Pleistocene Coral Reef Destruction in the Florida Keys: Paleotempestite Evidence from a High Resolution LIDAR XRF Analysis of Windley Key Quarry

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Abstract

Not all unconformities are alike, and for carbonates, their delineation and underlying cause can be difficult to resolve. One particularly problematic unconformity is a discontinuity surface, and among several within the Pleistocene Key Largo Limestone of Windley Key Quarry, is a laterally persistent ~1 m amplitude undulating sharp discontinuity surface. ^{234}Ur-^{230}Th dating by previous researchers reveals older ages (130 ka) above the surface and younger (126 ka) below. Is this discontinuity surface allocyclic, autocyclic or diagenetic? To address this problem, a novel approach integrating high resolution Light Detection and Ranging (LIDAR) and X-Ray Fluorescence (XRF) is employed. LIDAR reflectivity is correlated to XRF mineralogical constructed compositions and quantitatively mapped using reflectivity color extraction, which highlights aragonite, Lo Mg calcite, Hi Mg calcite, and minor clastic silt-clay occurrences. Below the discontinuity surface the corals (Montastraea *annularis* dominates with Diploria *labyrubthiformis*, Diploria *strigosa*, Diploria *clivosa*, Porites *astreoides*, Porites *porites*, Montastraea *cavernosa*, Siderastrea *radians* and Siderastrea *siderea*) are in growth position and exist today in various stages of aragonite to calcite inversion and solution-reprecipitation. Above the surface are tumbled and dislodged corals of similar diagenetic state, poorly sorted broken sand to cobble-sized rubble, disarticulated mollusks, and low Mg calcite mud. When cutting through coral heads the discontinuity surface is coated by Hi Mg calcite coralline algae. To break or fracture the observed Montastraea *annularis* species would take considerable wave energy (greater than 44 meganewtons/meters^2 reported). If due to a hurricane or tsunami, such an event would allow the observed subsequent regrowth or repatriation of the same species under continuous subaqueous conditions and help explain the observed ^{234}Ur-^{230}Th vertical stratigraphic age inversion. These observations suggest this discontinuity surface within the Key Largo Limestone to represent an autocyclic paleotempestite signature of a Pleistocene hurricane or tsunami rather than a short-lived Stage 5e eustatic sea level fall.

Problem Definition

1. Is the observed discontinuity surface within the Sangamon Key Largo Limestone a product of autocyclic or allocyclic processes?
2. How much time has passed, ~a vs ka, respectively?
3. How can a detailed 3D mineralogic, XRF constrained, LIDAR map of pre and post discontinuity event strata provide insight into possible hypotheses?

Study Area

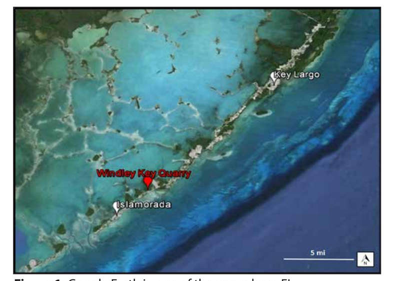

Figure 1: Google Earth image of the upper keys, FL.

Figure 2: Aerial view of the whole Florida state park and the Windley Key Quarry.

Figure 3: Inside Windley Key Quarry

The Florida Keys form a crescentic string of limestone islands connected by Highway US 1 (Hoffmeister, Multer, 1968). North is the Florida Bay and Gulf of Mexico, and south is the Atlantic Ocean. The keys are broken up into the Upper Keys and the Lower Keys, both of which are on continental crust and a passive margin. The Pleistocene Key Largo Limestone (formation of interest) crops out throughout the Upper Florida Keys. The area of interest is inside a quarry, which is located within Islamorada, Florida (Figure 1). Islamorada is one of the upper keys and is just south of Key Largo. Windley Key Quarry contains beautiful exposures of the Key Largo Limestone and has three main walls: approximately West, North, and East facing (Figure's 2 and 3). All of the walls are approximately 10 feet tall and have flat, laterally continuous tops. The walls are flat on top possibly because they were exposed, above the paleo water level, and were eroded.

