Submerged Paleo-Shorelines as Markers of Vertical Deformation around Lake Azuei, Haiti

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Key Points:

- Lake Azuei lies in the eastern extension of the Enriquillo-Plantain Garden Fault, which is one of two transform faults that defines the North American – Caribbean plate boundary.
- A former shoreline, now submerged ~ 10 m beneath the lake level of Lake Azuei, was mapped.
- Analyses were applied to determine whether that formerly horizontal paleo-shoreline has been deformed by tectonic activity.
- Radioisotope dating is applied to sediment samples from the lake; resulting dates will constrain the age of that paleo-shoreline – and thus constrain the possible rate of tectonic deformation in the region.

Key Index Words:

Haiti, Transform fault, Bathymetry, Sediment core, Paleo-Shoreline, Subbottom profiling (CHIRP) sonar, Tectonic deformation,

Abstract

Lake Azuei, one of the largest lakes in the Caribbean (10km × 23km), is found at the eastern end of the Cul-de-Sac basin in Haiti. The southern half of Lake Azuei is located on the eastern extension of the Enriquillo-Plantain Garden fault zone. That fault marks part of the Caribbean plate's northern boundary and relative motion across its trace combines shortening and strike-slip components. Over the last fifteen years the water level of Lake Azuei has risen a remarkable ~ 5m, submerging villages, cultivated land, and roads, thus greatly disrupting the livelihoods of nearby inhabitants. Using new (2017) and existing (2013) sub-bottom seismic profiling (CHIRP) data we compiled an updated and improved bathymetric map of Lake Azuei that revealed young folds protruding from the lakebed. Additionally the CHIRP data highlighted several paleo-shorelines. We imaged a paleo-shoreline at ~ 5m depth, resulting from the recent lake level rise, as well as a prominent paleo-shoreline at ~ 10m, suggesting a long period where the lake level was ~ 10m lower than today's level. This ~ 10m paleo-shoreline is covered by a thin ~ 20cm sediment layer, suggesting that it was only submerged centuries to millennia ago. We are currently testing if this ~ 10m paleo-shoreline has been slightly warped away from horizontality due to tectonic activity. Lastly, using three core samples collected from the lakebed, we are radiometrically dating the sediment layers present in the lake to

determine their ages and the rate of sedimentation. Grain-size and microscopic analysis will constrain the composition and depositional environments of the sediment layers.

