4.0 SURFACE FAULTING AND COASTAL UPLIFT

4.1 Introduction

Surface fault rupture, which is a manifestation of the fault displacement at the ground surface, often occurs as a result of moderate- to large-magnitude earthquakes (M ~ 6 or larger) occurring on active faults having mapped traces or zones at the ground surface. The likelihood of and amount of displacement during surface rupture is a function of earthquake magnitude, focal depth, fault geometry, earthquake rupture process, nature of near surface soils and bedrock, and occurrence of fault creep. The amount of surface fault displacement can be as much as 1 to 5 meters or more, depending on the earthquake magnitude and other factors. The displacements associated with surface fault rupture can have devastating effects on structures and lifelines situated astride the zone of rupture. While in most cases the easiest mitigation for surface rupture is avoidance, in some cases (i.e., lifelines, such as buried water, natural gas, or petroleum pipelines, or existing structures) it may be necessary to design mitigation to accommodate fault displacement while meeting specified performance objectives. Therefore, it is important to document the occurrence or non-occurrence of surface rupture, and if present, to document the location, fault geometry and displacement, nature of soil or bedrock at the surface, and effects on overlying structures.

Surface fault rupture is typically expected to occur along geomorphically well-expressed faults, such as the Enriquillo-Pantain Garden fault zone (EPGFZ), and during large magnitude, shallow earthquakes, such as the January 12, 2010 Haiti earthquake. Well-expressed reaches of the fault, roadways and pavements crossing the fault trace, and young geologic layers or geomorphic surfaces across the fault were targeted to examine for surface fault rupture or deformation.

4.2 Fault Rupture Investigations

The EPGFZ is well expressed across southern Haiti, passing through Pétion-ville and south of Port-au-Prince (Figure 3.1). As described in Section 3.0, the fault is characterized by linear valleys and bounding uplifted mountains, shutter ridges, sag ponds, and elliptical basins at extensional stopovers and bends along the fault trace (Figures 4.1, 4.2, and 4.3). The presence of these and other well defined geomorphic features that define the fault trace at the surface indicate that the fault has ruptured repeatedly at the ground surface in large magnitude earthquakes in the past. Therefore, given that most shallow crustal earthquake of M 7.0 have ruptured to the ground surface (Lettis et al. 1997), and given the location of the epicenter near the EPGFZ and the dominantly strike-slip nature of the earthquake focal mechanism, it was anticipated by most geologists that surface rupture would have occurred on the EPGFZ.

The GEER team conducted reconnaissance at several sites along the EPGFZ to assess whether the fault ruptured at the ground surface. The reconnaissance was coordinated with other researchers (Dr. Paul Mann of the University of Texas Austin, Dr. Rich Koehler of the Alaska Division of Geology and Geophysical Surveys, and Dr. Roger Bilham of the University of Colorado) who also were searching for evidence of fault rupture. Dr. Mann and Dr. Koehler conducted reconnaissance along the EPGFZ in the area east of Dufort and Fayette, including visiting several sites along the prominent linear valley east of Fayette (Figures 4.1 and 4.2). These sites were near and east of the epicenter of the earthquake, and the reconnaissance conducted by the other scientists documented that surface rupture had not occurred on the fault in the area of the epicenter and further east along the prominent linear fault valley. The GEER team met with Dr. Mann and Dr. Koehler, and two representatives from the Haitian Bureau of Mines and Energy on February 1 for the purpose of conducting reconnaissance along areas of the

EPGFZ west of the epicenter. The reconnaissance conducted by the GEER team focused on the central and western parts of the fault rupture zone identified from the aftershock locations, which encompassed an area extending about 50 km west from the epicenter (Figure 2.3). The observations made during reconnaissance and preliminary mapping of fault traces are described in this section.

Figure 4.1. View east towards Fayette and Leogane along parallel east-northeast trending traces of Enriquillo Plantain Garden fault. Fault trace marked by push-pins labeled “EPG flt”. Fault trace at right (left offset of river along prominent north-facing scarps) apparently steps north to linear valley of Momance River at top left of picture.

Figure 4.2. View south of prominent fault scarp crossing fluvial terrace on Momance River east of Fayette. Fault trace marked by push-pins labeled “EPG flt”.

