AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL065505

Key Points:
- A new seismotectonic study in Haiti and identification of active faults in Port-au-Prince
- A new faulting model for the Haiti *M*7 2010 earthquake
- A reappraisal of the seismic hazard in southern Haiti and Port-au-Prince after the earthquake

Supporting Information:
- Supporting Information S1

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Citation:
Saint Fleur, N., N. Feuillet, R. Grandin, E. Jacques, J. Weil-Accardo, and Y. Klinger (2015), Seismotectonics of southern Haiti: A new faulting model for the 12 January 2010 *M*7.0 earthquake, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL065505.

Received 27 JUL 2015
Accepted 18 SEP 2015
Accepted article online 25 SEP 2015

Seismotectonics of southern Haiti: A new faulting model for the 12 January 2010 *M*7.0 earthquake

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Abstract The prevailing consensus is that the 2010 M_w7.0 Haiti earthquake left the Enriquillo-Plantain Garden strike-slip fault (EPGF) unruptured but broke unmapped blind north dipping thrusts. Using high-resolution topography, aerial images, bathymetry, and geology, we identified previously unrecognized south dipping NW-SE striking active thrusts in southern Haiti. One of them, Lamentin thrust, cuts across the crowded city of Carrefour, extends offshore into Port-au-Prince Bay, and connects at depth with the EPGF. We propose that both faults broke in 2010. The rupture likely initiated on the thrust and propagated further along the EPGF due to unclamping. This scenario is consistent with geodetic, seismological, and field data. The 2010 earthquake increased the stress toward failure on the unruptured segments of the EPGF and on neighboring thrusts, significantly increasing the seismic hazard in the Port-au-Prince urban area. The numerous active thrusts recognized in that area must be considered for future evaluation of the seismic hazard.

1. Introduction

The M_w7.0 Haiti earthquake of 12 January 2010 occurred close to the city of Port-au-Prince in the Enriquillo-Plantain Garden fault zone (Figures 1 and 2). Several slip models have been proposed for the earthquake. They all concur on its transpressional nature and the fact that the bulk of the seismic moment was released north of Enriquillo-Plantain Garden strike-slip fault (EPGF) [*Calais et al.*, 2010; *Hashimoto et al.*, 2011; *Hayes et al.*, 2010; *Meng et al.*, 2012; *Mercier de Lépinay et al.*, 2011; *Symithe et al.*, 2013]. However, as no unambiguous surface breaks were observed [*Bilham*, 2010; *Prentice et al.*, 2010], the geometry of the rupture could not be constrained. Several authors [e.g., *Calais et al.*, 2010; *Douilly et al.*, 2013; *Mercier de Lépinay et al.*, 2011] proposed that the earthquake ruptured a previously unmapped north dipping blind oblique fault (Léogâne), instead of the main strike-slip EPGF.

By combining satellite data, aerial images, topography, bathymetric charts, and geological maps with observations in the field, we document the geometry and kinematics of active faulting in the epicenter area and farther east in the Cul-de-Sac-Enriquillo (CSE) Valley, wherein lies the city of Port-au-Prince. In light of our improved tectonic understanding, we propose a new faulting model for the 2010 earthquake and discuss its implications for seismic hazard in Port-au-Prince.

2. Seismotectonic Setting of the 2010 Haiti Earthquake

The island arc of Hispaniola is squeezed between two rigid blocks that converge obliquely at 2cm/yr: the Bahamas bank on the North American (NAM) plate and the Beata ridge on the Caribbean (CAR) plate (Figure 1a) [*Granja Bruña et al.*, 2014; *Mann et al.*, 1995; *Mauffret and Leroy*, 1997]. As a consequence, the deformation is partitioned between left-lateral strike-slip faults as the Septentrional fault (SF) and the EPGF and a series of folds and thrusts [*Mann et al.*, 1995; *Saint Fleur*, 2014] (Figure 1). The CSE Quaternary basin is bounded to the north by the frontal thrusts of the southwestward verging Haiti fold and thrust belt (HFTB) and to the south by the southwestward dipping thrusts that limit and uplift the oceanic crust (Massif de la Selle-Sierra de Bahoruco, MSB, Figure 1) (*Granja Bruña et al.* [2014], *Mann et al.* [1991a], *Pubellier et al.* [2000], and this study).