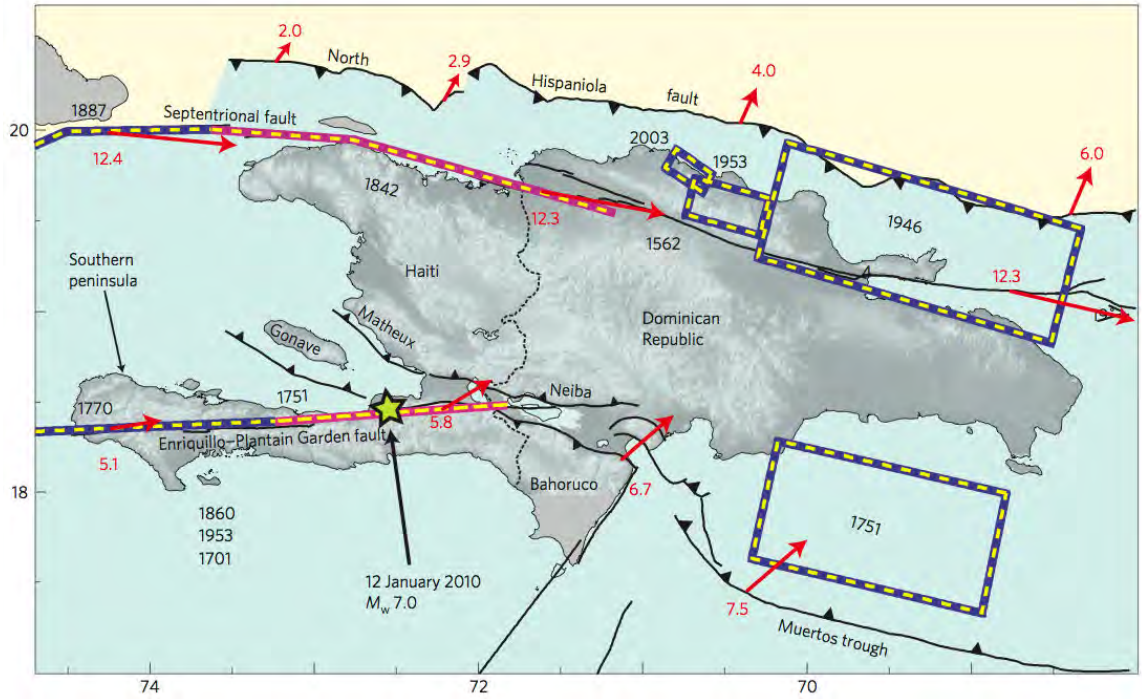
1. Introduction

In January 12, 2010 a magnitude 7.0 earthquake occurred on the Léogâne fault in southwest Haiti [Calais et al., 2010]. This earthquake caused terrible damage and loss of life in Haiti, especially in the densely populated region around the capital Port-au-Prince. Since the earthquake, a concerted effort has been made to analyze seismic risk in Haiti in order to better prepare for future earthquake threats [Calais et al., 2010; McHugh et al., 2011; Prentice et al., 2010]. One key area where research into seismic risk in Haiti is currently underdeveloped is Lake Azuei, one of the largest lakes in the Caribbean (10km×23km), which is located on the populous Cul-de-Sac plain only 20 miles from Port-au-Prince. This paper examines how paleo-shorelines produced by the fluctuating level of Lake Azuei can be a useful tool to quantify vertical deformation and thus assess the level of seismic risk.

2. Geologic Setting

The Léogâne fault, on which the 2010 M7.0 earthquake occurred, conjoins with the Enriquillo-Plantain Garden Fault (EPGF), which is one of two major transform faults demarcating the boundary between the Caribbean plate and the North American plate. The EPGF travels through the southern peninsula of Haiti, along the southern edge of the capital city of Port-au-Prince, and across the Cul-de Sac basin before potentially terminating at Lake Azuei, the largest lake in Haiti [Mann et al., 1995; Symithe and Calais, 2016; St Fleur et al., 2015]. Lake Azuei is located in an active and complex geologic setting, where the southern and northern portions of Hispaniola are not only sliding past each other in a sinistral (left-lateral) motion, but are simultaneously squeezing together, resulting in transpressional tectonics: figuratively squishing the central Cul-de-sac basin, on which Lake Azuei is located (*Figure 1*). One of the goals of this research was to investigate how this transpressional motion is accommodated in the central region of Haiti, and one of the most effective tools for performing this investigation was to apply marine seismic methods in Lake Azuei.

Figure 1: Major tectonic structures across Hispaniola, including the left-lateral Enriquillo-Plantain Garden Fault and Septentrional Fault [after Calais et al., 2010]. Black numbers indicate dates of historical earthquakes, and their estimated ruptures are indicated with either a colored line (strike-slip) or a colored box (thrust). Arrows indicate estimates of relative velocities (in mm/yr) across the plate boundaries.



3. Paleo-shorelines

Past studies have shown how paleo-shorelines can be used to determine the amount of vertical deformation caused by tectonic activity in a given area [e.g., Cormier et al., 2006; Polonia et al, 2004; Jara-Munoz et al., 2017]. Paleo-shorelines, when they are formed, are horizontal features. If one can trace a paleo-shoreline in a tectonically active area, one can determine whether or not that paleo-shoreline has been vertically deformed by measuring its depth at many separate locations and testing to see if these measurements vary geographically. If the depth measurements of the paleo-shoreline do vary spatially, they document vertical deformation. Then, by radiometrically dating the paleo-shoreline and surrounding geologic layers, one could calculate the associated rate of deformation. The rate of deformation, which provides information on how often a large earthquake is likely to occur in a particular area and what type of earthquake it might be (strike-slip, thrust, or combined), is an important factor for determining seismic risk.

GPS measurements, which record instantaneous deformation rate, and historical records dating back to the sixteenth century demonstrably show that a destructive earthquake should be expected the Enriquillo-Plantain Garden Fault this century (e.g. Symithe et al., 2013). It is imperative to accurately quantify the historical deformation rate along the EPGF so that decision makers can better predict the timeframe when this earthquake might occur. By measuring the vertical deformation of Lake Azuei using varying depth measurements of a paleo-shoreline, one can calculate some past deformation rates that will allow for a more accurate characterization of seismic risk along the EPGF.

