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Searching for blind faults: The Haiti subsurface imaging project

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Abstract

On 12 January 2010, Haiti suffered a magnitude 7.0 earthquake near Port-au-Prince, which resulted in a catastrophic loss of life and infrastructure. The effects were particularly severe on the Léogâne fan delta, close to the earthquake's epicenter. Because no unambiguous rupture to the surface has been found, the suspected fault that caused the event has been labeled “blind.” A geophysical team from the University of Houston has undertaken expeditions to Haiti in 2012–2014, with support from the SEG Geoscientists *Without* Borders program, to try to help build Haiti's geophysical capability and assist in finding subsurface evidence of the proposed blind fault. The team reconnoitered the epicentral region of the 2010 earthquake and selected sites on the Léogâne delta fan for land surveys. The team enjoyed a productive and pleasant interaction with local villagers while receiving access to survey areas and assistance with operations. The resulting 2012 seismic and gravity data provided promise for more detailed surveys that the team undertook in February 2013. Measurements indicated that the soil sediments near Léogâne are Class E — a substantial geohazard. The University of Houston team found a broad and unfaulted anticline in the overlying fan deposit that is consistent with seismogenic movement on a north-dipping reverse fault at greater depth. The axis of the subsurface anticline is in alignment with an east-west-trending zone of localized highway damage and a coral reef that was uplifted during the 2010 earthquake. Lake sonar surveys have given some excellent images of the associated Enriquillo–Plantain Garden fault zone (EPGFZ). As a result of this work, the team plans to bring larger seismic sources to create more detailed and deeper seismic sections (land and lake) and to assist in further development of Haitian geophysical capabilities. The project has provided a remarkable learning experience for staff and students as well as for Haitian colleagues.

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Introduction

Hispaniola's Léogâne area was the epicenter of the devastating Haiti earthquake on 12 January 2010. The tragic event involved many fatalities and destroyed much of Haiti's infrastructure and technical capability in its most populated urban corridor, centered on the capital city of Port-au-Prince (Figure 1). The earthquake's effects were particularly pronounced on the Léogâne fan delta, where 80% to 90% of concrete buildings were destroyed along with the deaths of 20,000 to 30,000 residents who occupied those buildings.

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Figure 1. (a) The Haiti Presidential Palace on 14 January 2012. The grounds have been cleaned, but the building is largely destroyed. (b) Cleanup continues in Port-au-Prince.

Teams of geologists who visited the area in the days and weeks after the earthquake, along with detailed studies of aftershocks by seismologists, proposed a range of interpretations of the type of fault associated with the earthquake. Visits to the Léogâne area in the aftermath of the earthquake showed no evidence for surface ruptures of faults in the area (Koehler and Mann, 2011). Detailed studies of aftershocks in the epicentral area revealed the presence of a north-dipping fault in the bedrock underlying the less consolidated soils of the Léogâne fan (Douilly et al., 2013). Because this proposed fault did not express itself to the surface, it is called a “blind” fault; aftershocks indicated it was at a depth of about 4 km beneath the fan surface.

With support from SEG's Geoscientists *Without* Borders program, our University of Houston (UH) and Haitian team has been making geophysical measurements in the Léogâne fan delta area (1) to understand sediment properties of the delta and why shaking was so intense in that event and perhaps would be in future events, (2) to image the shallow section to seek evidence of the blind fault, and (3) to better understand the linkage between the Léogâne fault and the adjacent EPGFZ. While doing so, we aspire to help develop geophysical capability and personnel in Haiti.

Much has been accomplished in humanitarian terms and technical understanding of the earthquake in the last few years. Geophysical efforts in particular help to assess Haiti's geologic hazards, assist in building technical capacity, aid in the development of Haitian personnel, and afford an intensely useful experience for students and staff (from the United States, China, Turkey, Taiwan, and India) and our Haitian colleagues.

The Léogâne fan of southern Haiti is one of the largest subaerial fan deltas in the Caribbean. Remote-sensing data and fieldwork of uplifted coastlines (Hayes et al., 2010) indicate that the Léogâne fan was uplifted by the earthquake in a pattern consistent with the hypothesis of the blind Léogâne fault. The technical need to analyze the area is critical for understanding the earthquake system and related faults — especially which faults have released stress and which have not — and for understanding where strain buildup could occur.

Geophysical investigations

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The UH team undertook a reconnaissance visit to Haiti (Figure 2) in January 2012. Our group coordinated the visit with a United Nations–sponsored Haiti Earthquake Memorial Conference in Port-au-Prince on 12 January 2012, exactly two years after the earthquake. We met with several of our geoscience counterparts in the U. S. Geological Survey (USGS), Haiti Bureau of Mines and Energy (BME), and other geoscience institutes.

