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Interactive comment on "Divergence of seafloor elevation and sea level rise in coral reef regions" *by* Kimberly K. Yates et al.

Kimberly K. Yates et al.

kyates@usgs.gov

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We greatly appreciate Reviewer 1 providing constructive comments on the broader conceptual aspects of our paper related to his expertise, and for acknowledging that he is not a technical expert on the methods we applied in this study. We understand that the reviewer has doubts regarding the accuracy of results generated using historical and modern elevation data. However, in the absence of specific comments regarding our use of these data, we are uncertain as to how to address any specific concerns for the reviewer. We, therefore, provide a discussion to help clarify the methods by which we evaluated the data, calculated error, and additional analyses we performed to validate it's use.

Our study examined changes in seafloor elevation within 5 regions characterized by

extensive coral reef ecosystems that included reef flats as well as reef crest and slope habitats, adjacent (non-coral dominated) habitats such as seagrass beds, sand bottom, and hard bottom communities, and (in some cases) deeper water habitats. Our Maui study site included the coastal region surrounding the entire island to a depth of 20 m and examined changes in elevation from 1961/65 to 1999. Our St. Thomas study site included the entire southern coastline of the island including habitat out to 5 km offshore and examined changes in elevation from 1966/73 to 2014. The Buck Island study included an extensive area east of the island and to a depth of 37 m, and examined changes in elevation from 1981/82 to 2014. Our Florida Keys study site included outer reef track and surrounding habitats of the Upper Florida Keys and Lower Florida Keys, and examined changes in elevation from 1934/35 to 2002.

While the methods used to collect, process, validate and analyze the data used in this study are complicated, the general concept of the method is relatively simple. We have created a flow diagram that depicts the core processing steps (see Figure 1), and we will include this figure in our revised manuscript. We measured the differences between historical and modern seafloor elevation using data sets from the time periods indicated for each study site. Using this method provides a measure of the net change in seafloor elevation due to all of the constructive processes that cause accretion (or increases in seafloor elevation) and the destructive processes that cause erosion (decreases in seafloor elevation), and, therefore, provides a mechanism for assessing the combined impact of natural and anthropogenic processes that affect seafloor change. Although the general concept is straightforward, a number of very rigorous analyses were performed to test the validity of comparing historical and modern data sets; very conservative methods were used to calculate error associated with the methods; and the effect of that error on our results was quantified and reported. The key findings of this study indicate that all habitat types (including non-coral dominated habitats that are typically supported by carbonate sediment production on coral reefs) within these ecosystems have experienced a net loss in seafloor elevation causing a general decrease in mean seafloor elevation at the regional-scale.

The type of elevation change analysis we performed (using comparisons between historical and modern elevation data sets) has traditionally been used by coastal engineers to monitor seafloor changes such as sediment accretion and erosion, and migration of shipping channels, sand bars, mud banks and other seafloor features in coastal environments, and the methods are well documented. We provided a few references for examples of this type of work on page 3, line 4 (e.g. Byrnes et al., 2002; Taylor and Purkis, 2012; Byrnes et al., 2013). We present results from the first application of this method to coral reef ecosystems, and feel that this method is most appropriately used over the large spatial scales of this study.

Following published methods for use of historical elevation data sets, we performed visual inspection of all of the historical (Hsheet) data, relative to 2016 aerial and satellite imagery with a resolution of 1 m, to measure differences between stable coastal and geographic features (Lukas, 2014). For example, in the Upper Florida Keys we were able to locate a historic bridge that was surveyed in the 1930s and still exists today. We overlaid the georectified 1934 Hsheet on 2016 georectified Worldview imagery and used measuring tools in ArcMap to examine the offsets in this structure. The maximum offset of bridge boundaries between historical and modern locations was 4.8 m. See Figure 2, in this discussion, for that example.

This offset is similar to the sum of errors reported in our horizontal error analysis in Section 2.5.2, page 10, lines 16 - 28. Incidentally, we chose to sum the estimated sources of horizontal error (rather than to calculate a root mean square error, RMSE) because no horizontal error information was provided in the metadata for our historical data, and summing of sources of potential error (derived from the literature) provided a more conservative estimate of error. In other study sites, we were able to identify stable, rocky coastlines and/or man made features (such as shoreline berms) for these types of comparisons. In offshore areas, we examined areas in the historical data where the boundaries of large patch reefs were outlined by soundings when depths were too shallow to pass over the reef and deviations were made from linear transect lines.