4. Fluctuating Lake Level

Another startling component of the geographic nature of Lake Azuei is the fact that over the last fifteen years the lake level of lake Azuei has risen ~ 5 meters [Monaktian et al., 2017]. Lake Enriquillo, a neighboring lake in the Dominican Republic has risen ~ 10m. Neither lake has an outlet to the sea nor are they connected to each other, making their levels particularly sensitive to variations in hydrographic conditions. The cause for these large lake level changes is believed to be increased precipitation due to climate change. The presence of many paleo-shorelines in Lake Azuei shows that past climatic events have controlled the lake level. As part of this study, we also identified a paleo-shoreline above the current lake level, at ~ 28m amsl, using satellite imagery. This paleo-shoreline is recognizable as a subtle change in vegetation. Its elevation corresponds precisely to the lowest elevation around the lake (~28 m), suggesting that it formed when the lake rose another ~7m above its present level and spilled over its sill point. These observations point to the fact that the lake level has a large and variable range and that it may continue to rise.

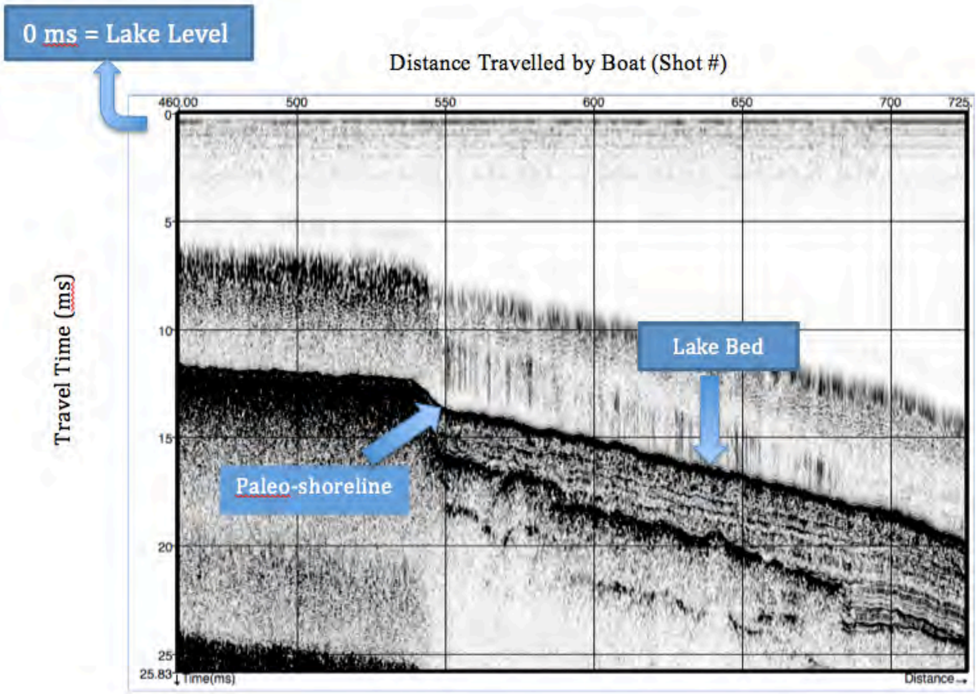
This lake level rise has had serious effects upon the local economy and livelihoods of the local Haitian population [Kushner, 2017; Grogg, 2012]. The rising lake has submerged acres of arable land, and even swallowed whole villages: displacing large numbers of people and disrupting local enterprises. It is necessary for local authorities to understand the causes and rate of lake level change to help mitigate its socio-economic impacts. Although the slow rate of vertical tectonic deformation might contribute only minimally to this sudden rise in lake level, a future earthquake beneath the lake would only worsen the challenges facing the surrounding population.