Geologic History

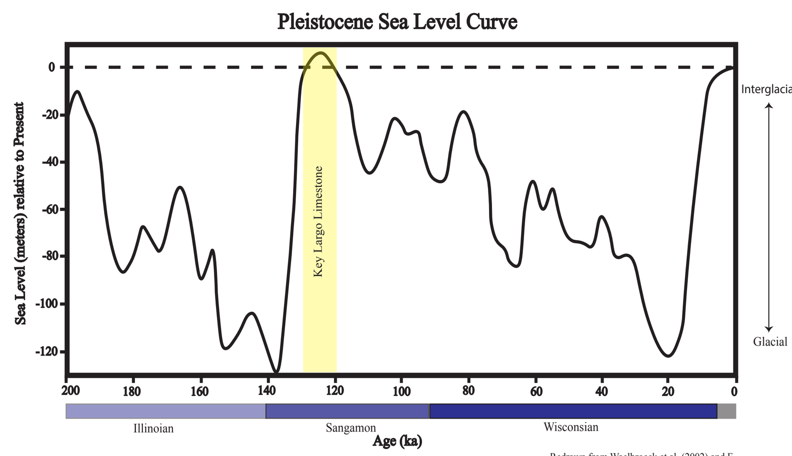

Figure 4: Sea level curve during the Pleistocene. The Key Largo Limestone Formation originated during the last interglacial, around 120 ka, where sea level was up to 8 m higher than today.

During the Pleistocene, a shallow marine embayment slowly separated the Keys from the mainland, then over time, sediment fill produced shallower and thus warmer seas where carbonate and plant growth flourished (Multer, 2002). The Key Largo Limestone has been estimated to be about 120-140 ka and is a Boundstone/Biolithite with Montastraea *annularis* dominating more than half of the framework (Stanley, 1966). The transition from glacial Illinoian to interglacial Sangamon occurred approximately 125,000 years ago (Figure 4). Sea level rose to ~8m above the current level, such that all of southern Florida was an epeiric sea. This sea level peak, around 120 ka, accompanied Key Largo Limestone deposition. During the Wisconsian stage, about 85,000 years ago, global glacial onset began to lower sea level, exposing and killing the reef. Karstification ensued. The Key Largo Limestone makes the upper Florida Keys, Soldier Key to Bahia Honda, and in some areas measures to as much as 145 feet (Hoffmeister, 1974). Today, Windley Key Quarry sits 18 feet above sea level, which is the highest natural elevation in the Florida Keys (State of Florida, 2012).

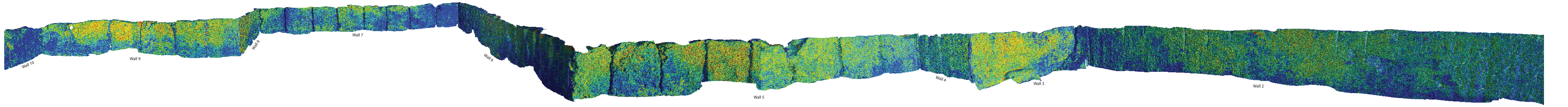

Figure 8: Reflectance of walls 2-10 between 325-328 decibels

The computer program RiscanPro 2.0.1 is used to view, process, and interpret LIDAR scans. Multiple filters are run to clean up the data. For example, the terrain filter omits vegetation and unwanted objects and the octree filter condenses the data by eliminating dense clusters of points. Once the point data is clean, it is triangulated to create a mesh. The most useful attribute is reflectance viewed between 325 and 328 decibels. Reflective percentages are referred to as LIDAR intensity. This means the strength of the returning light pulse varies with the composition of the surface object reflecting the return.

Data Collection

LIDAR

LIDAR (light detection and ranging) is a device that scans a terrestrial environment and produces a high-resolution image (Figure 5). This remote sensing device sends out light pulses that reflect and return to the LIDAR. The LIDAR records the time difference between the laser pulse's departure and return. The user determines the amount of light pulses the LIDAR will use. Displayed, each light pulse is recorded as a 'point', so each scan will generate a 'point cloud'. The more light pulses used, the denser the point cloud will be resulting in a high resolution image. Once a scan is complete, the LIDAR took seven pictures, each time rotating 51.43 degrees to create a 360 degree image. These pictures are later meshed with the point cloud data to view the scan's 'true color'.