Dr. Mann and Dr. Koehler identified several locations near Dufort where the location of the EPG fault was well constrained and accessible, and the combined team visited these sites on February 1. These sites are located along Road 204 (Jacamel Road) and west of Road 204 (Figure 4.3). Road 204 passes south from the intersection with Road 2 across the plain and up the slope of the east-west trending mountain range. The EPG fault lies along the base of the range, at a prominent break-in-slope from the plains to the lower part of the range. The team confirmed that Road 204 is not displaced where it crosses the fault and range front. A distinct linear valley and shutter ridge occur at the base of the hills about 0.75 km west of Road 204, providing a well-constrained location of the active trace of the EPG fault. The team inspected the fault over a distance of several hundred meters across the small valley, along several transects extending across the shutter ridge and through the valley bottom to bedrock areas exposed on the hillslope above the valley. The fault is constrained to lie at the prominent break-in-slope at the base of the hill or within a few tens of meters east in the valley bottom (Figure 4.4). South of this valley, the EPGFZ is marked by the prominent break-in-slope and a series of side-hill benches (Figure 4.5). The team observed minor cracking in the valley floor at one location, and a linear north-facing scarp at the base of the hillslope. It was concluded that the minor cracking in the valley floor likely represented effects of shrink-swelling in the soil and that the north-facing scarp was the result of hoeing/tilling for agricultural purposes (Figure 4.6). Therefore, the team concluded that the fault did not rupture at the ground surface through the small valley.

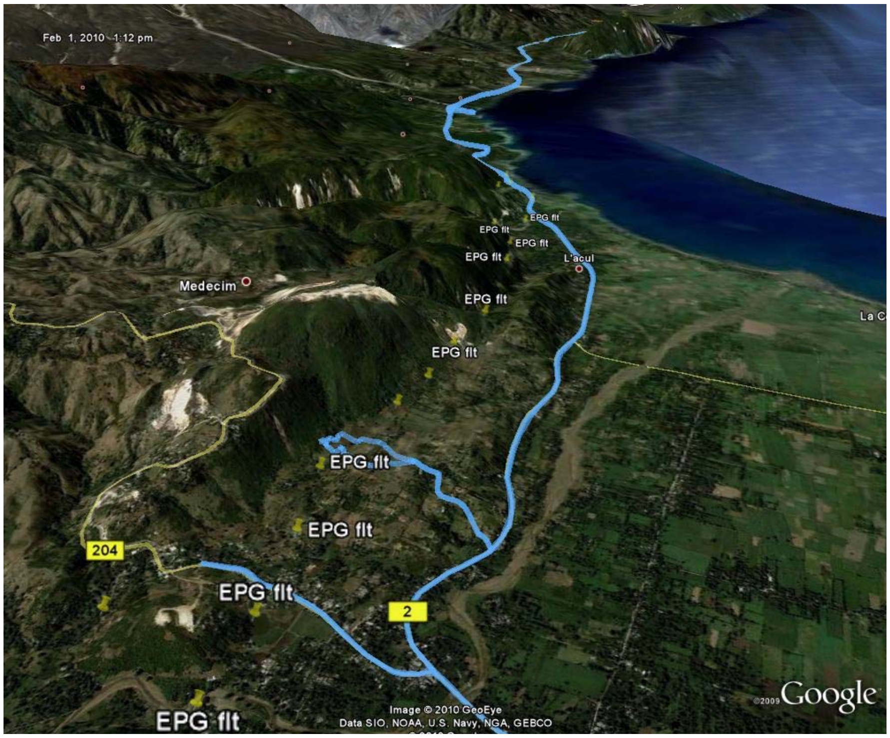

Figure 4.3. View southwest along EPG fault west of Dufort. Reconnaissance track marked in blue shows location of fault traverses on and west of Road 204. Fault trace marked by push-pins labeled "EPG flt".


Figure 4.4. View west along trace of EPG fault at linear valley southwest of Dufort (west of Road 204). Fault trace likely between base of slope (between red arrows) and center of linear valley. No fractures or other evidence for fault rupture observed at this site (N18.444306, W72.643722,).

Figure 4.5. View east along trace of EPG fault from hill above linear valley west of Road 204 (along red arrow) (N18.445819, W72.6431718).

Figure 4.6. View west along agricultural scarp in linear fault valley west of Road 204 (N18.444527, W72.643777).

