indicate high-energy currents. The washover fans are composed of the sediment that was deposited once the storm energy began to ebb and this bypass ceased. Given that during most of the storm event the flow velocities were too high for deposition, the short time interval over which these deposits formed likely accounts for their small scale (Figure 16). Since most of the previous studies on washover fans focused on barrier islands that were not submerged at depth during the storms that affected them (Schwartz 1982), the differences observed in the small, ungraded deposits on Little Ambergris Cay are likely the result of unusually high flow velocities and storm surge levels that completely submerged the area where the storm made landfall. The small size of the washover fan deposits on Little Ambergris Cay is probably also due to the height and strength of the storm surge. A huge amount of sediment bypassed the island entirely rather ran being deposited and adding to the sediment bodies.

The hurricane deposits described in this study differ from those described in previous studies in both the geological setting and the storm conditions. These deposits are associated with a massive open-ocean storm event on a low-topography carbonate platform, different from more topographically complex continental coasts experiencing oblique storm trajectories. The Caicos platform is often used as an analogue for ancient
carbonate depositional environments (Dravis & Wanless 2017); our observations suggest that even large hurricanes may commonly only produce small, ungraded washover fans on carbonate platforms, rather than the laterally extensive graded beds commonly observed in other settings. This indicates that small, massively bedded washover fans in the rock record may counter-intuitively indicate large storm events, as they are examples of the ebb of a major storm and not its peak energy, which causes sediment bypass rather than deposition to occur. Using the description established by this study of this type of hurricane deposit, it may be possible to begin to identify storm events in the rock record of carbonate platforms, and to better understand the source of analogous modern deposits.

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Figure 1: Little Ambergris Cay Drone orthomosaic map showing the locations of the washover fans and the channel lobes. The drone images used for this map were collected prior to Hurricane Irma, so that none of the hurricane deposits are present.
Figure 2: Storm track of Hurricane Irma showing the location of Little Ambergris Cay, directly in the path of the hurricane, and the relative strength of the storm during its traversal of the island (Modified after figure 1 in NOAA report, 2017)
Figure 3: Washover fan sample points mapped on one of the drone orthomosaic maps. The washover sand bodies formed by northward storm surge are clearly visible in this image. The sample points from which we obtained our data are marked. Note significant size increase to the East.
Figure 4: Drone orthomosaic image of channel lobes on the northern side of the island. These are also a product of northward flow. Sediment was carried over the island and deposited at the channel mouths. These sediment bodies are larger-scale than the washover fans. See scale on island orthomosaic map (Fig. 1) for exact channel lobe dimensions and size chart (Fig. 8) for washover fan dimensions. Lobes are on the order of >200m in length, >100m in width.
Figure 5: Water depth map of Little Ambergris Cay. Warmer colors show highest land elevation, cooler colors show deepest underwater areas. Darker is deeper. The interior of the island is submerged by a shallow lagoon that varies slightly in depth with tides. See facies map (fig. 6) for correlations of vegetation and microbial mat growth with elevation. The maximum elevation of the island is about 4m (Stein et al. 2016).
Figure 6: Little Ambergris Cay facies map showing sediment and vegetation types, with the washover fan area delineated. There are no major mangrove growths or impediments to deposition that should govern or constrain the size and shape of the washover fans; channel lobes are in an area of patchy mangrove growth. Hurricane deposits are constructed of oolitic sand and occur in areas of mainly microbial mat growth (Stein et al. 2016). Modified after a figure produced by the 2016 Agouron Advanced Geobiology Field Course.
Figure 7: Washover fan with no internal structures.
Figure 8: Washover fan length data showing relative washover fan size. The first chart shows our seven sample sites as marked on the sample points map (Fig. 3); the second chart shows mean lengths of washover fans from Morton et al.’s 2003 study at seven different locations. Little Ambergris Cay washover fan deposits, even the much larger-scale washover fan #7, consistently fall in the low end of the range of sizes observed in previous studies.
Figure 9: Washover fan median grain size. Grain size decreases westward. This grain size change is the only observable sediment trend consistent among the washover fans, and could be due to a loss of transport of larger grains in the eastern fans preceding the loss of transport threshold of the western fans. D50 axis represents median grain size.
Figure 10: Microscope image of oolitic sand from the Little Ambergris Cay washover fans. Median grain size of individual ooids is about 440 microns. See D50 chart (fig. 9) for median grain size range.
Figure 11: Drone images show evidence for reworking of channel lobe deposits by longshore currents between September 13, 2017 and July 3, 2018 and (top and bottom, respectively).
Figure 12: Changes in median grain size and sorting of the channel lobes between the first and second samplings. Note that only four channel lobes remain in the second sampling.
Figure 13: Beach ridge elevation shown on a logarithmic scale at five transects in the washover fan area, beside the size of the washover fans. There seems to be no correlation between topography and the size of the sediment bodies.
Figure 14: The larger, eastern fans were in a polygonal mat facies area, while the smaller, western fans were in EPS mat facies area. The EPS bacterial mats correlate with slightly greater water depth (see Fig. 5), and the flow energy in the eastern washover fan area may have dropped more slowly, leading to less immediate deposition and more sediment bypass. The larger fans to the east may be a result of slightly shallower water leading to a quicker drop in flow velocity and more deposition. Modified after a figure produced by the 2016 Agouron Advanced Geobiology Field Course.
Figure 15: Flow velocities for washover fans and channel lobes with sliding, lifting, and rolling flow velocities required to transport the boulders into the interior of the island. The high flow velocities suggest that smaller grains would have been in suspended transport. The plot on the right shows flow velocities required to transport the sand sizes composing the washover fans, and the plot on the left does the same for the channel lobe deposits. Both are shown in relation to the flow velocities required to transport the boulders into the interior of the island. Equations used to make the calculations are from Soria et al. 2018. The boulder dimensions used were average intermediate axis of 29cm and an average short axis of 14.5cm. P<2.5 gives conditions for significant sediment bypass. Equations used are from Soria et al. 2018.

Colored lines are sand velocities, black lines are boulder velocities.
Figure 16: At the height of the storm surge, sediment was in bypass. When the storm surge ebbed, flow was cut off by the beach ridges and the sediment was deposited from transport instantaneously, disallowing the formation of any internal structures.

**Height of storm surge: sediment bypass of beach ridges**

**Ebb of storm surge: cutoff of flow and instantaneous deposition from transport**

Storm surge represented by blue arrows, sediment in transport by red arrows, beach ridge by orange triangle.