There were no significant misalignments between historical and modern boundaries for reefs that experienced minimal erosion. We performed these visual inspections for all historical (Hsheet) data from all study sites and found similar alignment agreement.

Additionally, where it was possible for us to visit study sites (e.g., areas of the Florida Keys and Western Maui), we visually inspected the seafloor for erosion features that were consistent with trends identified by our analysis. For example, our data from the Florida Keys shows some offshore areas along relict spur and groove formations where seafloor elevation is increasing. Visual inspection of these areas showed infilling of spur and groove with sediments (see Figure 3 in this discussion).

We then performed an experimental exercise to determine the potential impact of horizontal error of up to 10 m (2 x the sum of our estimated horizontal uncertainties) on volume change calculations (see ‘Section 2.5.2, page 11, lines 1 - 20) to account for estimated systematic error plus any additional, random error of up to an additional 5 m. We note that 10 m of horizontal error is consistent with horizontal error typically reported for data plotted at a 1:20,000 scale (Anders and Byrnes, 1991; Fletcher et al., 2003; Morton et al., 2004). These results indicate that horizontal error of up to 10 m and the resulting offsets in sounding points affects our volume calculations by 10% to 21% (depending on density of data points) and does not change the outcome or conclusion of our study. These results are consistent with reports that, over large areas (such as in our study), random errors largely cancel-out relative to change calculations derived from two surfaces (Byrnes et al. 2002).

We also performed an analysis of submerged substrate such as pavement or bedrock that may have some areas that showed no accretion or erosion to independently evaluate the potential vertical error associated with comparing historical and contemporary sounding methods. We did not include these results in the original manuscript because no subaqueous surface areas, including bedrock, are exempt from elevation change, and this analysis does not represent a true control. For example, our data indicate areas where pavement has been exposed due to erosion of overlying sediments, and areas where pavement has been buried by deposition of sediments, growth of corals, etc. However, we include the analysis and results in this discussion as supporting evidence that validates comparison of these data sets. For the pavement analysis, we examined habitats labeled 'pavement' in the UFK and LFK, 'uncolonized pavement' in St. Thomas, 'colonized pavement' in Buck Island, and 'coral pavement' in Maui (see Table 2 in manuscript). We filtered the elevation-change data points for these habitats to include only data with elevation-changes between historical to modern points of less than +/- 0.5 m (1.65 x RMSETotal). We then calculated the average difference between these points and the corresponding standard deviations. See Table 1, in this discussion.

More than 50% of elevation-change points in the UFK, STT and BI showed elevation changes within our 1.65 x RMSETotal of 0.5 m, and standard deviations for these location were all within our RMSETotal of 0.29 m. 17% and 23% of points were within +/- 0.5 m for the LFK and Maui, respectively, with standard deviations below RMSETotal of 0.29 m. Average differences between historical and modern elevation data in these locations were very small (ranging from 3 to 6 cm) indicating that vertical resolution and accuracy of historical and modern elevation data are, in fact, comparable. However, standard deviations were large, confirming that all areas of pavement are not stable and, therefore, should not be considered a true control. Further examination of histograms for the pavement analysis data support the general conclusions for each of our study sites (see Figures 4a – e, in this discussion).

Histograms for the UFK, LFK, STT and Maui are all skewed toward negative values, consistent with regional-scale trends of seafloor elevation loss and export of sediments at these sites. While Buck Island (St. Croix, d in the figure) shows a more even distribution of points among elevation losses and gains consistent with the lower regional-scale mean elevation losses observed at this study site. Notably, of the five study sites, the 'colonized pavement' we examined for BI was the only pavement habitat to show a very small increase in elevation that could be due either to coral growth on the pavement or burial of pavement by sediments. The latter supports our suggestion that less sediment is exported from this system. While we feel that these results are consistent with our general conclusions and further validate our results, we do not feel that they adequately serve the purpose of a control.