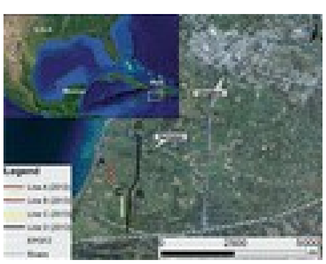

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Figure 2. Google Earth images of the Caribbean region and the Léogâne area. The location of geophysical surveys (colored lines) with respect to the city of Léogâne and the Enriquillo–Plantain Garden fault zone (ENPGZ) (white dashed line) are drawn.

For the 2012 effort, we concentrated on selecting accessible sites that would be as close to the epicenter of the events as was known. Transporting equipment from Houston to those sites in Haiti is interesting, but with patient collaborators in the BME and good humor, we deployed our instruments in Léogâne and other sites near Port-au-Prince.

We acquired test geophysical data, including hammer seismic surveys into multicomponent receivers using a Geometrics 60-channel Stratavisor plus a 24-channel Geode, gravity lines using a Scintrex CG-5 gravimeter, and total-station and GPS surveys. The data were all of reasonable quality, and the areas looked promising for further investigation. Based on these reconnaissance surveys, we planned to return to Haiti.

In February 2013, we returned. As with the surveys in 2012, there was a great deal of local interest in the effort. With our Haitian colleagues, we provided ongoing educational discussions with villagers. In the 2013 expedition to Haiti, we had considerably more equipment. We used two seismic recording systems: autonomous nodes (Geospace Seismic Recorders generously loaned to us by Global Geophysical, Houston) and our Geometrics Geode cabled recorders. We also had two sources: the GISCO slanted-weight drop to excite P-waves and S-waves and the Propelled Energy Generator (Figure 3).

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Figure 3. Seismic sources used during 2013 surveys included a GISCO slanted-weight drop (shown here) and a PEG accelerated-weight drop.

Overall, we acquired 4 km of 2D seismic line (lines B, C, and D) and 2D gravity lines. All the surveys were undertaken with personnel from the Bureau of Mines and Energy as well as local helpers.

Analysis and interpretation

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The 2D P-wave velocity structures for lines A and B were determined by traveltime tomography using first-break picks. P-wave values were calculated as 500 to 2250 m/s for a model 80 m deep (Figure 4a). Tomography results indicate a slight thickening of the low-velocity layer toward the southern end of the section. A similar trend was observed in the velocity analyses of all seismic lines. Velocity models suggest that the top 40 to 50 m of the subsurface contains highly saturated and seismically weak layers. The lower half-space had a velocity of 2250 m/s.

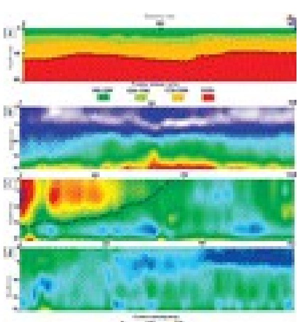

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Figure 4. Seismic sections: (a) 2D P-wave section for a model 80 m deep, estimated using traveltime tomography for line B. Red represents relatively high P-wave velocities (2250 m/s), and green represents lower P-wave velocities (500 m/s). Strata above the black dashed line are relatively slow and interpreted as seismically weak layers. S-wave velocity sections as determined from surface-wave inversion: (b) line A, (c) line D, and (d) line B. Yellow and red represent velocities of about 200 m/s. The dashed line in part (c) indicates a higher-velocity structure over a lower-velocity region.

Shear-wave surveys can provide additional subsurface images and sets of geophysical properties, especially those related to earthquake susceptibility. We applied a surface-wave inversion method, multichannel analysis of surface waves (MASW), to obtain the S-wave velocity structure (Figure 4b through 4d). S-wave velocities are used widely in geotechnical studies and soil classification.

The results obtained from MASW studies indicate average S-wave velocities of 180 m/s. According to USGS soil-type and shaking-hazard standards, those velocity values suggest that the near-surface soil at the Léogâne fan is most likely Class E type (soft clayey material). That type of soil can amplify shaking during an earthquake and result in liquefaction. The unconsolidated, soft, seismically slow soil might have been a contributing factor to the destruction in the area. Soil classifications from a recent study at Port-Au-Prince were found to be mostly Class C and D (Cox et al., 2011). The variation of the S-wave velocities might have been caused by weaker soil conditions over the Léogâne area as compared with the more lithified sedimentary rocks on which Port-au-Prince is constructed.

The time-migrated sections from the reflection-seismic lines revealed coherent re-flections to 400 ms (approximately 250 m in depth) for line A and to 500 ms (approximately 350 m in depth) for line B. On both seismic sections, we have interpreted evidence of channel systems and minor discontinuities. The overlying soft sediments might be thinning to the north (the fan toe). There is some evidence of a reflector at a depth of about 40 to 50 m that is consistent with the refraction and surface-wave inversion results. Combining all our measurements from studies to date gives us an interpretation shown in Figure 5.