The fold and thrust belts (MSB and HFTB) have been active since the Miocene [*Mann et al.*, 1995], controlling the ongoing growth of the highest relief of Haiti (i.e., Pic la Selle; Figure 1b). They extend offshore to the west, forming the Gonâve Island [*Mann et al.*, 1995], and to the east, structuring the Muertos Trough and thrust belt [*Granja Bruña et al.*, 2014] (Figure 1a). In the Gonâve basin, the most recent sedimentary layers are folded

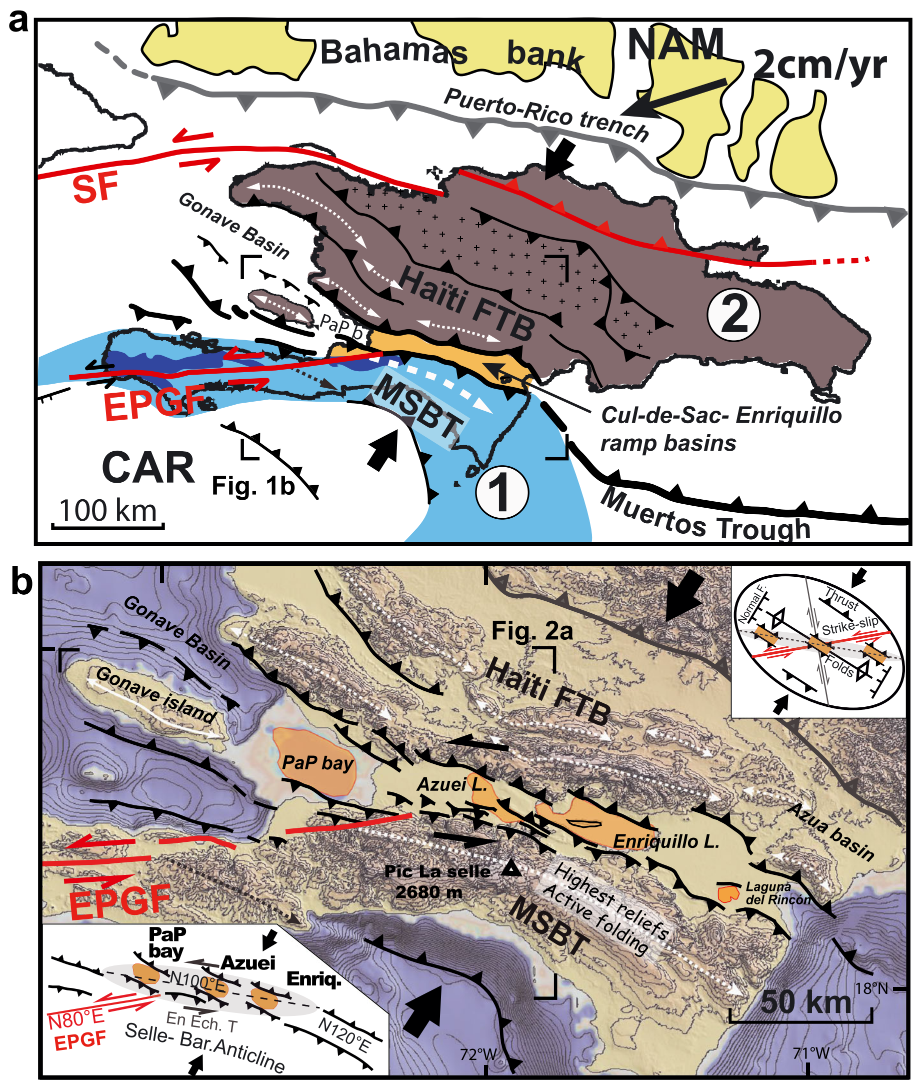

Figure 1. Tectonic setting and active faulting in Haiti. (a) Major anticlines (lines with arrows, dashed white: growing and grey: older), active thrusts (black), and strike-slip faults (EPGF and SF: in red) from this study [*Mann et al.*, 1995; *Pubellier et al.*, 2000; *Mauffret and Leroy*, 1997; *Granja Bruña et al.*, 2014]. Blue (1): rigid Beata oceanic crust block. Dark purples: toleitic complex oceanic crust outcrops. Orange: Cul-de-Sac and Enriquillo (CSE) ramp basins; brown (2): Hispaniola volcanic arc. Black crosses: metamorphic Cretaceous basement; yellow: rigid Bahamas bank. Haiti FTB: Haiti fold and thrust belt. Grey line: trench. Double black arrows: regional compression deduced from mean orientations of folds and thrusts. (b) Active faulting in southern Haiti. Topography and bathymetry (contours each 200 m) from Global Multi-Resolution Topography (GMRT) synthesis (http://www.geomapapp.org). Faults, folds, and symbols as in Figure 1a. Simple red and black arrows: strike-slip motion. In orange: *push-down* troughs of Port-au-Prince Bay and Azuei and Enriquillo Lakes in the CSE ramp basin. Inset (bottom left): fault geometry and kinematics. Grey ellipse: zone with en echelon troughs in N100°E direction. Inset (top right): simplified strain ellipse in southern Haiti.

and crosscut by thrusts that reach the seafloor, indicating late Quaternary activity [*Mann et al.*, 1995]. South of the Gonâve Island, a ~50 km long, south dipping, N120°E striking active thrust system (Trois-Baies) was recognized [*Mercier de Lépinay et al.*, 2011] (Figure 2a). The EPGF has propagated across Hispaniola only since the Pliocene [*Calais and Mercier de Lépinay*, 1995] and is therefore younger than the fold and thrust belts.

