Late Holocene structural style and seismicity of highly transpressional faults in southern Haiti

Jiannan Wang, Paul Mann, Robert R. Stewart

Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas, USA.

Key Points:

- First high-resolution sonar surveys of two actively deforming lakes in Haiti.
- High degree of regional, tectonic transpression is partitioned by *en echelon* thrust faults and associated folds adjacent to a major strike-slip, plate boundary fault.
- 3D deformation model integrates patterns of 2010 coseismic uplift, aftershock distribution, and mapped geologic structures.

Corresponding author: Jiannan Wang, `jwang61@uh.edu`

Abstract

The devastating 2010 Haiti earthquake (M_w 7.0) was caused by rupture of the Léogâne, blind, thrust fault located 5 km north of the 1200 km-long, left-lateral, Enriquillo-Plantain Garden fault zone (EPGFZ). Unexpectedly, the EPGFZ remained largely quiescent or slightly reactivated during the 2010 earthquake. However, the EPGFZ still formed a boundary between a coseismically uplifted lowland north of the EPGFZ and a subsided area in the highlands south of the fault. Here, we use high-resolution sonar data from two, Haitian lakes that straddle the EPGFZ and its northern flank to demonstrate the presence of a 10 – 15 km-wide, 120 km-long, late Holocene fold-thrust belt which deforms clastic, lowland basins along the northern edge of the EPGFZ. In the eastern part of the study area, sonar results from Lake Azuey show that the linear trace of the EPGFZ cutting the Holocene lake bed is more deeply buried and less active than the adjacent, newly discovered, northwest-striking, northeast-dipping Jimani thrust fault that is part of the adjacent transpressional belt of *en echelon* thrusts and folds. This structural relationship between a less active EPGFZ and more recently active, transpression-related Jimani thrust is remarkably similar to the 2010 epicentral area 70 km to the west between the less active EPGFZ and seismogenic Léogâne thrust during the 2010 Haiti earthquake. In this complex transpressional zone, we propose that coseismic deformation alternates at recurrence intervals of centuries between oblique, transpression-related structures (Léogâne, Jimani, and Trois Baies thrusts) and the main strike-slip, plate boundary fault zone (EPGFZ).

1 Introduction and tectonic setting of the 2010 Haiti earthquake

On January 12, 2010, a M_w 7.0 earthquake struck the densely populated, greater Port-au-Prince region of south-central Haiti and caused widespread destruction with over 230,000 fatalities and an estimated 10 billion dollars damage [*Prentice et al.*, 2010; *Bilham*, 2010; *Paultre et al.*, 2013; *Kocel et al.*, 2016] (Figure 1). Multidisciplinary, geological and geophysical studies about the 2010 epicentral area of south-central Haiti have been done, including: 1) coseismic, coral reef uplift observation along a 50 km-long area of coastline in the epicentral region combined with fault modeling [*Hayes et al.*, 2010]; 2) coseismic, vertical ground motion from radar interferometry [*Hashimoto et al.*, 2011]; 3) high-resolution, surface-fault-trace mapping using Light Detection And Ranging (LIDAR) and targeted field studies [*Cowgill et al.*, 2012]; 4) Global Positioning System (GPS) and 2010 aftershock-based studies and modeling of pre-, syn-, and post-2010 earthquake crustal motions [*Calais et al.*, 2010; *Nettles and Hjörleifsdóttir*, 2010; *Symithe et al.*, 2013; *Douilly et al.*, 2013, 2015]; 5) ground-based studies of Holocene scarps including coseismic ground fractures and late Quaternary scarps of the EPGFZ that remained unaffected by 2010 fault breaks [*Prentice et al.*, 2010; *Koehler and Mann*, 2011; *Rathje et al.*, 2014; *Saint Fleur et al.*, 2015]; 6) ground-based, near-surface, geophysical surveys of buried faults activated during the 2010 earthquake [*Kocel et al.*, 2016]; 7) near-coast surveys of submarine extensions of faults active in 2010 [*Hornbach et al.*, 2010; *Mercier de Lépinay et al.*, 2011]; and 8) deepwater, marine surveys and coring to determine the recurrence interval of major earthquakes based on anomalous sedimentary deposits related to shaking and increased erosion [*McHugh et al.*, 2011]. The consensus from these previous, on- and offshore, multidisciplinary studies is that the 2010 earthquake ruptured two, previously unrecognized west- to northwest-striking thrust faults located 2 to 5 km north of the 1200 km-long, left-lateral, Enriquillo-Plantain Garden fault zone (EPGFZ) that forms a major, plate boundary between the Caribbean plate to the south and the Gonâve microplate to the north [*Mann et al.*, 1995; *Calais et al.*, 2010; *Benford et al.*, 2012; *Corbeau et al.*, 2016] (Figure 1A, B). These two thrusts are separated by 6 km and include: 1) the subaerial, 8 km-long, blind, Léogâne thrust fault located 5 km north of the EPGFZ and trending at an angle of 8° to the EPGFZ [*Calais et al.*, 2010; *Douilly et al.*, 2013, 2015]; and 2) the submarine, 20 km-long Trois Baies thrust fault located 2 km north of the EPGFZ and trending at an angle of 20° [*Mercier de Lépinay et al.*, 2011; *Symithe et al.*, 2013] (Figure 1B, C).

