Sedimentary Signatures of Climate Variability and Tectonic Activity in Lake Azuei, Haiti: Possible Implications for Natural Hazards

Allyson N. Murray[1†]

[1]University of Rhode Island Graduate School of Oceanography, Narragansett RI, USA, (murray44@go.stockton.edu)
†Stockton University, Galloway NJ 08205

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Key Points:

- Carbon-14 dating of material from sediment cores will provide a maximum age for a paleoshoreline imaged at ~11 m depth
- The likely cause of the ~11 m paleoshoreline was wet conditions which caused the lake to flow east at the sill depth
- A shallow gas front occurs throughout most of the lake and is deeper in areas that are tectonically deformed

Key Index Words: Haiti, paleoshoreline, transform fault, sediment core, subbottom profiling (CHIRP), tectonic deformation

Abstract

Lake Azuei in Haiti is one of the largest lakes in the Caribbean (10 km x 23 km). The southern portion of Lake Azuei straddles the Enriquillo-Plantain Garden Fault, one of two transform faults that define the Caribbean-North American plate boundary. During a January 2017 expedition, sub-bottom seismic reflection (CHIRP) profiles were collected in a grid pattern across the lake. Using Opendtect, a seismic interpretation system, sedimentary layers were tracked laterally along each profile to construct 3D representations of these layers. The lake has a flat bottom, suggesting that it is infilled with turbidites. By imaging the deformation of these turbidite layers, we gained insight into vertical deformation affecting the lake floor. Additionally, the CHIRP data imaged a prominent paleoshoreline at ~11 m water depth, implying that it was stable for a long time and then rapidly submerged. Two sediment cores were collected from the lake bed, and their upper portions have been radiometrically dated using ^{210}Pb methods, indicating recent sedimentation rates of ~1 mm/yr. One core sampled a layer identifiable in the CHIRP profile and that extends laterally below the ~11m paleoshoreline. On-going ^{14}C dating of material sampled deep from the two cores will provide the maximum age for the paleoshoreline. We hypothesize this ~11 m paleoshoreline corresponds to a time when the lake overflowed into Lake Enriquillo to the east along a valley that is currently blocked by an alluvial fan. Alternatively, it could also represent a period of maximum aridity known as the Terminal Classic Drought.

1. Introduction

Lake Azuei is a brackish lake located in the Cul-de-Sac basin in Haiti about 30 km east of the capital city of Port au Prince. The lake is endorheic (with no outflow to other basins or the ocean), which means that its level is extremely sensitive to variations in precipitation. In the past 10 years there has been ~5 meter rise in lake level (Moknatian et al., 2017). This rise submerged roads, houses, and farmland surrounding the lake. The southern portion of Lake Azuei is presumably cut through by the eastern extension of the Enriquillo-Plantain Garden Fault (EPGF). The EPGF is one of two left-lateral strike slip fault trending E-W, which demarks the boundary between the Caribbean and North American plates. However, the trace of the fault is not well imaged in the surrounding landscape, leading to the publication of competing models, some advocating a purely strike-slip fault through Lake Azuei (e.g. Mann et al., 1995), and other a transpressional fault (Saint Fleur et al., 2015; Symithe and Calais, 2016). The January 12, 2010 M7.0 earthquake occurred along the previously unmapped Léogâne fault, a North-dipping fault that runs subparallel to and abuts the sub-vertical EPGF (Calais et al., 2010). This report contributes new result relevant to the climate history and seismic risk of eastern Haiti by studying sediment cores and seismic reflection profiles collected in Lake Azuei in 2017.

2. Geologic Setting

Lake Azuei is a large (10 km by 25 km), brackish lake located ~30 km from the capital city of Port-au-Prince. The lake is relatively shallow, about 30 meters deep at its depocenter. Lake Azuei lies along the boundary between the North American and Caribbean plates (Figure 1), which are moving at a rate of 19 mm/yr relative to each other (e.g., Benford et al., 2012). Two major transform fault systems define this broad plate boundary, the Enriquillo-Plantain

Garden Fault (EPGF) and the Septentrional Fault. These fault systems are both left-lateral and separated by about 200 km (e.g. Mann et al., 1995; Symithe and Calais, 2016).

The January 2010 M 7.0 earthquake ruptured along the Léogâne fault, which abuts the EPGF. The EPGF is well defined throughout most of southern Haiti, where it travels through the southern edge of Port-au-Prince, and across the Cul-de-Sac basin before presumably plunging below Lake Azuei (Symithe and Calais, 2016; Saint Fleur et al., 2015). The geological setting of Lake Azuei is controlled by transpressional tectonics. Not only are the Southern and Northern parts of Hispaniola sliding past each other in a left-lateral motion along the EPGF and the Septentrional fault, they are also being squeezed together. Indeed, GPS monitoring across Hispaniola document an overall NE-SW transpressional motion (e.g., Benford et al., 2012; Calais et al., 2010). The main goal of the Lake Azuei Project is to determine how this transpressional motion is accomodated between strike-slip and contractional structures using seismic reflection methods. Lake Azuei is located ~60 km east of the epicenter of the 2010 earthquake, which surprised the scientific community by rupturing an unknown transpressional fault rather than the well mapped EPGF.

Several folds are mapped around Lake Azuei (Symithe and Calais, 2016), as well as beneath Lake Azuei (Cormier et al., 2017). These folds could either be en echelon drag folds or fault-propagation folds. En echelon drag folds are surficial features which develop along strike-slip fault zones, and are oriented slightly oblique to the fault. Fault-propagation folds are surface expressions of a shallow-dipping blind thrust fault, and strike parallel to the fault (where a thrust fault does not reach the surface, it is referred to as a blind fault). In the case where the Lake Azuei folds would be fault-propagation folds, the associated blind thrust would be a south-dipping low-angle thrust fault which projects into the Cul-de-Sac Basin from the Massif de la

Selle (Symithe and Calais, 2016). Although this is the preferred model, en echelon drag fold cannot be ruled out based on existing data (Saint Fleur et al., 2015).