With respect to historical data, the U.S. Office of Coast Survey imparted strict standards on collection of data from the 1800's to 1950's that, in fact, allowed for less error than later in the 1900's when electronic means of collecting sounding data replaced lead lining and poling (Shalowitz, 1964). For data collected by the Coast Survey from the late 1800's to 1950's, maximum allowable differences at crossing data points was 0.06 m for depths less than 4.6 m, and 0.46 m for depths between 22 and 29 m (Byrnes et al., 2002). Lead line and poling resolution reported for the historical data sets was 0.15 m (similar to that of LiDAR), while fathometer resolution was 0.3 m. Furthermore, sounding poles were used in depths less than 3 m (where many shallow patch reefs are located). Many Hsheet descriptive reports indicate that the water was clear enough during surveys to see the bottom (which improves accuracy of the measurement). The most common error likely to occur during use of lead lines or sounding poles was overestimation of water depth due to angling of the line or pole as currents move the boat past the point of measurement. Overestimation of historical water depth would erroneously decrease elevation losses calculated using our methods. Therefore, it is more likely that our erosion estimates are underestimated rather than overestimated due to lead line and poling techniques. Furthermore, historical data sets from the same time frames that used similar collection methods are routinely used by the U.S. Army Corps of Engineers for coastal engineering projects, seafloor evolution and sediment budget studies, and to examine migration of coastal seafloor features over much smaller and deeper geographic regions than our study and have been proven for this purpose.

The maximum error was reported in each historical Hsheet description, and was quantitatively determined at the time the surveys were conducted by repeat surveys and cross tracklines. The maximum reported vertical difference between all of the repeat and cross-track line survey points (including deep water points) that were collected by the original surveyors for the purpose of determining historical data quality of the data sets we used in this study was 0.46 m (the standard set by the U.S. Office of Coast Survey); however, this is not a measurement of accuracy. We, therefore, reanalyzed all of the historical repeat and cross-track line survey data from the original historical data sets to perform a more rigorous systematic vertical error analysis (as opposed to simply using the reported maximum difference) of the historical sounding measurements that was not originally performed in the historical data QA/QC (see page 9, lines 2 – 29 in manuscript). We calculated the mean difference in depth between all pairs of repeat measurements and used these data to generate an RMSE for historical sounding data. Results from this analysis are termed RMSESounding in Table 4 (manuscript), and range from 2 to 37 cm. We also calculated the error associated with transformation of each data set to a common vertical datum using the latest release of VDatum software (version 3.6) from the NOAA National Geodetic Survey. The maximum cumulative uncertainty for VDatum regions of South Florida and the U.S Virgin Islands is 9.6 cm and 11.8 cm respectively, and the cumulative uncertainty values calculated for our data sets were 8.1 cm and 11.4 cm. No vertical transformations were performed on the Maui data because both historical and modern data sets were already in the common tidal datum of MLLW.

We then performed an analysis of vertical error using U.S. Federal Government Standards (see ‘Vertical error analysis’ section 2.5.1). Our vertical error analysis included error terms for:

1) modern LiDAR data sets (RMSELiDAR). LiDAR uncertainty was determined by independent validation of airborne LiDAR measurements with in-water acoustic sounding measurements performed at the time that the LiDAR data was collected and reported in the metadata for these data sets. 2) historical data sets (RMSESounding) as determined from our analysis of repeat measurements that were performed by the original surveyors at the time of data collection, and 3) uncertainty from transformation of data

to a common vertical datum as calculated using VDatum (RMSEVDatum) for each individual data set.

These uncertainty values specific to each data set (Table 4 in manuscript) were included in our calculations of RMSE (see page 8, equation 1 for RMSETotal).

Our average RMSETotal (Table 4 in manuscript) for all study sites was only 0.29 m. However, to take an even more conservative approach, we multiplied our RMSETotal by a factor of 1.65 to encompass 90% of the variance in our data and generate a more conservative RMSE of 0.48 m that we rounded up to 0.5 m; and we used this value to set minimum and maximum bounds in our volume calculations (Table 1 in manuscript). The minimum volume change values that we report in Table 1 were calculated by only including elevation changes that exceeded the range of -0.5 to +0.5 m to provide a very conservative estimate of volume change. These very conservative minimum volume change values also support our conclusions of net seafloor erosion at all study sites (Table 1 in manuscript). Additionally, the minimum elevation change unit in Figures 1 – 3 (in manuscript) is equivalent to our 1.65 x RMSETotal of 0.5 m to make is easier for the reader to visualize the data that was removed from our minimum bound volume calculations. Furthermore, our average RMSETotal of 0.29 m is half the reported error value for studies that used nautical chart data to create digital elevation models for examining the response of reefs to sea level rise (e.g., Leon et al. 2013 and Hamylton et al. 2014). We specifically did NOT use nautical charts for our analysis because they often represent smoothed, interpolated surfaces that are not as accurate as the sounding data from Hsheets.