Despite the proximity of the Léogâne and Trois Baies thrust to the neighboring EPGFZ, the EPGFZ remained largely quiescent and outside the zone of maximum, coseismic uplift and ground shaking and aftershocks related to the 2010 earthquake [*Nettles and Hjörleifsdóttir*, 2010]. The centroid moment tensor (CMT) mechanism of the main 2010 shock shows a primarily strike-slip motion, with a small component of reverse motion, on a steeply north-dipping nodal plane [*Nettles and Hjörleifsdóttir*, 2010; *Douilly et al.*, 2013]. Finite element modeling [*Douilly et al.*, 2015] suggests that Léogâne fault buried beneath at least 1 km of overlying undeformed clastic sediment in the area north of the EPGFZ absorbed most of the energy of the northeast-southwest compression along obliquely-striking, high-angle (21°-70° dipping) reverse fault planes. For this reason, there was insufficient stress to trigger slip during the 2010 earthquake on the EPGFZ 5 km to the south (Figure 1B). Previous GPS surveys [*Calais et al.*, 2010, 2016] along this area of the EPGFZ display vectors at almost right angles to these obliquely-striking thrusts and consistent with their preferred reactivation (Figure 1A, B).

Aftershock studies following the 2010 earthquake by *Douilly et al.* [2013, 2015] showed that the EPGFZ moved slightly at depth and acted as a 6 km-long, east-west and sub-vertical, connecting fault segment that transmitted seismogenic motion between the obliquely-trending, north-dipping, Léogâne fault in the east and the more obliquely-trending, southwest-dipping Trois Baies fault in the west (Figure 1B). However, post-earthquake geologic reconnaissance revealed no surface ground breaks along the proposed onland areas of EPGFZ in the epicentral region of the earthquake [*Prentice et al.*, 2010; *Koehler and Mann*, 2011; *Rathje et al.*, 2014]. A more recent study by *Saint Fleur et al.* [2015] proposed previously, unrecognized, 2010 coseismic groundbreaks along the obliquely-trending Lamentin thrust 11 km east of the epicentral area near the city of Port-au-Prince (Figure 2A).

En echelon thrusts spacing at distances of 1-8 km along the main strike-slip fault, obliquely intersect the main strike-slip fault at angles of 30° – 45°. These structures strike northwestward away from the EPGFZ with individual oblique, fault lengths extending into the deeper basins at distances of 4-29 km (Figure 2A). As a result of this distinctive and regular intersecting fault geometry between these oblique thrusts and the linear EPGFZ, earthquake rupture initiating on an oblique thrust, as seen for the Léogâne fault in 2010, is likely confined to that vicinity and may not connect with other oblique thrusts or even the EPGFZ itself [*Douilly et al.*, 2013, 2015].