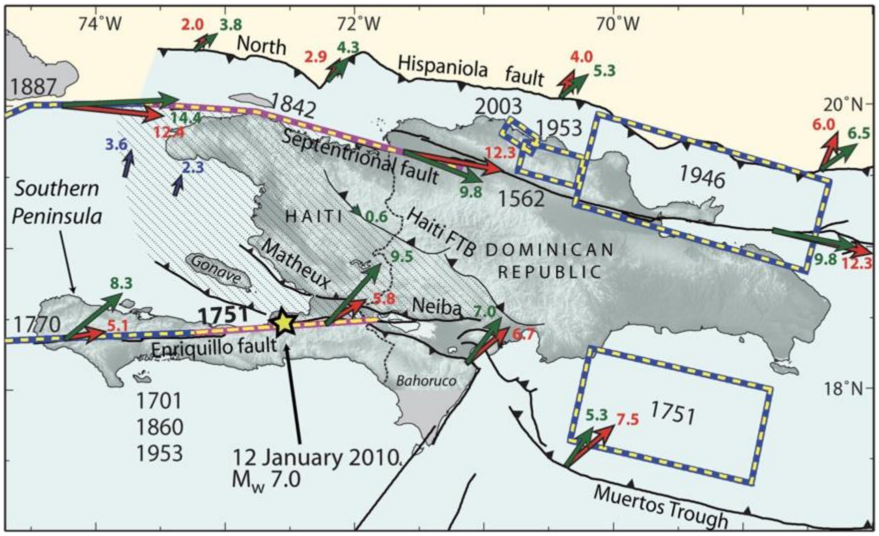

Figure 1: Tectonic context of Hispaniola, including the two major strike-slip faults that compose the broad Caribbean and South American plate boundary: the Enriquillo-Plantain Garden Fault and the Septentrional Fault. Relative plate motion velocity (mm/yr), based on GPS monitoring, is indicated by the arrows; green arrows indicate updated velocities compared by a prior model (in red). Historical earthquakes dates are denoted by black numbers, and their estimated rupture are indicated by either a colored box (dipping thrust fault) or a colored line (vertical strike-slip fault). From Benford et al., 2012

3. Paleoshorelines

A paleoshoreline is an ancient shoreline that is preserved above or below present water level. As such, it can provide a useful marker for prior horizontality and water level in an area where tectonic deformation occurs. These features are commonly mapped on land as "marine terraces" (e.g., Armijo et al., 1999; Muhs et al., 2014), but can also be imaged underwater using seismic reflection methods (Sloan et al., 2017) and/or high resolution multibeam bathymetry (e.g., Cormier et al., 2006). The marker of a paleoshoreline is the pronounced "shoreline angle", a sharp transition from flatter to a steeper slope. In order to groundtruth a paleoshoreline detected from seismic reflection and/or multibeam bathymetry, one needs to collect sediment samples across that paleoshoreline. The samples would then be inspected for shell hash, pebbles, or other characteristics of a beach facies.

In practice, since paleoshorelines are markers of original horizontality, they can be used to determine the amount of relative vertical deformation affecting an area due to tectonic activity, and thus provide useful constraints to assess the seismic hazard of an area.

4. Data and Methods

4.1 CHIRP data analysis

A three week expedition to Lake Azuei in January of 2017 collected high-resolution subbottom seismic reflection (CHIRP) data, multichannel seismic reflection data, and three sediment cores (Cormier and Sloan, 2017). In order to visualize and interactively interpret the seismic reflection data, we utilized Opendtect (https://www.opendtect.org). Opendtect is a free, open source seismic interpretation system, which can display seismic profiles in 2D and 3D, highlighting the spatial relations of the profiles relative to one another (Figure 2). Using this software, sedimentary layers, called seismic horizons, were digitally tracked laterally across CHIRP profiles. Particularly, turbidite layers, deformed layers, and erosional surfaces were tracked throughout the lake bed, with the goal to gain insight into vertical deformation and fault geometry.