The small (less than a meter) elevation changes reported in Table 1 (in manuscript) are mean values over the whole ecosystem or mean values for the habitat type (Tables 1 and 2 in manuscript). It must be noted that our mean elevation changes represent the net change encompassing all negative (elevation losses) and positive (elevation gains) values. We note that the standard deviations are large because individual measurements of elevation change were often very large (greater than 1 meter, see minimum and maximum elevation loss and gain data by habitat in Table 2, and in Figures 1, 2 and 3). We analyzed 118,710 data points from 59 habitats across all study sites. Review of the ‘Mean loss’ column in Table 2 (in manuscript) shows that of the 59 individual habitat analyses we performed, only one habitat in St. Thomas (reef rubble), and one habitat in Buck Island (seagrass) showed mean losses less than our RMSETotal of 0.29. Only two habitats in the Upper Florida Keys (discontinuous seagrass and not-classified), five habitats in St. Thomas (seagrass, macroalgae, unknown, and uncolonized pavement), five habitats in Buck Island (colonized pavement with sand channels, scattered coral/rock in unconsolidated sediment, reef rubble, colonized pavement and seagrass), and two habitats in Maui (rubble and mud) showed mean losses less than 0.5 m, or 1.65 x RMSETotal that encompasses 90% of the variability. Therefore, mean losses in 97% of the habitats we analyzed were greater than our vertical RMSETotal of 0.29 m, and 77% of the habitats we analyzed showed mean losses greater than 1.65 x RMSETotal or 0.5 m. In several cases, and particularly associated with coral-dominated substrate, mean losses exceeded 1 meter. Conversely, if one examines only those locations within habitats where elevation gains occurred (‘Mean gain’ column in Table 2), 92% of the 60 habitats show showed mean gains greater than our RMSETotal, and only 60% showed mean gains greater than our 1.65 x RMSETotal. Again, standard deviations are large for these data because they reflect the true nature of losses associated with a highly topographically complex system.

We feel that we have proven the validity of our results and use of historical and modern data sets for our analyses with our expanded error analysis and our use of a very conservative RMSE for data calculations. Our conclusions regarding loss of seafloor volume are based on actual measurements of elevation-change shown to be statistically significant in over 90% of the habitats we analyzed, and that account for all of the processes causing elevation loss in these regions. We have found no prior studies that fully account for all processes causing elevation change in coral reef ecosystems; and we recognize that total erosion at the regional scale has likely been underestimated in prior studies as a result. We have accounted for uncertainties, reported actual losses

that have already occurred, and made no assumptions regarding spatial and temporal scaling or distribution of elevation changes as are often made when modeling erosion from carbonate budgets. Our projections are based only on our measured rates for what has already occurred in these systems, and, therefore, likely underestimate future losses because they do not account for any future decreases in carbonate production, increases in carbonate dissolution and bioerosion, or increases in physical erosion due to increases in frequency and magnitude of storms. Similarly, our projections of increases in water depth are based on current, measured rates of seafloor elevation change and current rates of sea level rise. The water depth projections are also likely underestimated for the same reasons that seafloor volume loss may be underestimated, and because we have not accounted for any projected increases in rates of global sea level rise.

Responses to specific comments from Reviewer 1 (RC1).

RC1: Page 1, Line 1 : All dictionaries define Â′n sea floor ÂËŹz as Â′n the bottom of a sea or ocean ÂËŹz. Accordingly, using this term to describe the Pre-Holocene bed rock that underlies a coral reef body and forms its foundation is inappropriate.

The page and line reference for this comment refers to the manuscript title, which makes no reference to Pre-Holocene (or Pleistocene) bedrock. In Section 2.4 ‘Lower Florida Keys – volume to Pleistocene bedrock’, we discuss the thickness of the Holocene reef layer lying above Pleistocene bedrock, but do not use the term ‘seafloor’ in this section. In the Discussion, Page 15, Lines 15 - 25, we discuss the results of our Holocene reef-volume-change analysis and provide an estimate of how long it would take for the remaining Holocene reef to erode to Pleistocene bedrock, assuming a constant rate of erosion, but do not use the term ‘seafloor’. We make no explicit use of ‘seafloor’ in reference to Pre-Holocene bedrock. We are a bit confused as to where we have used the term inappropriately. Please clarify so we can correct or explain.