Coseismic deformation along a large transpressional strike-slip fault, such as the EPGFZ [*Calais et al.*, 2002] in Hispaniola or the San Andreas fault zone in California [*Segall and Lisowski*, 1990], either is accommodated by slip and major earthquakes on the main, strike-slip plate boundary fault, or is accommodated by the oblique, *en echelon* thrusts adjacent to the main fault, or is accommodated by both sets of faults (cf. compilation of types of destructive earthquakes in transpressional settings by *Hayes et al.* [2010]). Motions on distributed, *en echelon* thrusts do not necessarily spare or reduce coseismic rupture on the main strike-slip fault because the *en echelon* and main strike-slip fault remain separate fault planes, and the main strike-slip fault could continue to accumulate strain. In an extreme case, plate motions become increasingly transpressional as seen in the case of the EPGFZ as manifested in the obliquity of GPS vectors relative to the strike of the EPGFZ (Figure 1A, B) or in a restraining bend setting or during the plate reorganizations. In these settings, the *en echelon*, oblique thrusts might assume more and more plate-edge strain to the point that the plate boundary behaves more like a broad, thrust boundary and less like a narrow, strike-slip boundary.

These oblique and *en echelon* thrust faults in transpressional settings, including large restraining bends as in Hispaniola, potentially nucleate "uncharacteristic earthquakes" of varying recurrence intervals and sizes that are distinct from the recurrence intervals and sizes of the adjacent but independent strike-slip fault [*Fielding et al.*, 2013]. Restraining bend areas like Hispaniola can lead to the generation and increased activities on more favorably and obliquely oriented folds and thrusts whose coseismic rupture might alternate with much longer ruptures along the adjacent strike-slip fault. The number of these *en echelon* thrust faults, in restraining bend setting, can be large at observed spacings of 5-10 km dispersed along the trend of strike-slip faults that may be hundreds of kilometers in total length. For this reason, the identification of oblique *en echelon* thrusts, especially when buried or "blind", can be challenging, assessing their role with seismogenesis within a broad plate boundary [*Frankel et al.*, 2011].

2 Objectives and methods

2.1 Study area

This elongate, belt of transpressional deformation associated with *en echelon* thrusts occupies a topographically-low, densely populated Cul-de-Sac basin underlain by poorly consolidated clastic sedimentary rocks ranging in age from Miocene to Recent [*Massoni*, 1955; *Mann et al.*, 1995; *Terrier et al.*, 2014; *Saint Fleur et al.*, 2015]. In easternmost Haiti, this belt is overlain by the the shallow (33 m-deep), 138 km^2, brackish Lake Azuey near the border separating Haiti from the Dominican Republic [*Wright et al.*, 2015; *Piasecki et al.*, 2016]. Lake Enriquillo to the east is a larger, shallow (52 m-deep), 346 km^2, hypersaline, sub-sealevel lake located entirely in the Dominican Republic and separated from Lake Azuey by the eastward continuation of the same transpressional belt parallel and north of the EPGFZ in the Cul-de-Sac valley [*Mann et al.*, 1995] (Figure 1B).

In the western part of our study area, the more transtensional segment of the EPGFZ is overlain by the the 42.8 m-deep, 14 km^2, freshwater Lake Miragoâne (Figure 1B). All three of these shallow, inland, lakes experience variations up to 13 m in their surface elevations due to annual to decadal changes in climate and rainfall amounts including extreme rainfall associated with hurricanes [*Wright et al.*, 2015; *Piasecki et al.*, 2016; *Moknatian et al.*, 2017; *Rico*, 2017].

2.2 Objectives

The main goal of this paper are to better integrate the geologic structure of the 120 km-long study area, which parallels the trace of the EPGFZ and includes the 2010 epicentral area, using a wealth of geologic, geophysics, GPS, radar interferometry, aftershock, and modeling studies, most of which has been collected since the 2010 earthquake. Our primary objective is to use these information to structurally characterize the 10-15 km-wide, belt of late Holocene, transpressional deformation that forms a laterally-extensive, deformed belt along the inland, Cul-de-Sac intermontane basin in the east and the low-relief coastal plain along Port-au-Prince bay and the Canal du Sud to the west (Figure 1B). In particular, we focus on the identifying a family of *en echelon* thrusts, whose curvilinear strikes area are very similar to the Léogâne thrust now known to be responsible for most of the energy release and coseismic uplift during the 2010 Haiti earthquake [*Calais et al.*, 2010; *Douilly et al.*, 2013, 2015] (Figure 1B, Figure 2A).