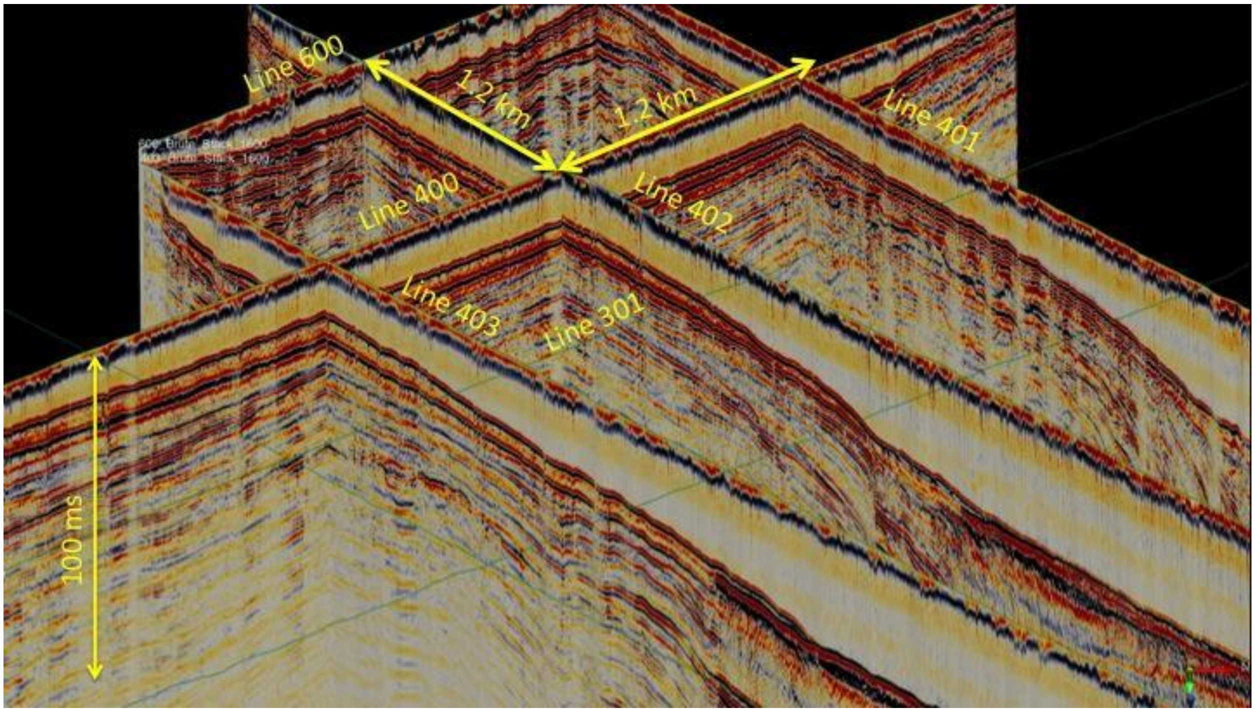

Figure 2: Fence diagram looking West of multichannel seismic profiles (Hearn et al., 2017)

After digitizing the horizons, several imaging softwares were used in order to graphically represent the data and horizons. These included GMT (https://www.soest.hawaii.edu/gmt/), and Fledermaus (http://www.qps.nl/display/fledermaus).

4.2 Gas Front and Paleo-shoreline identification

A gas front beneath the lake bed is clearly identifiable in the CHIRP profiles. The gas front is a bright reflector, which obscures most of the geological layers below it (Figure 3). The interaction of gas bubbles in shallow sediment with seismic signal results in “acoustic turbidity”, the strong attenuation of the signal and ensuing wipe-out of underlying reflectors (Hagen and Vogt, 1999). Gas found in shallow marine sediments is generally of biogenic origin, formed by bacterial reduction of organic matter in the upper 10s to 100s of meter of sediment (e.g., Hagen and Vogt, 1999).

The gas front was traced throughout all of the CHIRP profiles in order to assess the thickness of gas-free sediments throughout the lake.

The 11 m paleoshoreline was picked previously based on shoreline angle in CHIRP profiles (Lucier, 2017; Sloan et al., 2017). The ~11 m paleoshoreline generally exhibits a well-defined shoreline angle, as well as three other characteristics: 1) a transitional from acoustically opaque to acoustically transparent strata; 2) a near constant ~11 m water depth; 3) the presence, locally, of a thin (~30 cm), acoustically transparent layer draped across it (Figure 4)

There is however human error associated with picking the travel-time and coordinates of the paleoshoreline. For this reason, we tried to remain consistent with parameters for picking the paleoshoreline, looking for all the criteria mentioned above. However, it was difficult to pick exactly at this point, and the locations may be off by a few tenths of a millisecond, which would correspond to an estimated error of up to 30 cm. It was also impossible to pick paleoshorelines in the Southern portion of the lake due to the steepness of the slope.

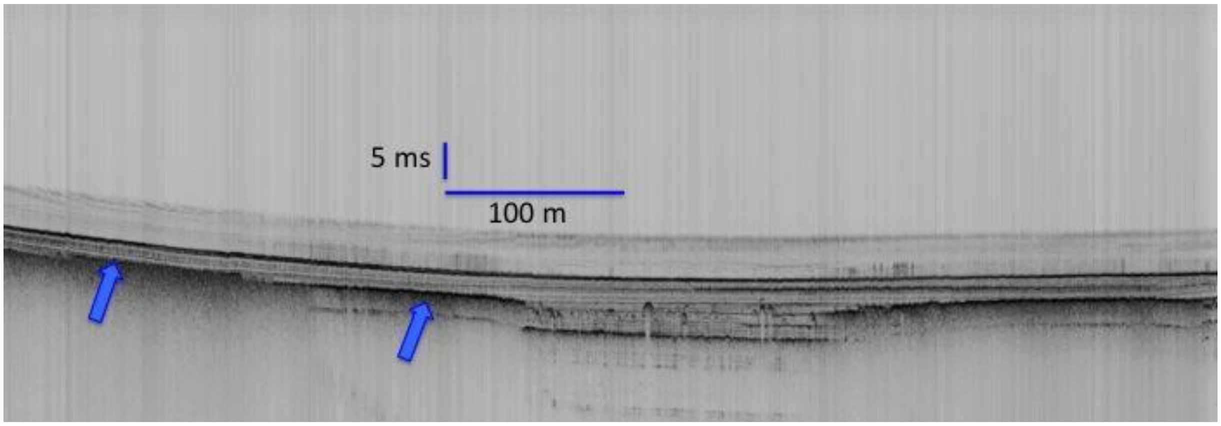

Figure 3: Gas front near the lake bed in CHIRP line 401. Blue arrows point to the gas front, which is a bright reflector in CHIRP.