5. Materials and Methods

5.1 CHIRP Data analysis

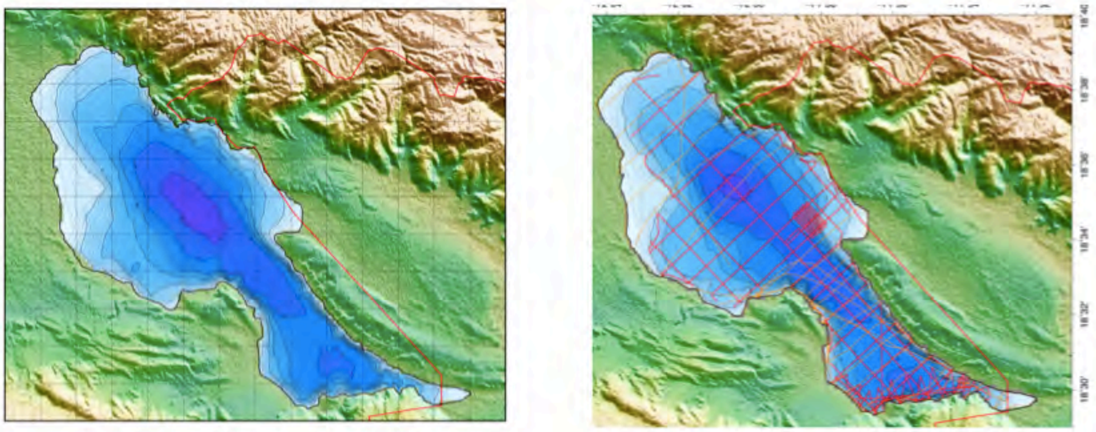
In January of 2017, a three-week expedition to Lake Azuei gathered subbottom profiling (CHIRP) data, multichannel seismic reflection data, and three sediment cores [Cormier and Sloan, 2017]. This on-going research project is funded by the National Science Foundation and is fully collaborative with scientists at the State University of Haiti. The CHIRP profiles provide information not only on water depth but also on sediment stratigraphy from ten to twenty meters depth below the lakebed *(Figure 2)*.

Figure 2: CHIRP profile across the ~10 m deep paleo-shoreline. The vertical axis is two-way travel time and is labeled in millisecond; 1 ms corresponds to approximately 75 cm water depth (assuming 1500 m/s for the speed of sound in water).



To interpret the seismic profiling (CHIRP) data recorded in Haiti, we utilized the free seismic interpretation software OpendTect (https://www.opendtect.org). OpendTect is a powerful interactive software that can display seismic profiles in 2D and 3D viewer modes and allows one to digitize "seismic horizons" (geological boundaries). Most importantly, it shows the profiles in their 3-dimensional contexts in relation to each other, allowing operators to visualize the field relations between key geological features. On these profiles, the lakebed was easily recognizable (*Figure 2*). We digitized the lakebed on every profile and compiled these lakebed horizons into a new and updated bathymetric map of Lake Azuei using the map-producing free software GMT (https://www.soest.hawaii.edu/gmt/). This new data revealed that some of the previous soundings of the lakebed collected in 2013 were erroneous. These erroneous data were removed from the new compilation and the updated bathymetric map showed that the deepest part of the lake is actually 5 m shallower than previously thought (30 m instead of 35 m deep), and is shifted toward the northwest (*Figure 3*).

Figure 3: Comparison of bathymetric maps.



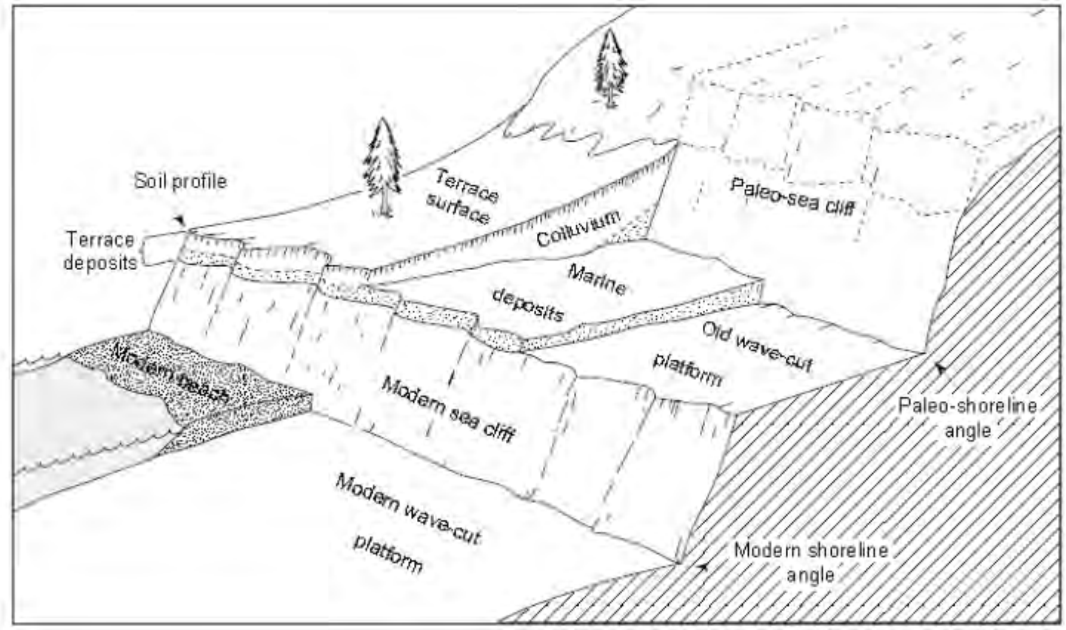
Bathymetric map compiled from the raw sounding data generously provided by M. Piasecki, City College - CUNY. These data were collected in 2013 (Monaktian et al. 2017)