RC1: Page 3, Line 17 : I question the use of Â′n the number of people living close to the reef sites ÂËŹz as a parameter for anthropogenic impacts. Is the number of inhabitants the reflection of the local human activity (fishing, : : :.) ?

We agree that population size alone does not reflect the total impact of human activity, which is why we stated that population size serves as the "simplest first-order parameter" for estimating anthropogenic impacts. Later on Lines 18-20, we further acknowledge that "Full analysis of anthropogenic impact factors (e.g., urban extent, developed land, terrestrial water run-off, water quality, etc.) is beyond the scope of this paper." The point we are making is that among our 5 study sites, the ones in proximity to higher human population densities exhibited larger net loss of seafloor elevation.

RC1: Page 12, Line 16, about Â′n the coral-dominated habitats ÂËŹz : It would be useful to have some information about the living coral cover. This will inform the debate on the real state of health of each studied reef site.

Thanks for this suggestion. We will provide information on percent live coral cover for those areas where it is available in our revised manuscript.

Page 14, Line 8 : about the chronic erosion processes. These are natural processes affecting reef systems. Reef growth reveals to be the subtle balance between constructional and destructional processes. They occur continuously on both pristine and degraded systems.

We fully agree and make no statement to the contrary. In the cited paragraph, our aim was to make the point that our estimates of seafloor elevation change reflect the net result of all constructional and erosional forces affecting these regions.

RC1: Page 14, Lines 20 – 21 : It is clear that reefs that are located closed to urban areas are suffering significant deterioration. It would be intersting to compare these results with a reef system located in a remote and not inhabited area.

We agree. With the exception of Buck Island (which is uninhabited, but not remote), we were unable to locate sufficient historical and contemporary bathymetric data to perform our analysis in more remote, uninhabited locations. We would be very interested in such a comparison as well.

RC1: Page 14, Lines 26-27-28 : about the assertion Â′n coral reefs in all three regions will be unable to keep up: : :: : :: : : (Church et al., 2013) ÂËŹz. This is an overinterpretation of the data presented herein. Using mean rates of reef accretion established at the scale of the Atlantic and Pacific to infer future responses of reefs to the rise in sea level is not receivable. A number of previous studies worldwide indicated that vertical reef accretion varies from site to site in a given region. There, some reefs will be able to maintain pace with sea level, while others will be unable to compensate for sea level rise.

This is a fair point. We will re-write that passage to indicate that the coral reef ecosystems at our study sites have lost pace with sea level rise, but local variability in coral growth rates may enable other reefs in these regions to keep pace with sea level rise. We did not use mean rates of reef accretion for the Atlantic and Pacific to infer future responses of reefs. Rather, we used these rates to infer/estimate the amount of reef accretion (in years) that has already been lost in the past few decades at our study sites.

RC1: Page 15, Line 29 and Page 20, Line 23 : Please correct the reference : Neumann and Macintyre, 1985

Thank you for pointing out this mistake. We will correct it in our revised manuscript.

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Richmond.: Mapping Shoreline Change Using Digital Orthophotogrammetry on Maui, Hawaii. J. Coastal Res. SI-38, p. 106-124, 2003. Lukas, M. Cartographic Reconstruction of Historical Environmental Change.: Cartographic Perspectives. n 78. DOI: 10.14714/CP78.1218, 2014. Morton, Robert A., Miller, Tara L., and Moore, Laura J.: National assessment of shoreline change: Part 1: Historical shoreline changes and associated coastal land loss along the U.S. Gulf of Mexico: U.S. Geological Survey Open-file Report 2004-1043, 45p., 2004.