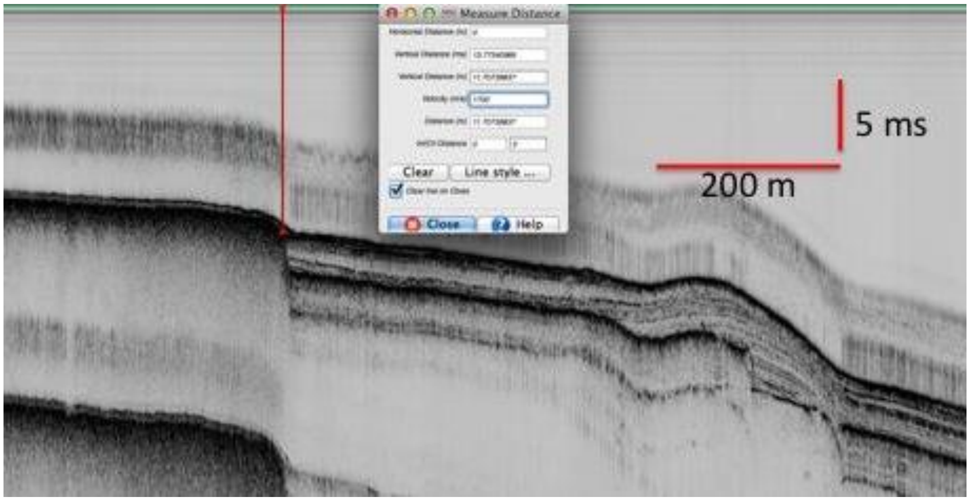

Figure 4: Paleoshoreline identification on line 603

4.3 Sediment core analysis

Three sediment cores were taken from the lake bed. Cores 1 and 2 sample the same location due to problems with collection of core 1. The coordinates of the cores along with associated depths are included in Table 1. The core locations were decided in the field based on the CHIRP profiles just acquired, and are shown on these profiles in Figure 5. Both sediment cores seem to sample layers identifiable in CHIRP that extend laterally below the ~11 m paleoshoreline, implying the layer is older than the paleoshoreline.

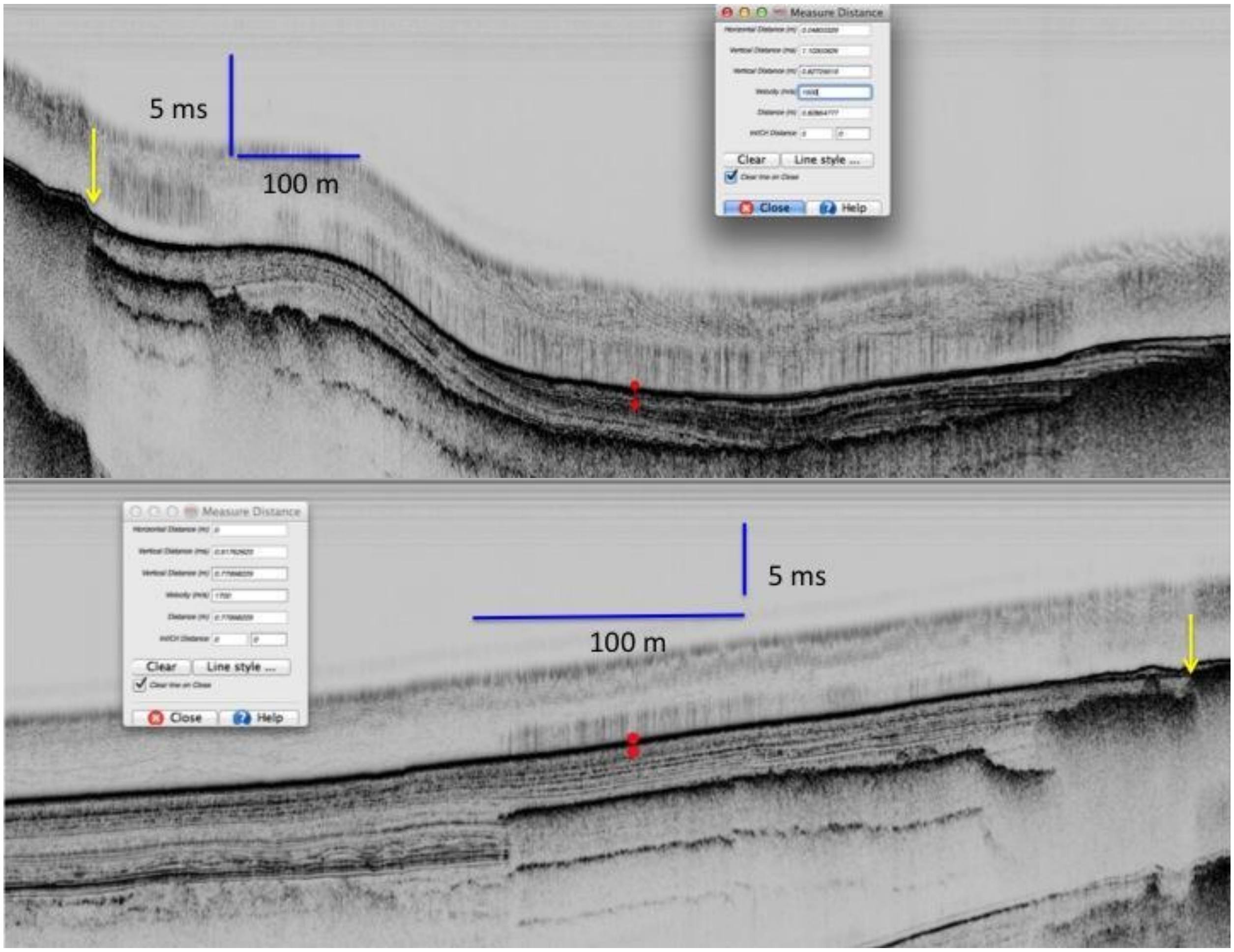

Figure 5: top. Location of core 2 on CHIRP line 803. bottom. Location of core 3 on CHIRP line 300. Scale bars are shown in blue, location of cores are shown with a red line proportional to their actual length, and location of the paleoshoreline is indicated by the yellow arrow. A two-way travel time of 5 ms in water corresponds to 3.75 m.