The Haiti earthquake had a strike-slip focal mechanism compatible with the geometry of the EPGF with a N80°E striking nodal plane parallel to the fault (Figure 2a). Aftershocks mainly occurred along the EPGF and Trois-Baies fault system [*Douilly et al.*, 2013; *Mercier de Lépinay et al.*, 2011]. Focal mechanisms of the largest show reverse fault motion on WNW-ESE striking, 30°–45° nodal planes [*Nettles and Hjörleifsdóttir*, 2010] compatible with NNE-SSW striking shortening and with the geometry of thrusts in the area such as Trois-Baies.

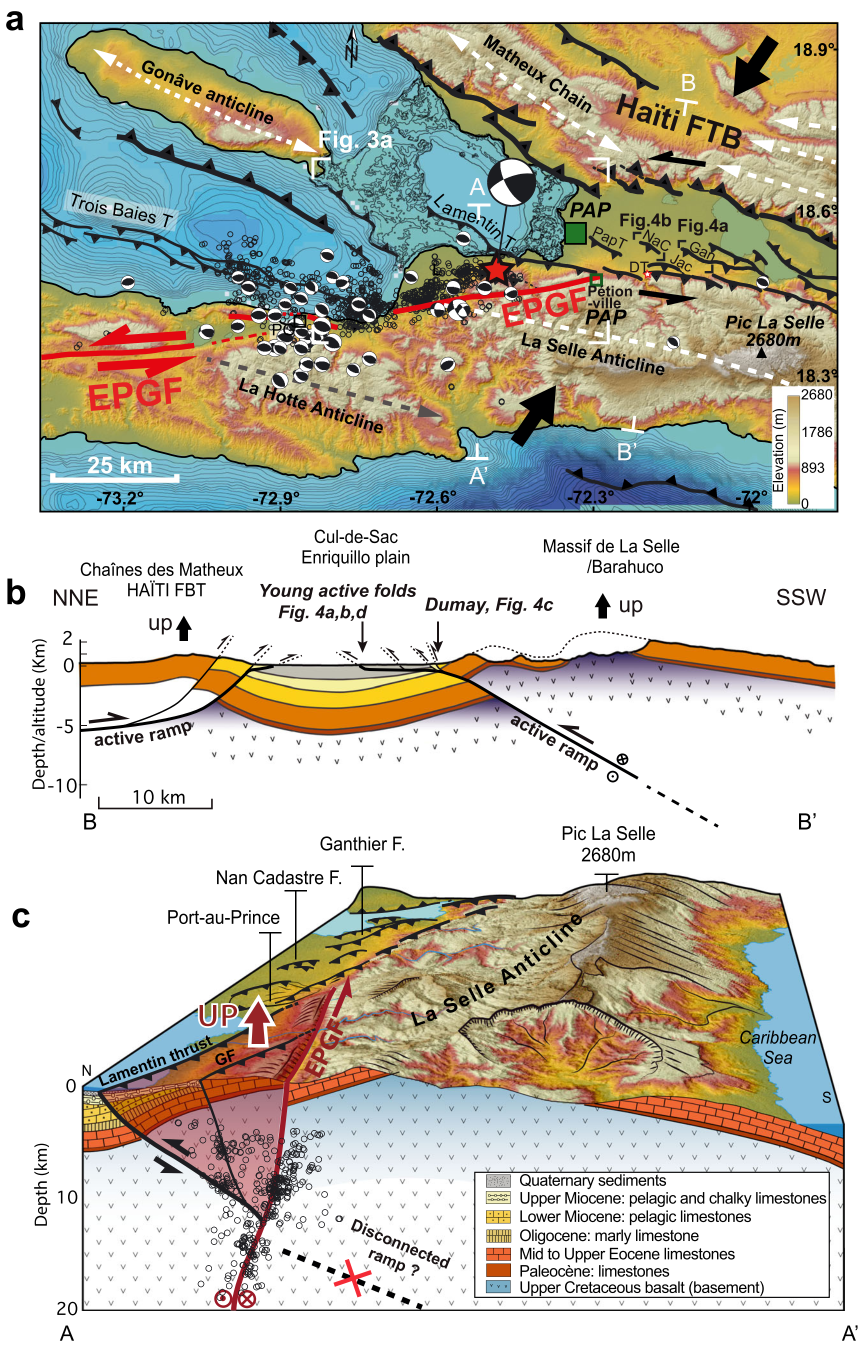

Figure 2. (a) Active faulting and seismicity in the southeastern part of Haiti. Topography and bathymetry (contours each 100 m), from Advanced Spaceborne Thermal Emission and Reflection (http://asterweb.jpl.nasa.gov/) and Shuttle Radar Topography Mission 30+ (http://www2.jpl.nasa.gov/srtm/), respectively, and the 1:25000 bathymetric chart of the Hydrographic and Oceanographic Department of the French Navy (contours at −2, −5, −10, −20, −30, −50, −100, and −130 m) in the Port-au-Prince Bay. Faults, folds, and symbols as in Figure 1. Red star: 2010 main shock epicenter from *Mercier de Lépinay et al.* [2011] with the centroid moment tensor from Harvard University (http://www.globalcmt.org); seismicity from *Douilly et al.* [2013], and focal mechanisms from *Nettles and Hjörleifsdóttir* [2010]. Location of Figure 3a is indicated. PAP, Port-au-Prince. Folds in CSE ramp basin with locations of Figures 4a and 4b are indicated: PaPT: Port-au-Prince thrust; DT: Dumay thrust; NaC: Nan Cadastre thrust (see Figure 4b); Jac: Jacquet thrust; Gan: Ganthier thrust (see Figure 4a). Red and white star near DT: location of Figure 4d. (b) NNE-SSW geological cross section across the Cul-de-Sac-Enriquillo plain. Geology from www.bme.gouv.ht and *Mann et al.* [1991b] (supporting information Figure S5) with colors of units as in Figure 2c. Profile location shown in Figure 2a; topography as in Figure 1. No vertical exaggeration. (c) Three-dimensional block diagram showing the geology, the aftershocks [from *Douilly et al.*, 2013], and the fault system along a N-S cross section (location in Figure 2a). The block highlighted in red is uplifting in between the LT and the EPGF.