Figure 5: LIDAR secured on a tripod in the field. This is a Laser Class 1 VZ-400 with a maximum range of 600m, precision of 3mm, and an accuracy of 5mm. It also contains an internal GPS and Wi-Fi capability, so scan data is downloaded real time to an adjacent computer. A Nikon D800 camera is mounted on top of the LIDAR

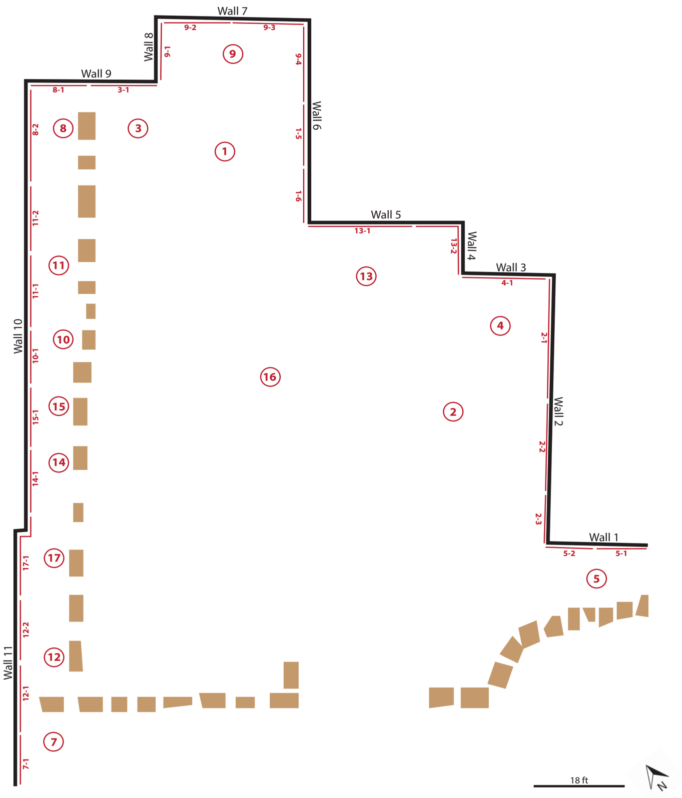

Figure 6: Map of Windley Key Quarry. Each scan position is circled in red and their high resolution scans are numbered along the quarry walls. 2-2 means Scan Position 2, high resolution scan 2. The brown blocks are large boulders (see Figure 3).

The LIDAR is moved multiple times to image all the quarry walls. These multiple scan positions are tied together by referencing common points. These 'tie points' are very reflective for quick identification on the scan image. 23 reflectors were securely placed around the quarry. Figure 6 is a sketch which highlights the walls that were scanned. There are 16 scan positions but a total of 69 scans. At each position the first scan is 360 degrees followed by carefully chosen higher resolution scans which allow the visualization of exceedingly fine detail, eg. Coral septa.

XRF

A portable X-Ray Fluorescence (XRF) Thermo Scientific Niton XL3t Ultra was used on the Windley Key Quarry walls to detect the major and light elements. Measurements were taken every 5 ft. laterally and every 1 ft. vertically across and up the walls. Measurements were also collected at areas of interest that did not fall in the grid. The sample time for each measurement was 210 seconds and 412 measurements were taken.

Once the scans in the field were complete the XRF was calibrated, using pure mineral samples from the University of Oklahoma's mineral collection. The calibration output was transferred to a spreadsheet and the values taken from the field were then reported. The elements of interest are iron (Fe), sulfur (S), magnesium (Mg), calcium (Ca), aluminum (Al), silicon (Si), and strontium (Sr). The measured standards of those elements were used to calculate the amount of pyrite, gypsum, aragonite, high Mg calcite, calcite, clay and quartz-chert present in each XRF measurement. The data is then displayed in excel graphs and compared to processed LIDAR scans to identify lateral and vertical trends.

Figure 7: XRF station 33 is in the middle of wall 6. The black circles (A-E) mark station letters which are, from the bottom up, 33a, 33b, 33c, 33d and 33e. Pie graphs to the right illustrate the amount of aragonite, calcite, high mg calcite, pyrite, gypsum, clay and quartz-chert present. Notice the discontinuity cutting across a Diploria *labyrubthiformis*.

XRF measurements every 5 ft. across the quarry walls (Figure 6) totaled to 82 stations. Depending on the wall height 4, 5 or 6 XRF measurements were taken at each station. Each sample is about 1 ft. apart, optimally over a flat surface. Figure 7 reveals only the results of station 33; however, all 82 stations have similar photographs that label each coral species and the gradational minerology. To better understand the mineralogy, extra XRF samples were taken inside and around the Diploria *labyrubthiformis* in the middle of the wall. Extra samples were taken here because the coral is well preserved and has a discontinuity surface cutting through it (red arrow). The sample locations and results are shown in Figure 10. These XRF results were used to calibrate LIDAR reflectance scans to show the limestones' mineralogical distribution.