The upper portions of the two cores were dated in 2017 using ^{210}Pb on the upper 10 cm of the cores. ^{210}Pb is a radiometric dating method applicable to the last ~150 years of sediment accumulation. Modern sedimentation rates for both cores was calculated to be ~1 mm/yr (Cormier et al., 2017). To the best of our knowledge, the only other sediment core collected from Lake Azuei sampled the deepest part of the lake and indicated a modern sedimentation rate of ~6 mm/yr (Eisen-Cuadra et al., 2013); this is consistent with our rates, as our two cores sampled the lake slopes where rates of sediment accumulation is expected to be lower. The rates cannot be extrapolated to the lower portion of the core due to presumed changes in sedimentation rates, as suggested from the studies of other lakes in Hispaniola (e.g., Curtis and Hodell, 1993; Lane et al., 2014). Organic material from the lower portion of the core is currently being dated using the Accelerator Mass Spectrometry (AMS) Radiocarbon Dating method with Beta Analytic. In order to prepare the samples for AMS Carbon-14 dating, the sediment was processes following a methodology similar to that used for other lakes in Hispaniola (e.g., Curtis and Hodell, 1993). The sediment was scooped from half of a 1 cm-thick interval in the split core using a steel spatula. Some particularly sticky samples were soaked overnight in surfactant (sodium hexametaphosphate) to help breakdown the clumped sediment before sieving. These samples were stored in a tube with the surfactant after being shaken through a centrifuge or a “vortex genie.” The samples were then washed through a 2 mm (#10) brass frame and stainless steel cloth sieve using deionized water (Figure 6). The remaining samples were then further washed through a 1 mm plastic sieve during deionized water, and then a 125 µm (#120) brass frame and stainless steel cloth sieve. The remaining material (<125 µm) was not examined for material useful in AMS C-14 dating, as plentiful gastropods and plant material was isolated with the three sieves. The samples were then placed in dishes according to grain size and kept wet with deionized water.

A reflected light binocular microscope was used to examine the samples. The most abundant specimen available were gastropods, but plant material including wood was also found. The specimen were picked from the dishes using a fine brush and/or tweezers and stored in a separate dish according to their nature (wood, plant, or gastropod). The number of whole gastropods, gastropod fragments, and plant material were recorded for each sample (Table 2).

The samples were then dried overnight at 100°C and weighed to ensure that at least 20 mg of dry material was available for a reliable AMS C-14 dating. The description and weights of the samples selected for C-14 dating are listed in Table 3.

Figure 6: Wet sieving set up. A 2 mm sieve on top of a 1 mm sieve.

5. Preliminary Results

The research performed this summer will provide some needed constraints about several thought provoking questions about the geological history of Lake Azuei. Namely, what is the origin of the 11 m deep paleoshoreline? Why is the paleoshoreline not detecting any vertical deformation in the presumed extension of the EPGF? How fast is the west side of the lake uplifting?

5.1 Maximum age of the 11 m deep paleoshoreline and possible origin

We are in the process of dating material from the bottom of the core using Carbon-14 dating methods. We anticipate the resulting dates will give insight into the climate history of Haiti.

One of our five samples, the plant material from Core 2 at 63-64 cm, could not be dated due to carbon replacement.

Two hypotheses could explain the origin of the ~11 m paleoshoreline. The first is that this shoreline represents a period of maximum aridity. Multiple papers (e.g. Curtis and Hodell, 1993; Caffrey et al., 2013; Lane et al., 2014) have reported a period of maximum aridity in the Caribbean. This period is also known as the “Terminal Classic Drought” and may be responsible, in part, for the collapse of the Mayan civilization, and ended around ~1000 years BP. A future project to test this hypothesis could be to collect cores across the paleoshoreline to precisely date its formation and, possibly, detect a signature of aridity in the sediment. However, this hypothesis cannot really explain why the paleoshoreline would have stabilized at 11 meters depth. If this depth corresponds to a period of maximum aridity, why did the lake not continue to dry up?

Another possible explanation for this ~11 m paleoshoreline is a period of increased precipitation. Sustained wet conditions may lead to the lake spilling over the lowest surrounding elevation (sill), with its level being maintained at that sill depth. Although there is currently no outlet to the lake, there may have been one in the past. A possible location for the sill depth that caused the ~11 m paleoshoreline is the Southeast corner of Lake Azuei, which is currently 33 meters above sea level. Because the 11 m deep paleoshoreline is actually at an elevation of ~10 m above sea level, ~23 m of sediment accumulation would be needed to explain the present topography. This does not seem impossible in this tectonic location since the 33 m-high sill is located on the eastern extension of the EPGF fault zone. Seismic activity, such as thrust faulting and/or earthquake-triggered landslides, and/or mudslides could cause the blockage. Such blockages have been reported in several other sites due to landslides and/or growth of alluvial fans (Atwater et al., 1996; Dai et al., 2005; Keefer, 1999); furthermore, earthquake-triggered landslides are common in Haiti (Gorum et al., 2013; Harp et al., 2016) The 33 m sill is located within a narrow corridor which connects Lake Azuei to Lake Enriquillo and is currently blocked by an alluvial fan. The city of Jimani is built on this alluvial fan, and experienced extensive flooding in 2004, suggesting that similar conditions in the past could have facilitated extensive flash floods and the rapid growth of that alluvial fan.