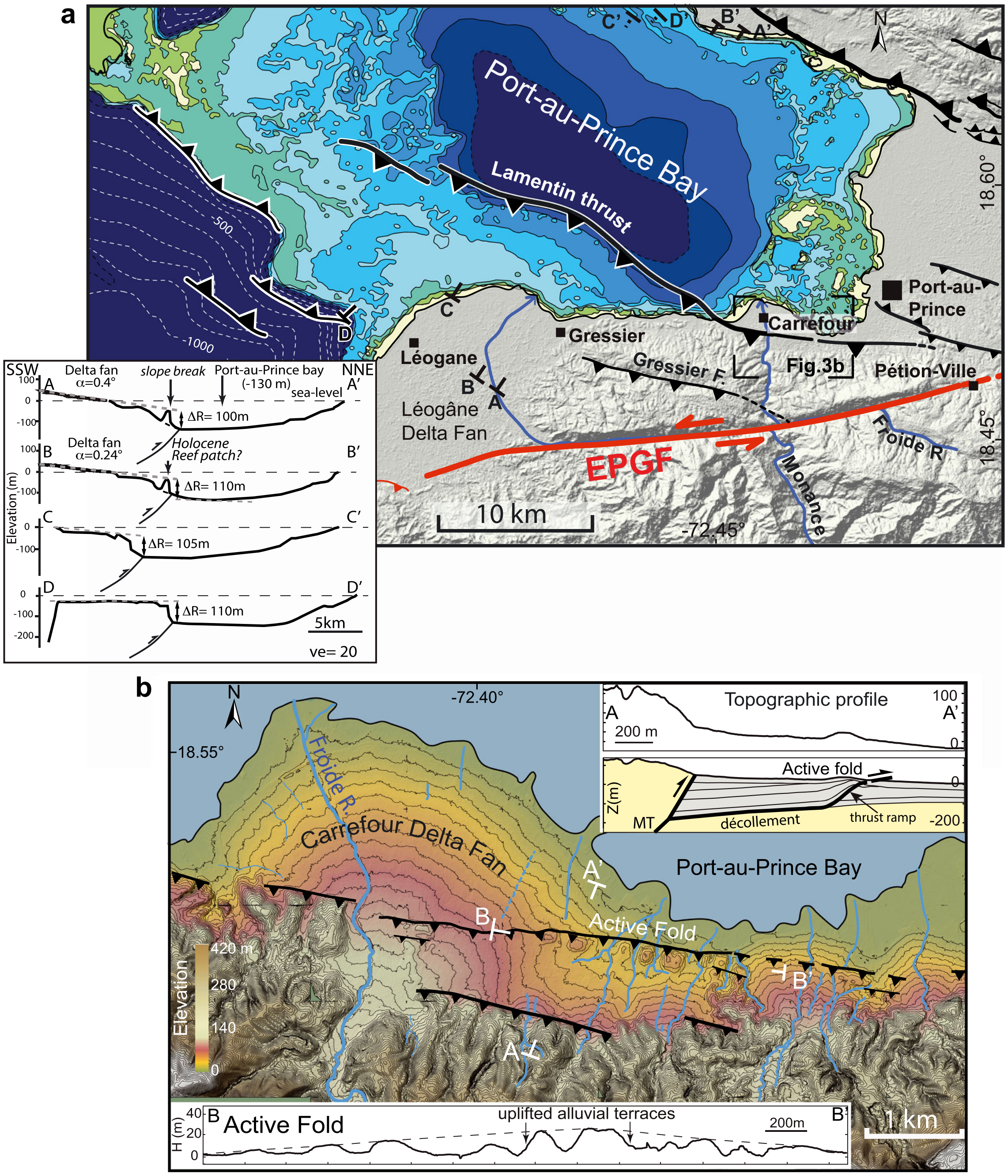

Figure 3. (a) Active faulting in the 2010 earthquake epicentral area. Active faults, symbols, topography, and bathymetry as in Figure 2a. Location of Figure 3b is indicated. SSW-NNE topographic profiles are shown in the inset. Δ*R*: fault throw at the seafloor. Vertical exaggeration (VE): 20X; *α*: slope of the Léogâne delta fan. (b) The Lamentin thrust in Carrefour. Topography from lidar data (contours at 5 m vertical interval). Rivers in blue, with thicker traces for larger ones. Inset in the lower left corner: topographic profile BB′ along of the Lamentin fold crest (VE: 5X). Inset in the upper right corner: topographic profile AA′ perpendicular to the Lamentin thrust system (VE: 2.5X) and the most plausible geometry of the thrusts (with no vertical exaggeration). In yellow: upper Miocene limestone; in grey: Quaternary conglomerates. MT: main thrust. The width of the fold and the slope of the fan surface constrain the rooting depth of the emergent ramp to the décollement [e.g., *Meyer et al.*, 1998].

3. Active Faulting in the Epicentral Area

High-resolution air photographs (30 cm pixels) and lidar topography (1 m) allows us to identify active structures exhibiting youthful morphology north of the EPGF. A >3 km long, 230 ± 50 m wide alignment of hills, up to 26 m high and striking N112°E lies in the Carrefour City (Figure 3 and supporting information Figure S1). It is located at the foot of the mountains and stand above the active Quaternary delta fan surface, disrupting its slope. Current channels flow in between the hills, leaving perched alluvial terraces on their flanks, suggesting that they correspond to an actively growing fold. The fold is likely related to an emergent thrust ramp rooted on a south dipping, low-angle, shallow décollement. This décollement splays from a master high-angle thrust located below the higher relief, overthrusting the upper Miocene limestone units onto Quaternary conglomerates (Figure 3, inset).

Offshore, west of the fan, the bathymetry of the Port-au-Prince Bay is disrupted at shallow depth (<130 m) by a steep, linear, WNW-ESE striking step that is up to 110 m high and is likely the emergent front of a thrust, in continuation of the onshore one (Figure 3a). It uplifts the bay's fringing reefs, which do not follow the coast as expected. Instead, they form a cordon linking the Léogâne delta fan to the Gonâve Island, implying that this area is shallow enough to permit reef development. This zone is actually bounded to the NE by the thrust system we named Lamentin (LT) and by an antithetic thrust system to the SW. Farther to the northwest, a similar fault system made up of two antithetic reverse faults may control the uplift of the Gonâve Island [*Mann et al.