2.3 Survey design

In order to understand the geologic and structural styles of transpression within this belt, including the age relations between deformation in the north-flanking belt and the EPGFZ itself, we collected a total of 94 km of high-resolution (2-10 kHz) sonar profiles in 2014 from the 138 km^2, brackish Lake Azuey and 37 km of profiles from the 14 km^2, fresh-water Lake Miragoâne (Figure 1B). The EPGFZ strikes through both of the lakes, so 80% of our lines on Lake Azuey and 90% of our survey lines on Lake Miragoâne was dedicated to the across fault-strike, north-south profiles.

The average speed of the boat towing the sonar was 3 knots, and we used a sonar pulse rate of 4 per second. Our 2-10 kHz sonar frequency range gives sub-bottom layer resolution of about 10 cm. These surveys were the first sonar surveys in Haitian lakes. Both lakes straddle the projected active trace of Haiti's EPGFZ and its adjacent, transpressional fold-thrust belt, therefore provide new constraints on the location, structural style, and timing of deformation within both structural provinces. We incorporate these lake data with previous geologic mapping, geophysical observations related to the 2010 earthquake, and regional information on plate motions in this region (Figure 1B).

3 Tectonic setting of transpressional deformation in south-central Haiti including unresolved tectonic and structural questions

3.1 Previous strike-slip deformational model vs. Haiti thrust belt deformational model

There are two regional structural models to explain the present-day structure of the broad, 250 km-wide zone of transpression spanning the entire width of the island of Hispaniola.

3.1.1 Strike-slip, regional structural model

The first is the strike-slip-dominated model, driven by oblique motion and transpression between the thick and buoyant Bahamas platform on the North America plate, the Caribbean plate, and the Gonâve microplate [*Mann et al.*, 1995; *Dolan et al.*, 1998; *Mann et al.*, 2002; *Calais et al.*, 2002, 2016] (Figure 1A, B).Structures and tectonic geomorphology formed in this 250 km-wide, transpressional zone include: GPS studies [*Calais et al.*, 2002, 2010; *Hayes et al.*, 2010; *Symithe et al.*, 2013; *Douilly et al.*, 2013, 2015] reveal strain partitioning along the EPGFZ and the subparallel Septentrional strike-slip fault zone (which is the plate boundary between North Hispaniola microplate and Gonâve microplate) (Figure 1A). As a result of transpression, the central Hispaniola has the highest topography, up to 3 km, in all of the northern Caribbean region. The left-lateral strike-slip rupture of the EPGFZ in the 18th century inferred from historical earthquakes [*Bakun et al.*, 2012] with average left-lateral offset amounts of 1.3 – 3.3 m as expressed along offset streams of the EPGFZ [*Prentice et al.*, 2010] and by left-lateral, channel offsets of 7 – 8 m along stream channels by the Septentrional fault zone [*Prentice et al.*, 1993; *Leroy et al.*, 2015]. *Saint Fleur et al.* [2015]'s study indicates the folding and thrusting of 10 – 15 km-wide belt of Miocene to Quaternary rock adjacent to the EPGFZ. In addition, *Mann et al.* [2002]; *Grindlay et al.* [2005]; *Kroehler et al.* [2011] suggest a strong, southwestward, backthrusting of the Gonâve microplate, in southern Hispaniola in Haiti and Dominican Republic to the southwest onto the Caribbean plate (Figure 1B, C). Southwestward backthrusting of Hispaniola is manifested by the accretionary wedges present along the Muerto trench south of the Dominican Republic [*Bien-Aimé Momplaisir*, 1986; *Bruña* *et al.*, 2009] (Figure 1B) and along the southern margin of Haiti (South Haiti accretionary prism [*Bien-Aimé Momplaisir*, 1986] (Figure 1C), along with the associated, localized, negative gravity anomaly associated with plate flexure under a thrust load [*Mann et al.*, 2002; *Bruña et al.*, 2009] (Figure 1A)).