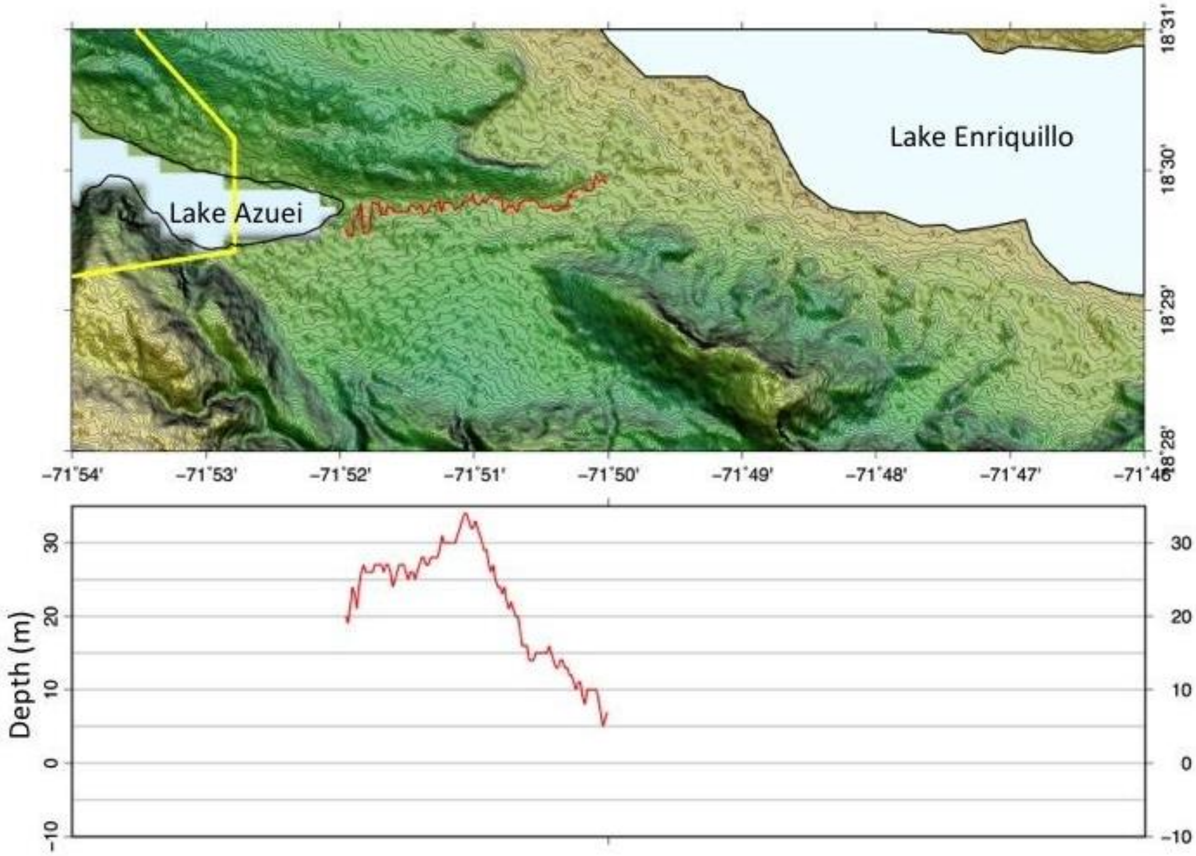

Figure 7: Location of possible outlet to Lake Azuei in past, which is now obstructed by an alluvial fan (clearly visible near 1751'W).

5.2 Distribution of biogenic gas in lake sediment and tectonic activity

Gas fronts were imaged throughout most of the CHIRP profiles, and in many cases, it was seen to rise very close to the lake bed (Figure 8). This gas front obscures most of the geological layers beneath it. Such gas front is commonly imaged in subaqueous sediment and is interpreted to be of biogenic origin, formed by bacterial reduction of organic matter in the upper

10s to 100s of meters of sediment. However, there are two environments in Lake Azuei where a gas front is deeper or is simply absent (see Figure 8): 1) The gas front is deeper in tectonically active areas (folds and faults), presumably because fractures and fissures in deformed sediments provide pathways for biogenic gas to escape (e.g., Leithold et al., 2018). This includes the monoclinal fold on the west side of the lake where a gas front seems to be absent and the smaller folds east and south of the lake; 2) CHIRP penetration exceeds 8 ms (~6 m) at the lake decopenter, below 29-30 m water depth (lines 401 and 602). MCS profiles collected along the same tracks also reveal deeper penetration in this area. This observation is compatible with anoxic conditions in the lake depocenter as it would preclude bacterial reduction of organic matter and, therefore, would preclude the formation of biogenic gas. CHIRP profiles, therefore, may provide a useful tool to estimate the spatial extent of anoxic conditions.

Another line of support for anoxic conditions at the depocenter is metal geochemistry performed on a 50 cm-long sediment core collected there in 2011. That core had a negative cerium anomaly, which is typical of sediments deposited under anoxic conditions (Eisen-Cuadra et al., 2013). If anoxic conditions do occur at the depocenter of Lake Azuei, this area may contain finely laminated sediments, potentially providing a detailed, undisturbed record of climate, as well as of prior earthquake events (seismites). Additionally, the high sedimentation rate of ~6 mm/yr at the depocenter (Eisen-Cuadra et al., 2013) would favor a good stratigraphic separation between events.