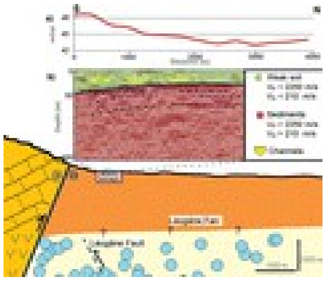

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Figure 5. South-north cross section of the Léogâne fan area with the EPGFZ and 2010 earthquake hypocenters annotated with blue circles (Douilly et al., 2013). Inset data: (a) Bouguer anomaly gravity A-A′ decreasing to the north and (b) seismic-reflection section B-B′ interpreted to show shallow, weak sediments overlying more competent rock.

We have been approached by the charitable organization Living Water International to assist with locating and logging water wells that the group plans to drill in Haiti in 2015. We hope to assist in the water-well program as well as acquire ground truth about sediments, from cuttings and logs. It is clear, however, that we need a more powerful seismic source to penetrate several kilometers deep to provide a better chance of imaging the proposed fault.

We focused our land efforts on the Léogâne epicentral area, but nearby lakes to the east (Lake Azuéi) and west (Mirogoâne Lake) present an opportunity to conduct much longer surveys in fault-related zones and to further develop Haiti's abilities. Thus in July 2014, we undertook sonar measurements using our EdgeTech subbottom profiler (2 to 10 kHz) to acquire about 100 km of high-resolution sonar lines (Figure 6). Oxfam Italy generously provided further support for these surveys in the past because of its interest in developing land-use plans for the lakes and surrounding areas.

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Figure 6. The Haitian and University of Houston team attach the subbottom profiler (chirp sonar) to a vessel in Lake Azuéi in July 2014.

We made measurements over the 130-km^2 brackish Lake Azuéi and 15-km^2 freshwater Lake Mirogoâne, which both straddle the active trace of the Enriquillo–Plantain Garden fault zone. An example of the chirp data (Figure 7) shows the active EPGFZ with an adjacent active anticline, both of which deform the late Holocene lake sediments. The lake sonar data are helping to improve understanding of the general fault system as well as details of the lakes' bathymetry and geologic evolution.

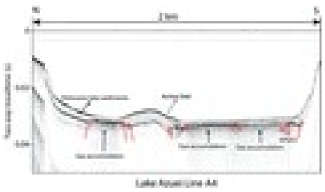

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Figure 7. An example of the chirp data shows an active anticline that is deforming Holocene lake sediments in Lake Azuéi along with active strands of the EPGFZ.

As originally proposed, we plan to return in 2015 with a more powerful source to image deeper in the section on land. In addition, we will undertake further acoustic surveys, also using larger sources, on the two lakes. We look forward to working with our Haitian colleagues (Figure 8) and joining with them in further capability building and understanding of earthquakes.

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Figure 8. The University of Houston crew, Haiti Bureau of Mines and Energy employees, Haitian logistics personnel, and local villagers after finishing seismic node surveys.

Summary

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A geophysical team from the University of Houston has undertaken expeditions to Haiti in 2012–2014 with support from the SEG Geoscientists *Without* Borders program. We established a good working relationship with members of the Haiti Bureau of Mines and Energy and local logistics experts. The team also developed a cordial collaboration with villagers while receiving access to survey areas and assistance with operations. We reconnoitered the epicentral region of the 2010 earthquake and selected sites on the Léogâne delta fan for land surveys. The quality of the 2012 data provided promise for more detailed surveys that we undertook in February 2013.

Our results have supplied reconnaissance near-surface images and have characterized the soil sediments as seismically slow, soft soil that is a geohazard in the Léogâne area. There is some evidence of discontinuities in the shallow-seismic sections from the Léogâne area but no obvious major faults. Lake sonar surveys acquired in July 2014 have given some excellent images of the associated Enriquillo–Plantain Garden fault zone. As a result of this work, we plan to bring larger seismic sources to create more detailed and deeper seismic sections (land and lake) and to assist in further development of Haitian geophysical capabilities. The project has provided an exceptional learning experience for an international team of staff and students as well as for our Haitian colleagues.

Acknowledgments

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We are grateful to SEG's Geoscientists *Without* Borders program for supporting this project and to Global Geophysical in Houston for loaning the land node system to the project. We express our appreciation to the Haiti Bureau of Mines and Energy, its employees (Robert Altidore, Julon Pochette, Nicole Dieudonne, and Sophia Ulysse), and Alexander von Lignau of the Haiti Ministry of Finance for helping to coordinate the Léogâne surveys. We are also thankful to Schlumberger-GEDCO for donation of the VISTA seismic-processing package and to Oxfam Italy for assistance with lake surveys.

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