Figure 4.7. View south of shutter ridge blocking drainage (center) and offset stream channel (center right) along fault south of L'acul. Fault trace marked by push-pins labeled "EPG flt".

The GEER team traversed Road 2 west of Road 204, where Road 2 is parallel to and crosses over the EPGFZ near L'acul, on several occasions between February 1 and 4 during additional reconnaissance investigations (Figure 4.7). No evidence of lateral road displacements or equivocal shear cracks was found on the roads across the fault crossing areas. However, a number of cracks and areas of settlement were observed along the road. These features were evaluated and we concluded to be the result of settlement of the road fill/embankment settlement over soft subgrade soils (see Section 8.0 Road Fill Performance), and possibly in some cases due to localized liquefaction. None of these features were found to represent surface fault rupture.

The EPGFZ extends along the base of the range for about 2.5 km west-southwest from L'acul, and passes offshore into Grand Goâve Bay. The fault apparently bends or steps northward in the offshore region, and then extends west-northwest along the coast to Petit Goâve Bay at Port Royal, approximately 20 km further west. The bend or step northward would be on the order of 1.5 to 2 km wide, or possibly wider, based on a westward projection of the EPGFZ fault from L'acul, and an eastward projection of the EPG fault from Port Royal. At the coast at Port Royal, the EPG passes along the base of the prominent steep linear south-facing range front, and extends west-northwest along the base and lower portion of the hillslope. Numerous offset drainages and side hill benches are visible on aerial imagery, with two parallel fault traces extending along the base and lower portion of the range front.

With the assistance of a local resident to guide the team along un-improved cart and horse paths off the paved road, the GEER team conducted traverses across the fault on February 4 at two locations in the area north and west from Port Royal (Figure 4.8). At the two sites, which were located along about a ¾ km length of the range front, two parallel fault traces are marked by prominent side hill benches, offset drainages, and a sharp steeply dipping contact between colluvium and limestone bedrock (Figures 4.9 to 4.11). The team traversed footpaths that extended north upslope across the fault at both sites. No fracturing or evidence for fault rupture was observed at the bedrock-colluvial contact (a northern fault trace) or along the base of the side-hill benches and alignment with diverted drainages (a southern fault trace). When asked whether and where they had observed any ground cracking, several local residents described ground failures due to landsliding on slopes on the opposite side of the valley, and one location of ground cracking on the coast east of Port Royal. We were not able to travel to the coast to evaluate the ground cracks because of impending darkness, but based on the description of the cracks as being near the water, and due to the prevalence of lateral spreading along the coast, it is likely that these fractures were due to ground failure rather than fault rupture. Thus, based on our observations and the information from the local residents, the team concludes that the EPGFZ did not rupture at the surface where it extends onshore from Petit Goâve Bay.

Figure 4.8. View west of prominent parallel west-southwest trending fault traces along south-facing slope of hills west of Petit Goâve Bay and Port Royal. Reconnaissance track marked in blue shows location of fault traverses west of Port Royal. Fault trace marked by push-pins labeled “EPG flt”.

Figure 4.9. View east-northeast along fault west of Port Royal. Side-hill bench bounded by two fault traces at left and center of photo (above red arrows). No fractures or other evidence for fault rupture observed at this site (N18.440027, W72.923304).

Figure 4.10. View north across fault (at upper break in slope) west of Port Royal. Side-hill bench and blocked drainages at center of photograph (between red arrows) (N18.439666, W72.916444).

Figure 4.11. View north across fault at west of Port Royal. Fault passes perpendicular to track in middle of photograph at colluvium-bedrock contact (at red arrows upslope from team members). No fractures or other evidence for fault rupture observed at this site (N18.44150, W72.916389).

4.3 Coastal Uplift

Coastal uplift, while not typically a life or structural damage hazard, has implications on performance of infrastructure dependent on maintenance of static grade (e.g. gravity storm drains, port facilities), and also influences general drainage and flooding patterns. Additionally, uplift represents evidence of broad, vertical crustal movements associated with fault rupture, and thus observations of coastal uplift help confirm the focal mechanism and slip distributions inferred from teleseismic data.