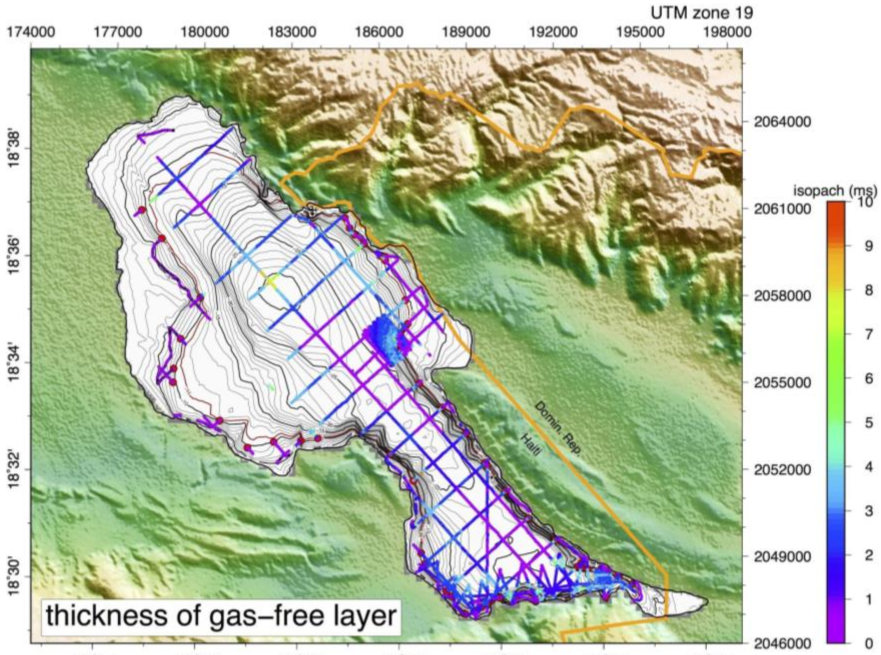

Figure 8: Thickness of gas-free layer throughout Lake Azuei. Difference between the bathymetry and the depth to the gas front, when gas is present.

5.3 Areas of tectonic deformation and their style

The ~11 m paleoshoreline has a remarkably constant depth around the lake bed (Figure 9). However, in certain portions the paleoshoreline is raised 1-2 m. Interestingly, the paleoshoreline is deformed away from the presumed fault locations and undeformed where the fault is presumed to be. Further analysis is needed to determine why. Possibly, the 1-2 m of uplift in the western region of the lake results from a single large earthquake on the subjacent blind thrust fault (Hearn et al., 2017), while no similarly large earthquake has affected the southern section of the lake since the formation of the paleoshoreline.

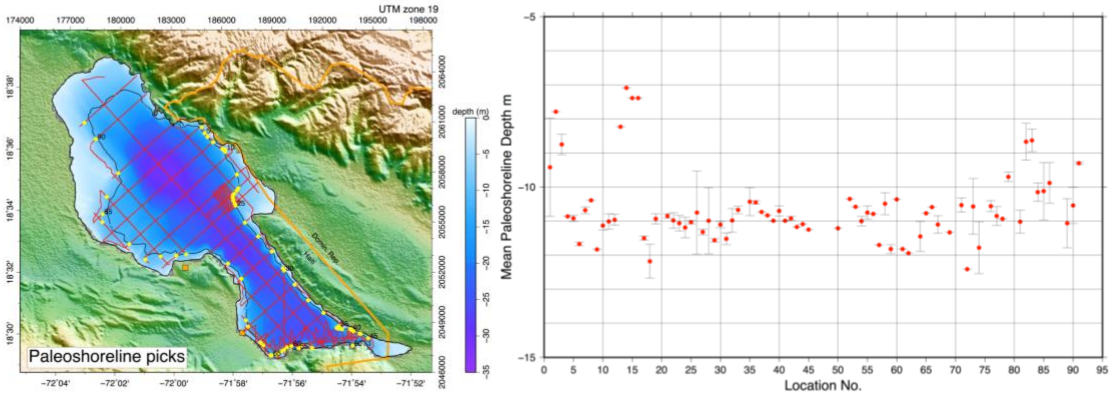

Figure 9: (a) Location of paleoshoreline picks (yellow dots); the 11 m contour is indicated with the thin black line. (b) Mean paleoshoreline depth in meters. Numbers along the horizontal axis corresponds to the numbers on the map (after Sloan et al., 2017)

Sediment deformation was found throughout Lake Azuei, and was prevalent in the Southern portion of the lake in the form of folds (Figure 10). There were also signs of liquefaction in the western portion of the lake, above a large monoclinal fold imaged with the MCS data (Figure 11).

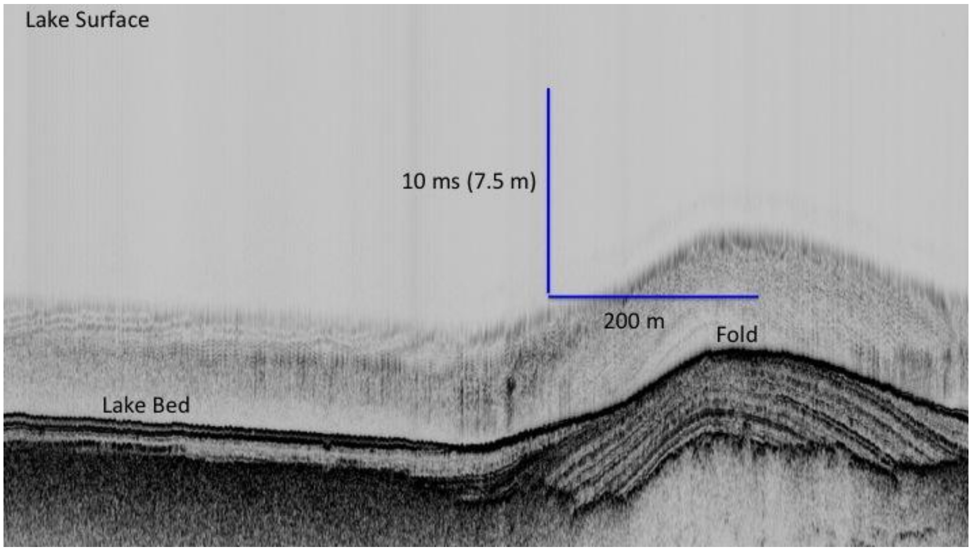

Figure 10: Fold in lake bed on line 803 in south eastern portion.