*, 1995]. Overall, the size and geometry of the LT system are analogous to the Trois-Baies fault system (Figure 2a). The surface trace of the LT merges with the EPGF near Pétion-Ville (Figures 2a and 3a), implying that the two faults also connect at depth. Another southward dipping thrust (Gressier) connects to the EPGF and thrusts Eocene and lower Miocene marine sediments of the MSB anticline over upper Miocene and Quaternary sediments filling the CSE basin (Figures 2c and S5). The crustal block squeezed between the LT and the EPGF exhibits morphological evidence for ongoing uplift at many sites (supporting information Figures S2 and S3).

4. Active Faulting in the Cul-de-Sac-Enriquillo Plain

The LT system extends into the Port-au-Prince area and farther east. A series of a few kilometers long and a few tens to a hundred meters high very young small folds and thrusts strike parallel to the Lamentin thrust and exhibit the same morphology (Nan Cadastre, Ganthier, Dumay, and Jacquet: Figures 2 and 4 and supporting information Figure S4). The N115°E striking Ganthier fold is 8 km long, 1 km wide, and 150 m high (Figure 4a). It is incised by several small, narrow gullies a few meters deep, along which the deformed Quaternary alluvial conglomerates can be observed in cross section (Figure 4c). The Nan Cadastre fold disrupts the morphology of the flat Cul-de-Sac Plain south of the Nan Cadastre village. It is 4 km long, 80 m high, strikes N115° to N130°E, and is doubled to the east (Figure 4b). As in Carrefour City, the folds are likely related to an emergent thrust ramp rooted on a south dipping, low-angle, shallow décollement which splays from the master high-angle ramp located under the higher relief of the MSB anticline (Figures 4b (inset) and 2b). Emergent secondary propagating thrust ramps also splay from the main décollement in the plain (Figure 2b). One of them can be seen in section in Dumay, in a terrace riser of the Rivière Grise (Figures 2a, 2b, and 4d). These thrusts dip 50° southward at this place, offsetting Quaternary lacustrine deposits and conglomerates by a few tens of centimeters.

5. Fault Kinematics and Implications for the Earthquake Faulting Mechanism

Along with the northeastward dipping thrusts of the trans-Haitian belt to the north, the southwestward dipping thrusts we identified bound and control the morphology of Port-au-Prince Bay and Azuei and the Enriquillo Lakes (Figure 1b). These troughs form "push-downs" arranged in echelons along a N100°E direction, attesting to a sinistral strike-slip component of motion (Figure 1b (inset, bottom left)). This is compatible with a maximum compressive stress oriented N30°E, perpendicular to the mean strike of the folds and thrusts and ~ 50° anticlockwise from the main N80°E striking trace of the EPGF. In this area, the MSB anticline is cut and partly offset by the EPGF [*Mann et al.*, 1995; *Saint Fleur*, 2014] (Figures 1 and 2).