3.1.2 Criticisms of the strike-slip, regional structural model

Two criticisms have been proposed for the strike-slip model. First, *Corbeau et al.* [2016] has questioned whether the predictions of the GPS-based block models, which predict significant shortening, are accurate in that little transpression-related shortening can be observed from regional seismic profiles in the offshore area of the Gulf of Gonâve north of the southern peninsula of Haiti, or in the area of the Jamaica Passage east of Haiti. Second, *Symithe and Calais* [2016] have proposed that there is no geologic evidence for a continuation of the EPGFZ east of latitude 72.27°W in the eastern Cul-de-Sac Valley, Lake Azuey and Lake Enriquillo in the Dominican Republic (Figure 1B). Instead, *Symithe and Calais* [2016] propose that large rates of north-south shortening predicted from GPS block models is taken up entirely by low-angle thrust structures in the eastern Cul-de-Sac and Enriquillo Valleys that were modeled using GPS data as part of their study.

3.1.3 Trans-Haitian fold-and-thrust belt regional structural model

The Trans-Haitian fold-and-thrust belt model originated with a study by *Pubellier et al.* [2000], who proposed a low-angle southwestward-verging fold-and-thrust belt along the southwestern edge of the central Hispaniola block. The thrust front of this feature was thought to be actively propagating from the main Trans-Haitian fold-and-thrust belt, located in the Chaîne des Matheux (Figure 1B, Figure 2A), southwestward into the area of the Léogâne plain and the Cul-de-Sac basin (Figure 2A, B). *Pubellier et al.* [2000] proposed that the EPGFZ originally formed as a left-lateral strike-slip fault, but became inactive in the late Miocene when deformation in southern Hispaniola became compressional and the Trans-Haitian fold-and-thrust belt had propagated into the southern area of the Cul-de-Sac basin and Léogâne plain, where it emerged or "daylighted" to form the *en echelon*, convergent structures (compiled on the map in Figure 2). *Pubellier et al.* [2000] also proposed that the EPGFZ was reactivated as a normal fault in the Quaternary as a result of crustal loading of the southern, foreland area by the overthrusting Trans-Haitian fold-and-thrust belt.

Following the 2010 earthquake and the recognition of the north-dipping blind Léogâne thrust fault, *Calais et al.* [2010] proposed that this fault is the leading edge of the Trans-Haitian fold-and-thrust belt rather than being an *en echelon* thrust genetically linked to the EGPFZ. In the interpretation proposed by *Calais et al.* [2010], the northward dip of the Léogâne thrust made it difficult to link its origin with the EPGFZ, whose dip had been established in this area as a vertical to high angle (> 60°), south-dipping fault plane with evidence of late Holocene, left-lateral offsets of drainages [*Prentice et al.*, 2010]. Moreover, *Symithe and Calais* [2016] noted that Trans-Haitian fold-and-thrust belt regional model of *Pubellier et al.* [2000] was more consistent with an increasing amount of GPS data supportive of a larger magnitude, north-south shortening in central Hispaniola than with the existence of an eastward extension of the left-lateral EPGFZ into the eastern part of Haiti and the Dominican Republic (Figure 1B and Figure 2A).

3.1.4 Criticisms of the Trans-Haitian fold-and-thrust belt, regional structural model

First, *Mercier de Lépinay et al.* [2011] pointed out two problems with linking the origin of the Léogâne thrust to the southwestward-propagating edge of the Trans-Haitian fold-and-thrust belt: 1) the dip of the fault generating the main thrust, derived by *Mercier de Lépinay et al.* [2011], was more steeply dipping (64°) than expected for a blind thrust at the leading edge of a fold-thrust belt; and 2) the orientation of the N84°E fault plane of the main shock is significantly oblique to the N120°E-oriented leading edge of the Trans-Haitian fold-and-thrust belt as proposed by *Pubellier et al.* [2000]. In this paper, we discuss other inconsistencies with the zone of deformation north of the EPGFZ being the result of southwestward propagation of the Trans-Haitian fold-and-thrust belt.