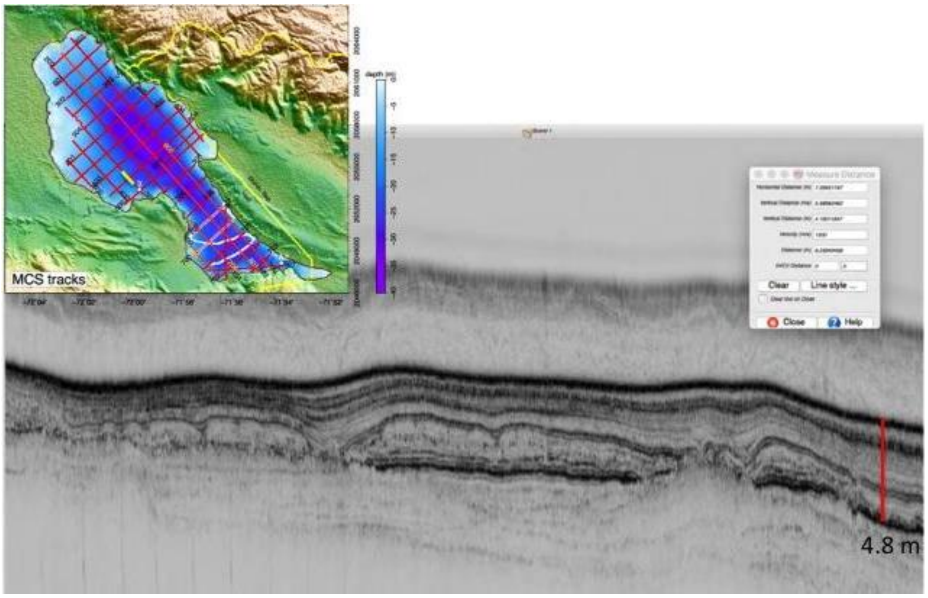

Figure 11: Possible liquefaction in western portion of the lake bed.

There were no gas flares imaged in the water column in the CHIRP profiles. In contrast, some recent studies along other submerged active faults have imaged pervasive gas seeps, suggesting that faults provide ready pathways for gas and fluids (e.g. Dupre et al., 2015; Kluesner et al,, 2016). In that respect, the lack of any gas flares beneath Lake Azuei is an unexpected result. Possibly, since the lake is so shallow (about 30 m deep) and possible relatively young, there is not enough gas accumulation within the sediment infill to sustain gas flares.

Further results from continued analysis will be presented at the 2018 fall meeting of the American Geophysical Union in Washington DC (Cormier et al., 2018).

6. Impact to other studies (HaitiDRILL)

There is currently an international initiative to promote scientific drilling in Haiti and specifically in Lake Azuei (project HaitiDRILL). Due to the heightened seismic risk in the area, there is a critical need for further exploration and understanding of the transform fault zone. One way to increase this knowledge is to drill into the fault zone and surrounding areas. A deep drilling site has been proposed for Lake Azuei to the International Continental Drilling Program (ICDP); the main objective of that international project (Haiti-DRILL) would be to drill in close proximity to the EPGF and constrain its tectonic evolution. The newly acquired seismic reflection profiles, especially multichannel seismic, would provide the critical information needed for selecting a drilling site in the lake, especially with respect to safety issues. For example, we imaged a lot of gas throughout the lake bed in our CHIRP profiles, and it would not be good to drill into a pocket of pressurized gas. Through the use of MCS profiles, which have deeper penetration, it would, for example, be possible to confirm the absence of pockets of high gas concentration. Additionally, structures can be imaged to see what would be worthy of drilling into. Hopefully, the results from our project will aide in the funding of the HaitiDRILL project. That project would not only advance our understanding of the tectonic evolution of the region, but deep drilling would also provide the data needed to unravel the timing of the closure of a presumed open seaway between the Atlantic and Caribbean (Mann et al., 1995), provide an estimate of earthquake recurrence in the area (paleoseismology), and potentially help establish the longest sedimentary record of climate change in the northern Caribbean (e.g., Hodell et al., 1991). Lastly, it could nail down the timing of the arrival of the first inhabitants in Hispaniola, the Arawak (Taino) people through their impact on the environment, for example by dating the appearance of maize pollen and evidence of increasing fire (e.g. Lane et al., 2008, 2009, 2014).

7. On-going Work

We are currently in the process of analyzing our paleoshoreline data to interpret tectonic deformation rates in the lake bed. We are waiting for the AMS C-14 dates to come back from processing in order to confine the age of the ~11 m paleoshoreline.

Core	Location UTM (x,y, in meter)	Length
LA17-BC01-1A	193720, 2048138	56 cm
LA17-BC02-1A	193720, 2048138	87 cm
LA17-BC03-1A	183585, 2053384	74 cm

Table 1: Sediment cores along with location in UTM coordinates and associated length

Core	Depth (cm)	# of gastropods	# of gastropod fragments	# of plant material
LA17-BC-02-1A	6-7	Not counted	Not Counted	Not Counted
LA17-BC-02-1A	34-35	180	200	24
LA17-BC-02-1A	42-43	35	16	13
LA17-BC-02-1A	63-64	37	10	36
LA17-BC-02-1A	76-77	5	0	0
LA17-BC-02-1A	83-84	0	0	0
LA17-BC-03-1A	23-24	8	9	0
LA17-BC-03-1A	33-34	5	9	0
LA17-BC-03-1A	53-54	39	10	1
LA17-BC-03-1A	64-65	91	41	0
LA17-BC-03-1A	71-72	36	74	1

Table 2: Sediment cores and depth of samples taken for Carbon-14 dating along with the number of gastropods, gastropod fragments, and plant material found in the 2 mm and 1 mm fractions.

Core	**Depth (cm)**	**Description**	**Sample weight (mg)**
LA17-BC-02-1A	42-43	Gastropods	97
LA17-BC-02-1A	42-43	Wood	46
LA17-BC-02-1A	63-64	Gastropods	42
LA17-BC-02-1A	63-64	Plants	86
LA17-BC-03-1A	71-72	Gastropods	179

Table 3: Sediment cores and depths of samples sent for Carbon-14 dating. The plant material from core 2 at 63-64 cm depth could not be dated.

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