The Lamentin and the Gressier thrusts correspond to the westward continuation of the fold and thrust belt that forms the southern boundary the CSE basin (Figures 2, 3, and supporting information Figure S5). However, unlike the frontal thrusts in the CSE basin, the Lamentin and Gressier thrusts are probably disconnected from the deeper part of the crustal ramp emerging at the front of the highest relief of Massif de la Selle and rather link directly to the EPGF (Figure 2c). Such geometry implies that only the eastern part of the massif is still actively uplifting and growing.

The 2010 aftershocks strikingly highlight the geometry of the fault system at depth (Figure 2c). They *first* define a subvertical plane that we associate with the strike-slip EPGF. From a depth of 10 km beneath the Léogâne delta fan, the aftershocks define a second cluster that branches off from the EPGF upward to the north and that we associate with the LT. Both the location of the thrust at the surface and the distribution

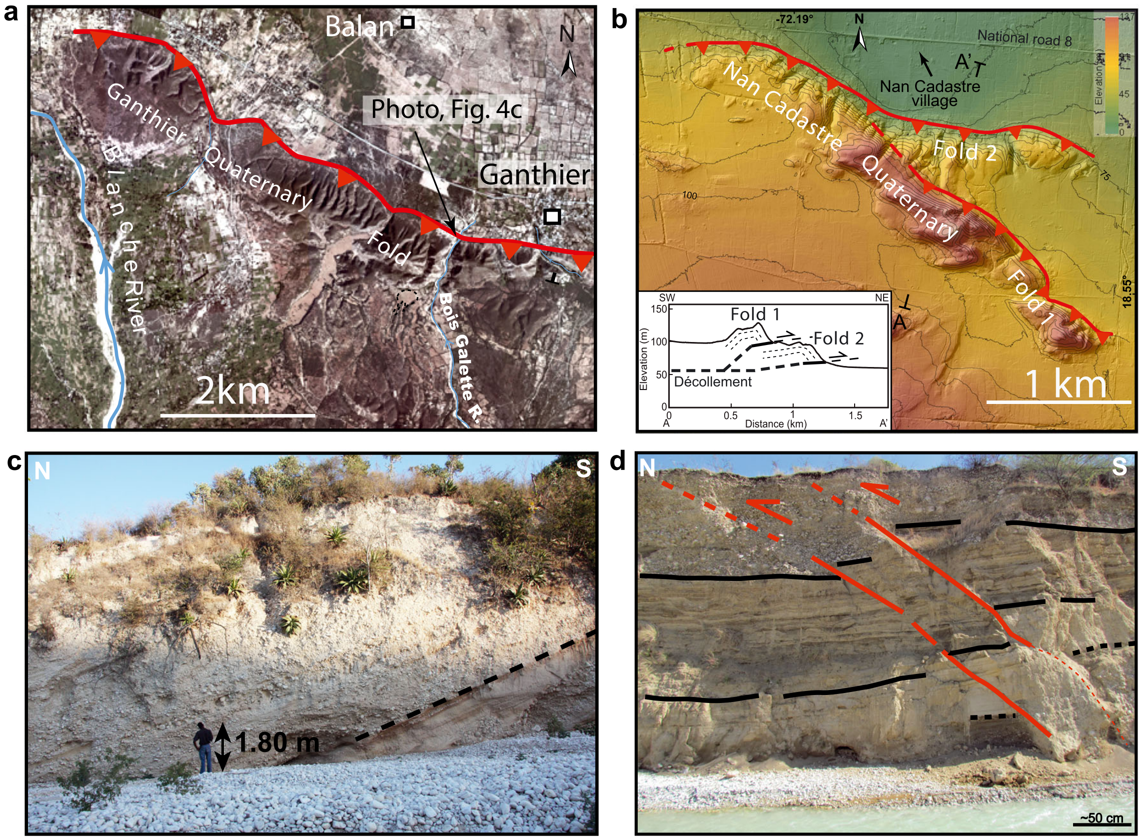

Figure 4. Active folding in the Cul-de-Sac-Enriquillo ramp basin. (a) Aerial photograph of the 8 km long Ganthier Quaternary fold. (b) Lidar topography of the Nan Cadastre Quaternary thrust folding. Inset: topographic profile AA′ and possible interpretation at depth. (c) Field photograph along the eastern flank of the Bois Galette River (location in Figure 4a) showing the folded alluvial sediments of the Ganthier fold dipping ~30°N. (d) Field photograph and interpretation of the 50 ± 15° southward dipping Dumay thrusts (in red) exposed in cross section on the eastern bank of the Rivière Grise (location in Figure 2a). The fault offsets by several tens of centimeters Quaternary sediments (lacustrine and conglomerates) incised by the river.

of the seismicity constrain the dip to be N40° on average, consistent with that of the MSB ramp (*Mann et al*. [1991b] and this study) (Figure 2b).