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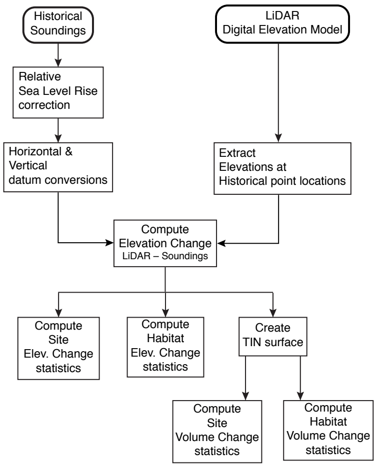

Figure 1. Flow diagram of the core data processing steps used to compute seafloor elevation and volume changes.

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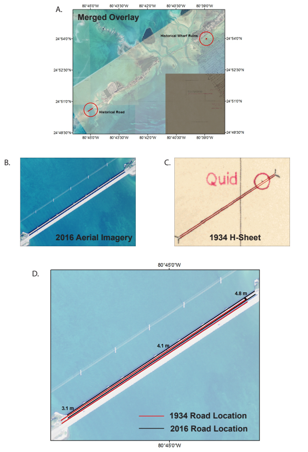

Figure 2. Example of visual inspection of historical Hsheets relative to modern aerial imagery as a primary 'check' for horizontal alignment. (a) overlay merging the (b) 2016 aerial imagery with (c) 1934 Hsheet. (d) ArcMap measurement lines.

Fig. 2. Figure 2. Example of visual inspection of historical Hsheets relative to modern aerial imagery as a primary 'check' for horizontal alignment. (a) overlay merging the (b) 2016 aerial imagery with (c) 1

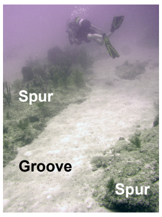

Figure 3. Infilling of spur and groove formation on the outer reef tract of the Upper Florida Keys.

Fig. 3. Figure 3. Infilling of spur and groove formation on the outer reef tract of the Upper Florida Keys.

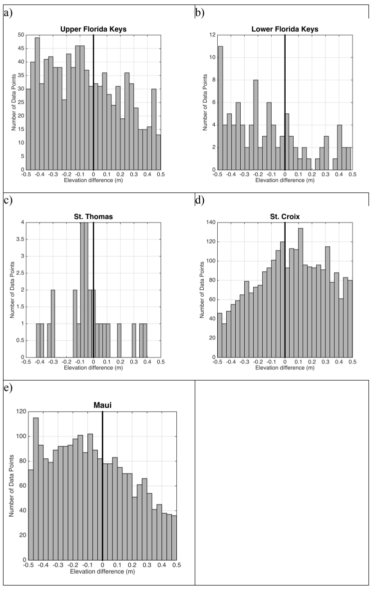

Figure 4. Histogram analysis of pavement elevation-change data.

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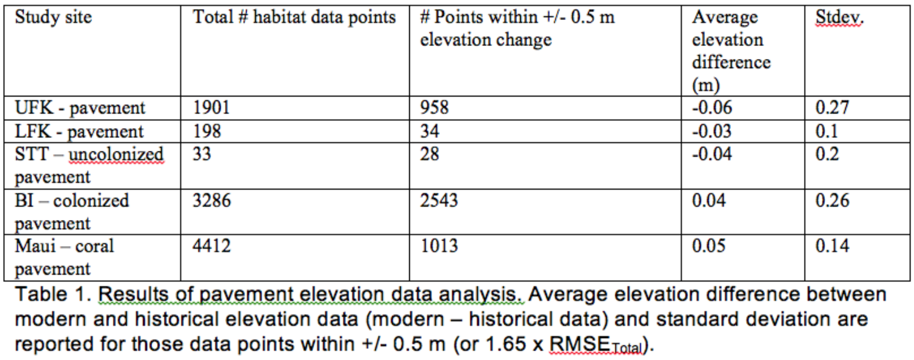

Study site	Total # habitat data points	# Points within +/- 0.5 m elevation change	Average elevation difference (m)	Stdev.
UFK - pavement	1901	958	-0.06	0.27
LFK - pavement	198	34	-0.03	0.1
STT – uncolonized pavement	33	28	-0.04	0.2
BI – colonized pavement	3286	2543	0.04	0.26
Maui – coral pavement	4412	1013	0.05	0.14

Table 1. Results of pavement elevation data analysis. Average elevation difference between modern and historical elevation data (modern – historical data) and standard deviation are reported for those data points within +/- 0.5 m (or 1.65 x $RMSE_{Total}$).

Fig. 5. Table 1. Results of pavement elevation data analysis.