Interpretation of aerial imagery and reports from Haitians in the coastal area of Léogâne indicated that several areas along the coast were uplifted as a result of the 12 January earthquake. The GEER team traveled to the Ca Ira area west of Léogâne on 1 February to observe one area where coastal uplift had been observed. At this site, the team observed an area of exposed coral and subtidal Turtle grass extending for more than 100 m seaward from the shoreline (Figure 4.12). Key observations from this area are as follows.

Turtle grass is a subtidal plant, and apparently does not grow in areas exposed at low tide. As observed during our reconnaissance, an extensive area of this grass was exposed above the water level (which was at or close to low tide during our reconnaissance). Much of the exposed grass was brown and appeared to be dying as a result of exposure to air/direct sunlight (Figure 4.13). The length of the grasses was about 10 cm, possibly indicating the minimum submergence depth at low tide prior to the 12 January earthquake.

The coral reef exposed at low tide consisted of largely dead coral heads (Figure 4.14), with small areas of new living coral at the top of the heads (Figure 4.15). The outer coral head is dead, which appears to indicate that uplift occurred previously at this site, followed by submergence and growth of new coral. The minimum subtidal depth at which coral grows is dependent on the specific coral species and other factors, but may be on the order of several tens of centimeters.

Local villagers indicated that the grasses and mud flats were not exposed at low tides prior to the 12 January earthquake, and that the high tides no longer extended to the sea wall as indicated by the water marks on these walls (Figure 4.16). The current tide chart for Port-au-Prince indicates the tidal range typically is about 0.4 to 0.6 m.

The estimated uplift resulting from 12 January earthquake is on the order of 50 centimeters based on elevational differences between pre-event high tide marks on a seawall (interpretation by Rich Briggs), tidal records for the date and time of the field visit, elevation of current high tide debris strandline, presence of living coral exposed in the coral head above the water (Figure 4.17), the height (length) of the exposed grasses, and reports on water level/tidal changes by local villagers.

Figure 4.12 Aerial view of coastal uplift in Ca Ira, near Legoane. (See GEER Haiti Report.kmz for location)

Figure 4.13. Reconnaissance team inspecting exposed grass and coral at Ca Ira, Léogâne. An extensive area of mud flats, grasses, and coral was exposed at low tide. (18.525333°N, 72.652008°W).

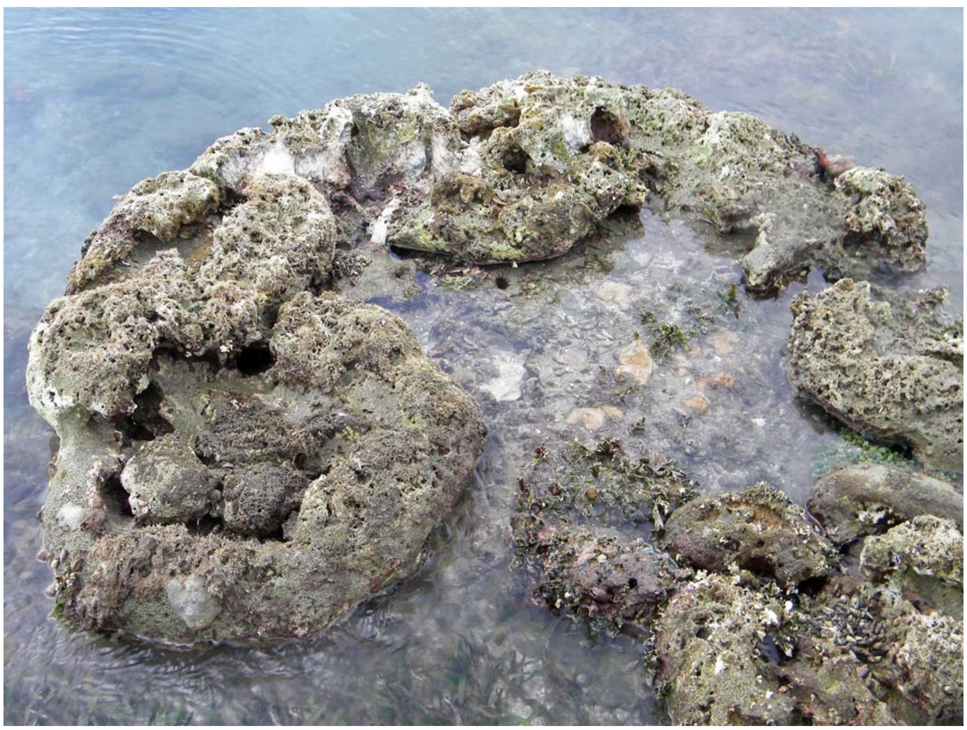

Figure 4.14 Coral head (~1.0 m diameter) with living coral at center exposed at low tide at Ca Ira, Léogâne (N18.525333, W72.652008).