Our revised active fault mapping in the area of the 2010 earthquake suggests an alternative rupture scenario to those primarily involving a north dipping blind thrust. Instead, we propose that the Haiti earthquake may have ruptured two patches, one along the LT and the other on the EPGF. In such a model, uplift of the Léogâne delta fan appears as an increment of the long-term topography built up in between the LT and the EPGF (Figure 2c).

6. Slip Model of the 12 January 2010 Haiti Earthquake

We performed a static inversion of interferometric synthetic aperture radar and GPS data (see supporting information Figures, table and texts S6–S11), using a two-fault elastic dislocation model that reproduces the geometry of the active faults described earlier: a N112°E striking, 40° south dipping thrust (Lamentin) and a N80°E striking, 65° north dipping fault (EPGF). We find that our model can satisfactorily explain the deformation by assigning 38% of the total seismic moment release to nearly pure reverse slip on the LT. The remaining 62% is released by oblique, predominantly strike-slip motion on the EPGF (Figures 5a and supporting information Figures S6–S9). The predictions of this model are also consistent with the coastal coseismic uplift of coral reefs observed around the Léogâne fan delta [*Hayes et al*., 2010] (Figures 5a and supporting information Figure S10). Spatiotemporal inversions of slip [*Douilly et al*., 2015; *Hayes et al*., 2010; *Meng et al*., 2012; *Mercier de Lépinay et al*., 2011] suggest that rupture propagated from east to west. Hence, the rupture could have initiated on the Lamentin thrust and then propagated westward to terminate on the EPGF. Peak slip on the Lamentin thrust would have occurred at depth, near its connection with the EPGF, resulting in a drastic reduction of the static