Updated bathymetric map. Orange lines indicate the tracks from the 2013 survey of M. Piasecki. Red lines are from the 2017 survey (this study).

5.2 Paleo-shoreline Identification

Using the CHIRP profiles we were also able to identify features indicative of paleo-shorelines. The most prominent of these telltale features was the "shoreline angle", which was identifiable due to the distinct change in slope of the lakebed, which was created by wave erosion at the former shoreline (*Figure 4)*.

Figure 4: Main morphological features generated at a shoreline (after Weber, 1983). The "shoreline angle" is generally the easiest feature to identify across a paleoshoreline.



Another noticeable feature that we used to identify paleo-shorelines was the observation that below the paleo-shoreline, on the lake-ward side of the paleo-shoreline the CHIRP sonar signal penetrates much further thereby revealing the stratigraphy of the geologic layers. On the other hand, the part of the profile above the paleo-shoreline, on its landward side, revealed little to no penetration below the lakebed (*Figure 2*). These combined observations are consistent with the hypothesis that during the time period when the paleo-shoreline was formed, the lake level must have held relatively constant for a length of time sufficient to produce a shoreline angle. This would have allowed a sandy or rocky beach to form on the landward side of the paleo-shoreline thus forming a hard and almost impenetrable seismic reflector, while in comparison sediments such as silt and mud would have deposited on the lake-ward side of the paleo-shoreline thus creating an easily penetrable, much softer, seismic reflector. Lastly, on some of the paleo-shorelines we imaged, we found that on the landward side of the paleo-shoreline pick, the lakebed appeared bumpy and irregular in the seismic profile, indicative of a rougher, uneven surface, while on the lake-ward side of the paleo-shoreline the lakebed was a much smoother reflector in the seismic profile.

Another feature that added complexity to the task of picking the paleo-shoreline was that a thin layer of sediment (~ 20 cm) had been deposited above the paleo-shoreline after it had been submerged. This layer of sediment was especially pronounced on the landward side of the paleo-shoreline on the CHIRP profiles. In order to account for this sedimentation, we picked the paleo-shorelines below this layer of sediment.

We were able to identify several paleo-shorelines: a paleo-shoreline at ~5m depth (we assume this to be the paleo-shoreline from around 15 years ago before the recent and abrupt lake level rise), a paleo-shoreline at ~10m, which was very clearly defined and present on every one of our seismic profiles, and in a few profiles only, two paleo-shorelines at much deeper depths (~22m and ~35m). We chose to focus on the ~10m shoreline for our analysis of vertical deformation given that it was the most prominent and prevalent of all the paleo-shorelines we identified.

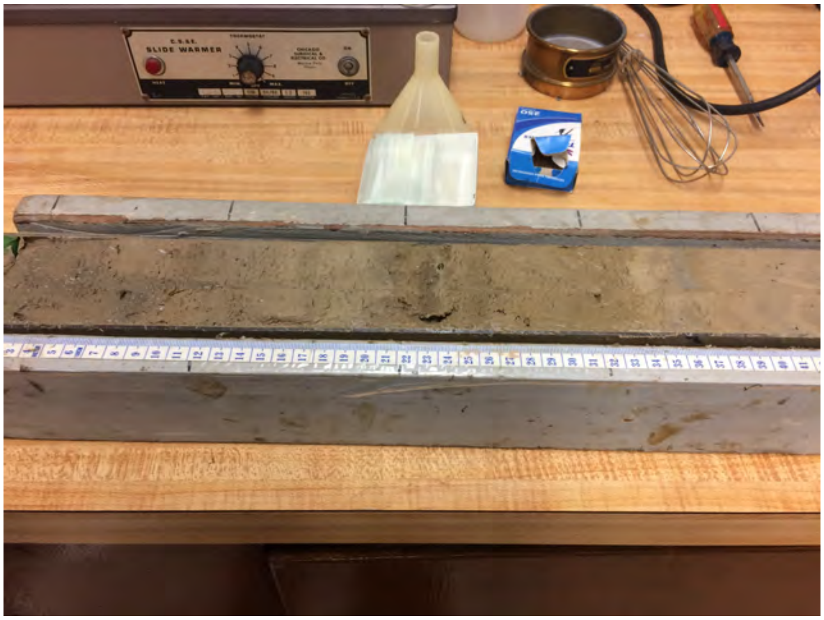
Using OpendTect, we took precise picks of the ~10m paleo-shoreline on each seismic profile where we could clearly identify it. We then performed screen captures of the ~10m paleo-shoreline on all the profiles on which it was located. The exact depth and x and y coordinates of our picks were read directly from the screen and this information was compiled in an Excel table. The next step will be to plot the depth measurements versus their geographic locations around the perimeter of the lake in order to objectively assess if there exists systematic trends that could be attributed to tectonic deformation.