Data Interpretation

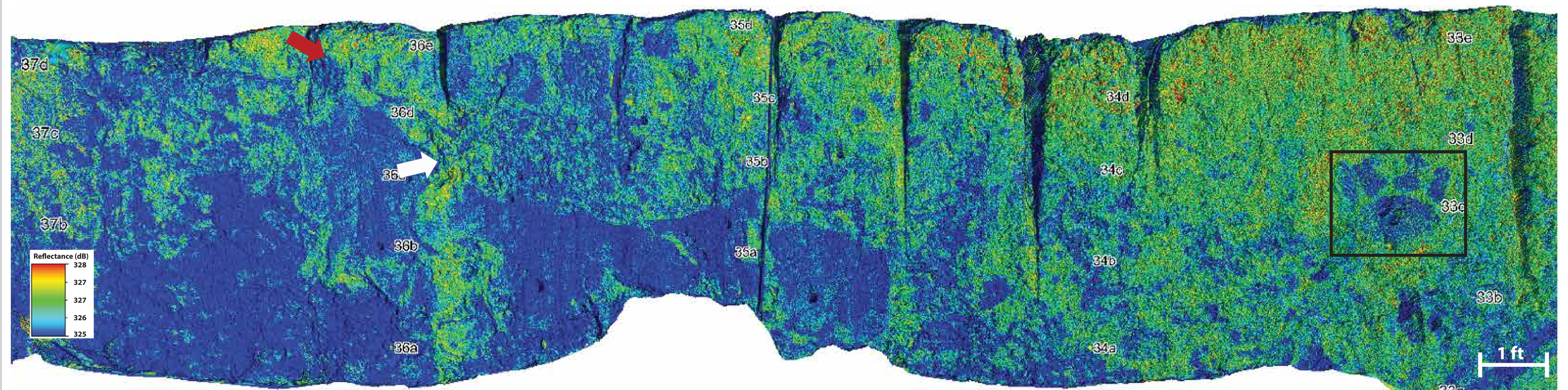

Figure 9: Reflectance of wall 6 (5.3 ft. high) using a gradational rainbow color bar between 325 and 328 dB. XRF sample locations have been added and notice the discontinuity surface marked by the red arrow. Figure 10 zooms in on the black boxed area. The surface is coated with high Mg calcite, thus it acts as a migration pathway and not a seal. The white arrow marks one location where fluids have leaked through the discontinuity surface and percolated down the wall accelerating aragonite to calcite inversion.