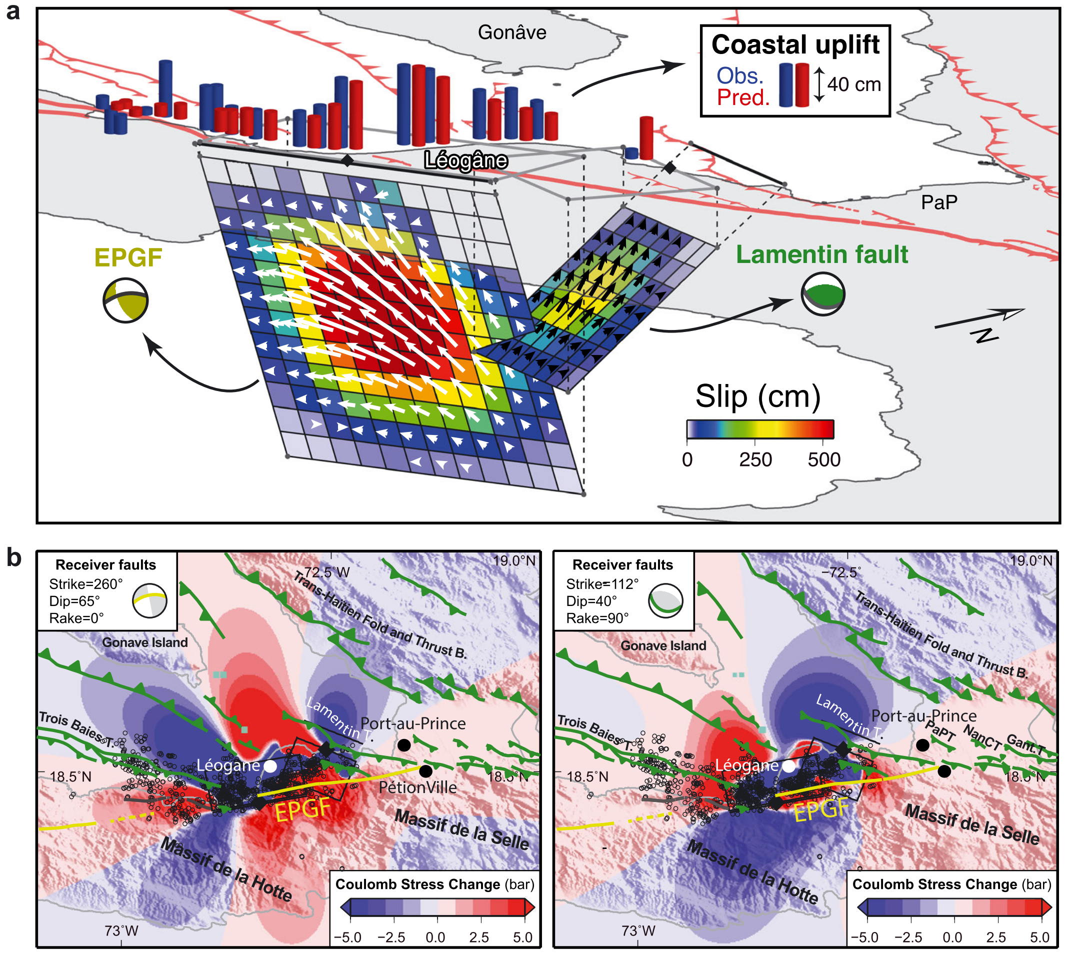

Figure 5. New static slip model for the 2010 Haiti earthquake and induced Coulomb stress changes. (a) Axonometric view from SE showing the slip distribution on two faults (EPGF and LT) determined by modeling geodetic data (GPS and interferometry) and coastal uplift values recorded by coral (see supporting information). Arrows (white for EPGF and black for LT) indicate the motion of the hanging wall with respect to the footwall. Land surfaces in grey. Red lines: active faults. Blue bars: coastal uplift measured by using corals from *Hayes et al.* [2010]. Red bars: uplift predicted by our model. Focal mechanisms indicated the EPGF (dark yellow) and Lamentin fault (green) geometry. (b) Coulomb stress changes induced by the slip model we determined, in map view at 7.5 km depth. Black rectangles: modeled faults. Epicentral locations of aftershocks from *Douilly et al.* [2013]. Insets in the upper left corners: parameters of the receiver faults used for the Coulomb stress calculation. Calculated for receiver faults having the same geometry as the strike-slip EPGF (dark yellow lines) and as the Lamentin thrust (dark green lines), respectively (Figure 5b, left and right).

(compressive) normal stress of the deeper part of the EPGF. This unclamping promotes slip on the EPGF for any reasonable value of the friction coefficient, which may be compatible with the rupture jumping from the Lamentin fault to the EPGF according to a mechanism of stress triggering [*King et al*., 1994]. The reason why the rupture did not propagate to the surface, as already observed in previous cases [e.g., *Archuleta*, 1984] is not well understood and would deserve further investigation. Stress modeling shows that reverse motion on the Lamentin fault tends to promote dominant reverse slip on the EPGF near the contact between the two fault planes (supporting information Figure S11), whereas strike-slip motion dominates westward as the stress perturbation induced by the Lamentin thrust fades at short range, explaining the apparent rotation of slip vectors on the EPGF fault plane (Figure 5a).

7. Coulomb Stress Changes: Implications for the Seismic Hazard in the Port-au-Prince Urban Area

Using the new slip model, we calculated the static Coulomb stress change ($\Delta\sigma$) imparted by the 2010 main shock on thrust faults with the same geometry as the LT (Figure 5b). A 5 bar increase of Coulomb stress, consistent with the numerous thrust aftershocks recorded along the Trois-Baies thrust fault system [*Symithe et al.*, 2013] suggests that some slip was actually triggered along this fault system following the 2010 earthquake. Stress level along the on land eastern section of the LT, below the city of Carrefour, has also increased significantly, increasing seismic hazard in this area. On the contrary, the stress has strongly decreased (>5 bar) along most of the offshore part of the LT, inhibiting occurrence of aftershocks in this area.

A similar static Coulomb stress change calculation for strike-slip faults oriented parallel to the EPGF shows that between Léogâne and Pétion-Ville, stress has increased by more than 5 bars along the EPGF, putting this section of the EPGF closer to failure. This segment is thought to have last ruptured in 1751 [*Bakun et al.*, 2012]. Considering the mean slip rate of ~7 mm/yr derived from GPS and assuming a full coupling [*Manaker et al.*, 2008], ~2 m of slip deficit has been accumulated since 1751, which is equivalent to an earthquake of magnitude 7 or larger [*Wells and Coppersmith*, 1994].

8. Conclusions and Discussion

The 2010 Haiti earthquake occurred in a tectonic context of oblique convergence between two rigid blocks of the North American and Caribbean plates. Deformation related to this oblique convergence appears to be partitioned between numerous folds and thrusts and strike-slip faults such as the SF and the EPGF. The earthquake likely involved two distinct faults, the LT and the EPGF, which, respectively, accommodate compression and strike slip, typifying the partitioning observed at regional scale. However, the earthquake may not be characteristic in the area, since evidence for past strike-slip ruptures with a few meters of slip has been documented along the EPGF surface trace [*Prentice et al.*, 2010]. Rupture on the LT might trigger a reverse component of motion on the EPGF locally; otherwise, the fault would rupture only in a pure strike-slip mode. Hence, the 2010 earthquake type is probably rare, as suggested by low topography of the Léogâne fan. However, we identified several other thrusts similar to the Lamentin in the CSE plain, some emerging in Port-au-Prince. They pose a significant threat in addition to that related to the EPGF and must be considered for future evaluation of the seismic hazard in southern Haiti.

Acknowledgments
We thank the Haitian Bureau of Mines and Energy and the National Centre for Geospatial Information for HR aerial photographs. We thank Y. Gaudemer, L. Barrier for fruitful discussions, J. Dyon for drawing, Belle Philibosian for proofreading, and INSU CT3 for funding. We are grateful to two anonymous reviewers for constructive reviews. This is an IPGP contribution 3674.

The Editor thanks Paul Mann and an anonymous reviewer for their assistance in evaluating this paper.

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