Figure 4.15 Living coral in coral head exposed at low tide at Ca Ira, Léogâne. (N18.525333, W72.652008)

Figure 4.16. Water mark for high tides on sea wall at Ca Ira, Léogâne. Residents indicate high tides no longer extend up the wall to the former high tide level (N18.524924, W72.650871)

Figure 4.17. Exposed coral head at Ca Ira, Léogâne. Team members measuring uplift of coral head. (N18.525333, W72.652008)

The GEER team also conducted reconnaissance along the coast near L'acul on February 4, where aerial imagery showed additional areas of exposed coral reefs (Figure 4.18). We note that the L'acul site is 0.5 to 0.75 km north of the Enriquillo-Plantain Garden fault zone (EPGFZ) which trends west-northwest to the coast (west of L'acul). Small areas of coral heads were exposed above the water at the time of our visit (Figures 4.19 and 4.20), and the water level apparently was approximately one hour prior to high tide. The team observed a much larger area that apparently is now exposed at low tide, based on the height (3 to 5 cm) of living coral exposed above the water level during our visit and the approximate tidal range of 0.4 to 0.6 m. In general, the amount of uplift estimated at the L'acul site appears to be approximately the same order of magnitude as that observed at Ca Ira. Dr. Mann is working with a team from the U.S. Geological Survey (including Dr. Carol Prentice) to further document and quantify uplift recorded by corals along the coast.

Figure 4.18 Aerial view of coral uplift near L'acul.
(See GEER Haiti Report.kmz for location)

Figure 4.19 GEER team members inspecting uplifted coral reef near L'acul Coral heads are exposed above water at right, approximately one hour prior to high tide. (N18.446463, W72.688354).

Figure 4.20 Fleshy living, or recently living, coral collected from the top of a coral spire projecting about 3 to 5 cm above water level at the time of the GEER field visit. (N18.446463, W72.688354)

Our reconnaissance indicates that uplift occurred over a minimum distance of about 8 km along coast, extending generally north-northeast between L'acul and Léogâne (See Figure 3.2 in Section 3.0 Regional Geology). The west-southwest trending EPG fault extends offshore in the area just south of L'acul; thus, this area of observed uplift is directly north of the fault. We note that the coastal uplift observed north of the EPG fault in this area is not consistent with the apparent long-term geomorphic expression of south-side up vertical slip on the EPG fault that has uplifted the hills south of the fault.

Our preliminary review of pre- and post-earthquake aerial imagery indicates that the area of coastal uplift may extend north from Ca Ira to Cheridan, and possibly east to near Carrefour. Additional areas of possible coastal uplift were observed along the coast to the west in the area north of Port Royal. In this area, the vertical component of slip is north-side up (hills are north of the fault), which is consistent with the potential uplift observed along the coast north of Port Royal.

The apparent broad region of uplift seems unusual for a well-defined, dominantly strike-slip faulting event. It is possible that broad distributed slip occurred along un-mapped folds or faults north of the EPG fault, as some of the aftershocks, and distal ends of the primary earthquake rupture process, have a component of reverse slip. We understand that Drs. Mann and Koehler are evaluating available industry offshore geophysical data which show a fault with relative uplift on the north in the vicinity of Leogane Point. New offshore geophysical data is planned to be acquired by Woods Hole Marine Laboratory. These existing and new offshore data should help understand the mechanisms responsible for the broad coastal uplift, and also strain partitioning between the EPGFZ and other possible geologic structures.