Comparison of XRF and LIDAR Mineralogy

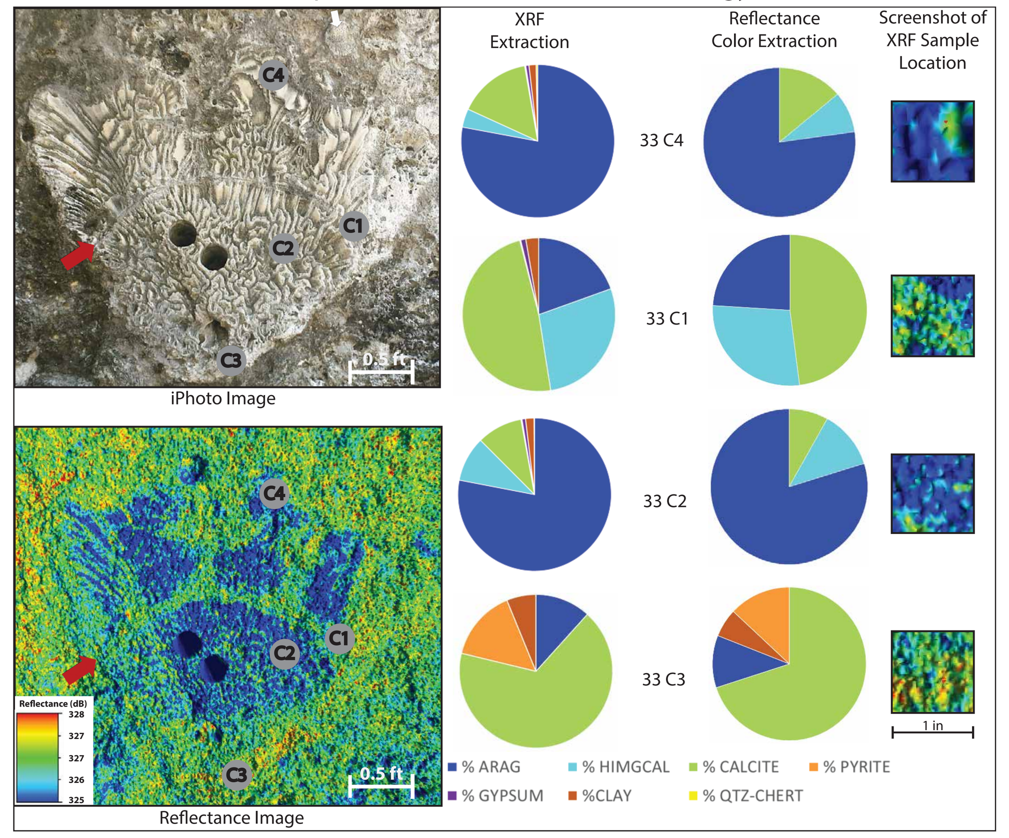

Figure 10: The close up view of this Diploria *labyrubthiformis* (iPhone image on top and reflectance below) demonstrates the power of a high resolution LIDAR scan. Inside each image are grey circles C1-C4, which represent exact XRF scan positions. The first column of pie graphs indicate the percentage of each mineral given from the XRF scan. The second column of pie graphs show the percentage of each color present in the image to the right. The images in the third column are screenshots of the exact XRF scan location on the LIDAR reflectance scan. The red arrow marks another discontinuity surface and the small white arrow in the top right corner points to an upside down coral.

To calibrate LIDAR reflectance scans to XRF mineralogy a screenshot of the exact scan location was run through a color extraction algorithm. The mineral percentage closely matched the percentage of each color present; therefore, a specific color represents a specific mineral. The lower values, the blues, represent aragonite rich areas where the higher values, the yellow/greens, represent areas with more calcite. Also, the lightest blues are high Mg calcite and the highest values, the reds, are clays and/or vegetation.

The majority of well distinguished or preserved corals are mainly composed of aragonite, as is 33C2 and C4. Other corals, that appear more weathered, are composed of various stages of aragonite inverting to calcite especially around the rims of corals. Low Mg calcite carbonate mud fill cavities, burrows, or previously porous areas. The undulating discontinuity surfaces are coated by high Mg calcite coralline algae.