There exists a degree of uncertainty for all of our paleo-shoreline picks. Picking the paleo-shoreline measurements was a subjective process. One estimate of the uncertainty will be the standard deviation of the curve derived from the plot of depth measurements-versus-distance around the lake. Another way to evaluate error will be for other investigators working on this project to repeat the measurements and then compare their results with our own. For now, we estimate that measurement errors do not exceed more than ~20 cm.

5.3 Sediment Core Processing

The analysis of the three sediment cores collected from the lakebed of Lake Azuei required a series of steps. The three cores were spliced and opened (*Figure 5)*.

Figure 5: Opened core. Ruler alongside the core indicates cm below top of the core.



We extracted samples from each core for radiometric dating. For each core we sampled material every centimeter for the top ten centimeters, then every other centimeter between the ten and twenty centimeter depth marks, and lastly every 5 centimeters from the twenty centimeter mark onwards until the bottom of the core. We took samples from all three cores: LA17-BC01-1 A which measured 56 cm, LA17-BC02-1 A which measured 87 cm, and LA17-BC01-3 A which measured 74 cm. We chose to utilize the isotope 210Pb for radiometric dating due to the fact that the only previous coring sample of Lake Azuei had suggested very high sedimentation rates, around 6 mm/year [Eisen-Cuadra et al., 2013]. This high sedimentation rate meant that our relatively short cores could only sample a few hundred years of sediment accumulation and therefore we chose a radioactive isotope that decays with a half-life of 22 years. Using CHIPR profiles, we could trace a sediment layer presumably deposited at the same time that the paleo-shoreline was forming through the exact location where we cored. It is possible that ongoing radiometric dating of the cores, and particularly of the layers corresponding to the paleo-shoreline will reveal the age of the paleo-shoreline. Even if we are not able to date the exact layer corresponding to the paleo-shoreline we will still be able to determine local sedimentation rates, which we could extrapolate to the paleo-shoreline layer. This information would allow us to quantify the rate of vertical deformation below Lake Azuei.

As well as radiometric 210Pb dating we took smear slides of all the sediment layers in the three cores, which will be examined under a microscope and photographed. Next, we drew diagrams representative of each core that show to scale all of the different sediment layers, and we provided written descriptions of each sediment layer including color identifications. We also took grain size samples at the same depth intervals as the radiometric dating samples.