4.4 Summary

The combined field reconnaissance efforts of three teams as of early February included multiple traverses across the Enriquillo-Plantain Garden fault in areas east and west of the epicenter, and along the entire length of the fault area where aftershocks have been recorded during the three weeks following the 12 January earthquake. Based on the observations of the absence of surface slip on the fault, and combined with the reports from local residents (such as described in the EERI/USGS/GEER reconnaissance report; Eberhard et al., 2010) that no ground deformation has been observed that could be attributed to surface faulting, the GEER team concludes that the EPG fault did not rupture at the surface on-shore, and that no surface faulting occurred onshore on any other faults. No information is available to assess whether displacement may have occurred on the off-shore extent of the EPG fault. However, given that the major moment release in the earthquake occurred at depth onshore and just west of the epicenter, the absence of surface faulting over the high slip portion of the fault plane strongly supports the interpretation that the rupture did not reach the surface onshore or offshore.

A particular issue to resolve in order to fully understand and quantify the earthquake hazard for Port-au-Prince and the surrounding region is whether the January 12 rupture occurred on the EPGFZ or on another fault. While the earthquake does not appear to have caused surface rupture, observations of coastal uplift described in the previous section document that the fault rupture uplifted a broad region (more than 8 km in width) north of the mapped fault. Given that such uplift over a broad region is not expected from a strike-slip earthquake, and based on the modeled component of reverse slip from the earthquake focal mechanism and the slip inversion (as described in Section 2.0, Figure 2.2), it is possible that the fault rupture did not occur on the EPGFZ, and that it occurred on a steeply dipping blind or buried oblique slip fault located north of the EPGFZ. If the EPGFZ did not rupture during the January 12 earthquake, the earthquake hazard for Port-au-Prince and region to the west may be larger than recently estimated by the U.S. Geological Survey (http://pubs.usgs.gov/of/2010/1019/). It also is possible that the EPGFZ only ruptures in larger magnitude earthquakes as described in previous seismic hazard assessments (M_W 7.5 to 8.5, Geomatrix Consultants, 2004; M 7.2 or larger, Mann et al., 2008). The absence of surface rupture along the geomorphically well-expressed fault during this large, shallow earthquake raises some concern regarding the ability to capture dependable recurrence estimates for large paleoearthquakes on the basis of paleoseismic trenching. Typically, it would be expected that paleoseismic trenching across a strike slip fault such as the EPGFZ would capture the record of large paleoearthquakes. This earthquake event is an important case study in this regard.

In the near future, additional work to survey land deformation and to document the uplift and subsidence history of the epicentral region is planned by geophysicists from Purdue University (Dr. Eric Calais and colleagues, http://haitigps.wordpress.com/purdue-geophysicists-in-haiti-conducting-gps-research/) and geologists from the University of Texas at Austin (Dr. Paul Mann) and the U.S. Geological Survey (Dr. Carol Prentice). These data, along with detailed seismological information collected from recently installed seismic stations in Haiti (Dr. Walter Mooney of the USGS), will provide information and constraints on the earthquake rupture and history of deformation of the region, and in particular will help identify the causative fault for the earthquake. However, detailed mapping and paleoseismic studies of the EPGFZ and possibly other active faults will be necessary to more fully characterize the earthquake hazard for the region near the fault.

References

Geomatrix Consultants, Inc., 2004, Seismicity Update, U.S. Department of State, New Embassy Site, Port-au-Prince, Haiti: Report prepared for Wiss, Janney, Elstner Associates, Inc., Emeryville, California.

Lettis, W.R., Wells, D.L., and Baldwin, J.N., 1997, Empirical observations regarding reverse earthquakes, blind thrust faults, and Quaternary deformation; are blind thrust faults truly blind? Bulletin of the Seismological Society of America, v. 87, no. 5, p. 1171-1198

Eberhard, M., Steven Baldridge, S., Marshall, J., Mooney, W., and Rix, G., 2010, The M_W 7.0 Haiti Earthquake of January 12, 2010: USGS/EERI Advance Reconnaissance Team

Team Report, V. 1.0, February 18 (http://www.eqclearinghouse.org/20100112-haiti/wp-content/uploads/2010/02/USGS_EERI_HAITI_V1.pdf).

Mann, P., Demets, C., Prentice, C.S., and Wiggins-Grandison, M., 2008, Enriquillo-Plantain Garden Strike-Slip Fault Zone: A Major Seismic Hazard affecting Dominican Republic, Haiti and Jamaica: 18th Caribbean Geological Conference, Santo Domingo, Dominican Republic (http://www.ig.utexas.edu/jsg/18_cgg/Mann3.htm)