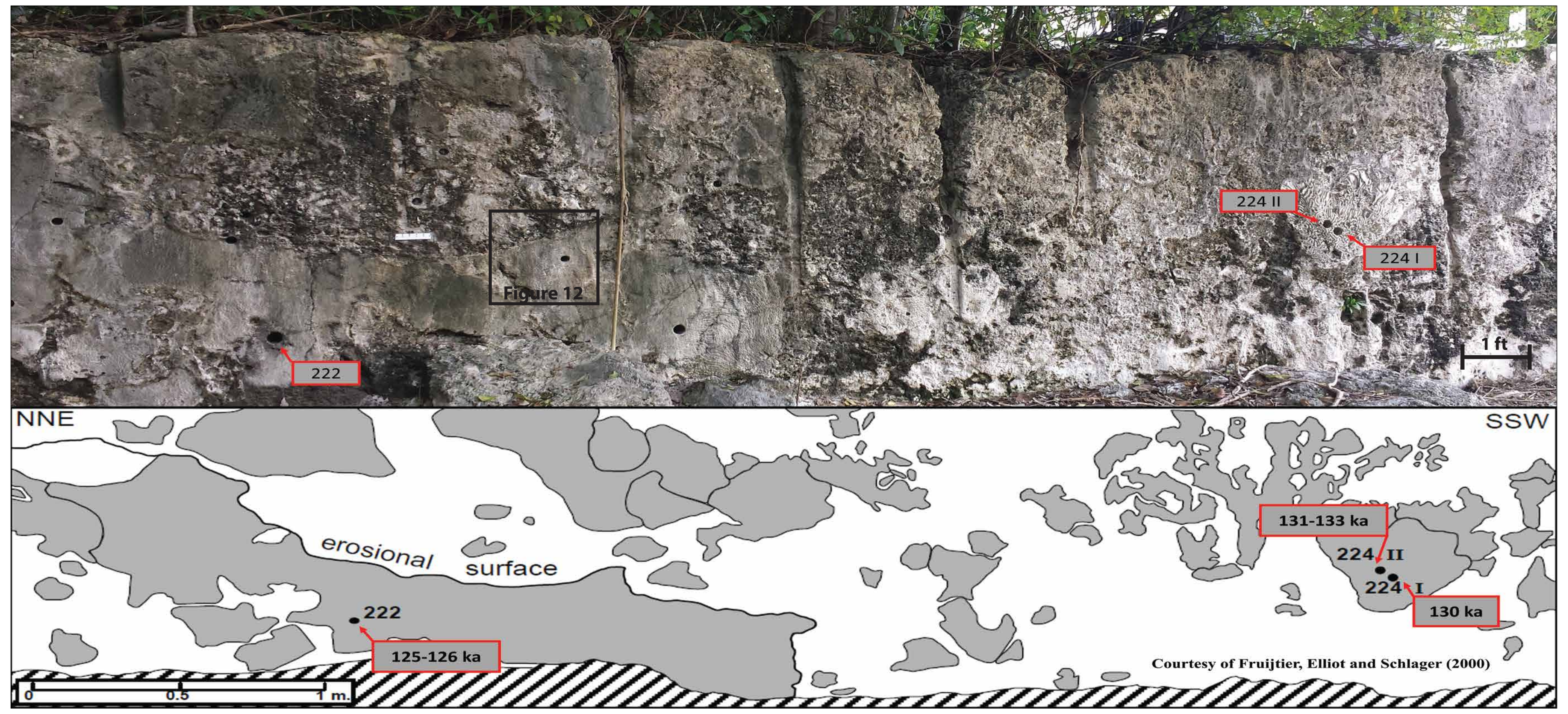

Figure 11: Fruijtier, Elliott, and Schlager (2000) found the (^{234}U ^{230}Th) date of a coral below the surface to be younger (125-126 ka) than one above the surface (130-133 ka). They believe Uranium leakage is to blame for the 5,000+ year age difference. Major dissolution or recrystallization of a coral from aragonite to calcite may mobilize ^{238}U. Another possibility is a catastrophic storm ripped up and transported the older coral (sample 224) to its current location. Other evidence being above the erosional surface is an abundance of coral rubble, the iPhoto image from Figure 10 shows a close up view of this coral and right above it is an upside down coral and Figures 12-16 below.

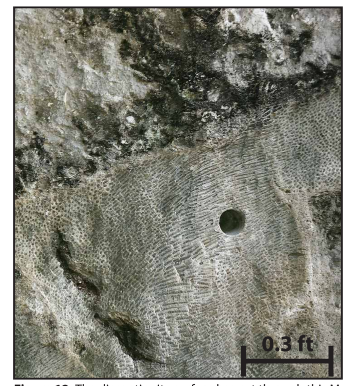

Figure 12: The discontinuity surface has cut through this M. *annularis*. A gradual sea level fall nor diagenesis would terminate a coral as shown. It also seems to be titled sideways.

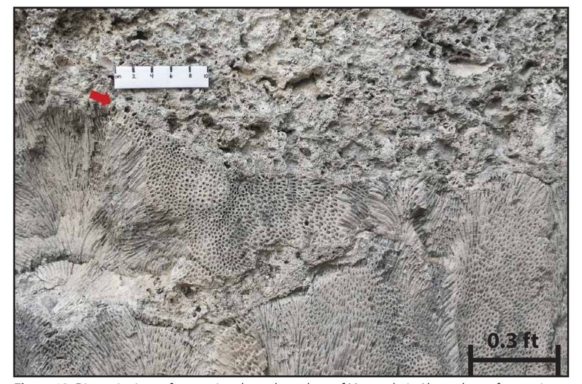

Figure 13: Discontinuity surface cutting through a colony of M. *annularis*. Above the surface notice coral rubble consisting of broken coral, mollusks, and halimeda flakes.

Figure 14: At the bottom of wall 10 a M. *annualris* lay on its side.

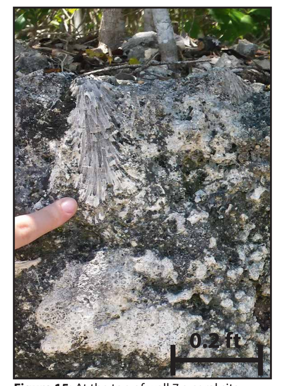

Figure 15: At the top of wall 7 a coral sits upside down in a jumbled mix of mud and coral rubble.

Figure 16: Coral rubble consisting of halimeda flakes, broken coral, burrows, mollusks and bivalve shells.

Conclusions

Repatriation of like coral species and similar species density niches without obvious vadose diagenetic signatures above and below the surface, coral rubble floating in mud above the discontinuity surfaces, and toppled corals no longer in growth position posit the results of a huge storm event rather than eustatic sea level fluctuations. This hypothesis also explains why the dates of the coral rubble above the discontinuity surface turned out to be older than those below. Other discontinuity surfaces are under investigation.

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