6. Preliminary Results

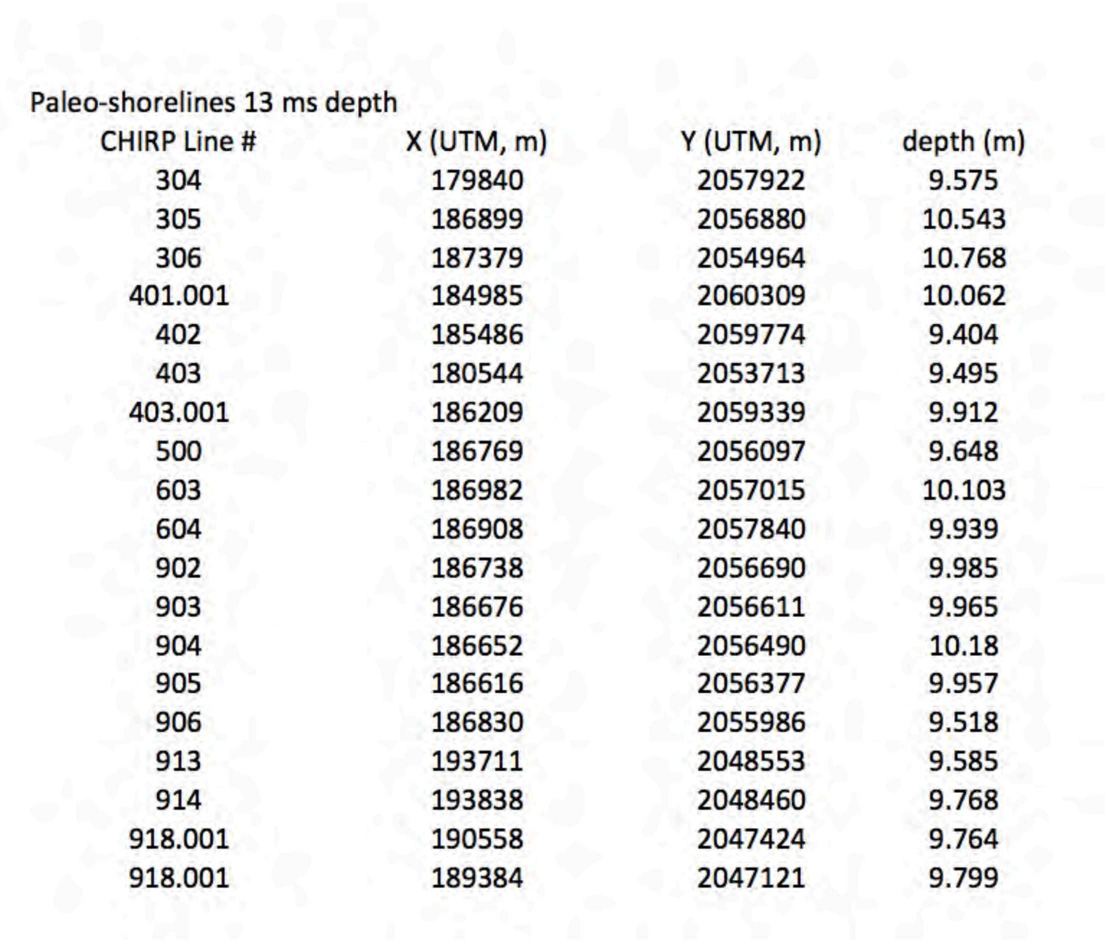
The research performed for this study has revealed several significant, thought-provoking, and beneficial results that point to a need for further research of the Lake Azuei area. First, using the CHIRP data we were able to compile an improved bathymetric map of Lake Azuei, which revealed a shallower depocenter depth and different depocenter location. It also highlights a very flat lakebed (< 0.1° slope) surrounded by steep slopes (~5°). Additionally, using the ~10m paleo-shoreline that we identified, we are in the process of determining the amount of vertical deformation affecting this region, if any (*Table 1*). Any trend, or lack thereof, will allow us to form a hypothesis about the amount, rate, and location of vertical deformation below Lake Azuei.

The majority of the results of this research are still forthcoming. Analysis is continuing and further results will be presented at the 2017 fall meeting of the American Geophysical Union in the papers of Cormier et al., 2017 and Sloan et al. 2017.

8. Conclusions

In conclusion, the use of paleo-shorelines to determine vertical deformation is a growing field of study that allows geophysicists to identify vertical deformation of a lakebed or seafloor. For this specific study we successfully identified and catalogued a paleo-shoreline in Lake Azuei, Haiti. We are currently in the process of analyzing our paleo-shoreline data to discover any trends indicative of tectonic deformation.

Table 1: Measurements of ~ 10 m paleo-shoreline.



Paleo-shorelines 13 ms depth

CHIRP Line #	X (UTM, m)	Y (UTM, m)	depth (m)
304	179840	2057922	9.575
305	186899	2056880	10.543
306	187379	2054964	10.768
401.001	184985	2060309	10.062
402	185486	2059774	9.404
403	180544	2053713	9.495
403.001	186209	2059339	9.912
500	186769	2056097	9.648
603	186982	2057015	10.103
604	186908	2057840	9.939
902	186738	2056690	9.985
903	186676	2056611	9.965
904	186652	2056490	10.18
905	186616	2056377	9.957
906	186830	2055986	9.518
913	193711	2048553	9.585
914	193838	2048460	9.768
918.001	190558	2047424	9.764
918.001	189384	2047121	9.799

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