4 New observations of the Late Holocene structural style along EPGFZ in southern Haiti

4.1 Significance of *en echelon* thrusting and folding north and south of the EPGFZ

The presence of a strike-slip fault at any scale is indicated by the presence of *en echelon* arrays of thrust faults, normal faults, folds, fractures, dikes, and other linear features in narrow, elongate zones [*Sylvester*, 1988]. On Figure 2A, we have compiled geologic information on *en echelon* folds and faults in a 10 – 15 km-wide zone of deformation along both the northern and southern flanks of the EPGFZ. Folds form as fault propagation folds along oblique, thrust faults, vary from 1 to 8 km in lateral spacing; and deform Miocene and younger fine to coarse-grained, basinal, and coastal plain rocks in the belt that is 10 – 15 km wide and extends parallel to the EPGFZ for 120 km (Figure 1B and Figure 2A). Folds in Neogene clastic lithologies of the Cul-de-Sac basin contrast with more continuous and longer wavelength, *en echelon* fold axes present in more massively-bedded Cretaceous to Eocene rigid, basaltic, and carbonate lithologies exposed in the 2 km-high range south of the EPGFZ, the Massif de Selle (Figure 2A). The trend of fold axes is similar to the north and south of the EPGFZ (Figure 2B).

The *en echelon* distribution of complex Holocene folding and thrusting in the 10 – 15 km wide zone of deformation north of the EPGFZ is also reflected in the complex pattern of 2010 coseismic and vertical deformation recorded by the interferogram from the 2010 epicentral area on the Léogâne plain west of the Cul-de-Sac basin [*Hayes et al.*, 2010; *Hashimoto et al.*, 2011; *Bilham and Fielding*, 2013] (Figure 2A). *Douilly et al.* [2013, 2015] and *Kocel et al.* [2016] use aftershocks and shallow geophysics to show that the 2010 Léogâne thrust fault and sub-parallel faults are overlain by at least one kilometer of undeformed and sub-horizontal strata.

4.2 Significance of curvilinear fold and thrust patterns in the transpressional belt north of the EPGFZ

The shaded relief DEM (digital elevation model) shown in Figure 2B reveals the curvilinear, *en echelon* fold morphologies that are defined by low, bedrock hills of Neogene sedimentary rocks exposed on the flat-lying Cul-de-Sac basin. These curvilinear fold axes can be related directly to a broad zone of left-lateral, simple shear produced along the sub-vertical and left-lateral EPGFZ based on several, basic observations seen on Figure 2B. The most prominent folds are present along the southern edge of the Cul-de-Sac basin within 15 km of the EPGFZ. In contrast, the central and northern edges of the Cul-de-Sac basin exhibit no prominent folding even directly adjacent to the base of Eocene-Miocene carbonate rocks forming the range [*Pubellier et al.*, 2000] (Figure 2A). The map-view shapes of fold axes along the southern margin of the Cul-de-Sac basin are asymptotic, or gently curve into east-west parallelism with the main trace of the EPGFZ along the southern edge of the Cul-de-Sac basin, as broad zones of shearing of thick, sedimentary basins (see the inset of Figure 2B; modified from *Odonne and Vialon* [1983]). Deeper, structural depressions form in the zone of convergent intersection between the east-west-striking EPGFZ and the northwest-striking, secondary thrusts as seen in the southern part of Lake Azuey, where the lake bends from an east-west trend adjacent to the EPGFZ to a more northwest trend in the central and northern part of the basin (Figure 2A, B).

4.3 Geologic structure of the area of *en echelon* thrusts in the epicentral area on the Léogâne fan-delta

4.3.1 Geologic structure of the Léogâne fan area

A cross-sectional profile of the 2010 epicentral area related to the activation of two conjugate thrust faults was modified from aftershock data from *Douilly et al.* [2013, 2015] is shown in Figure 3 (Line A–A'). Both faults are buried by about 1 km of late Quaternary sand and gravel of the Léogâne fan delta [*Kocel et al.*, 2016] and an additional 1 km of Paleocene limestone. Aftershocks indicate that the main thrust event ruptured a depth range of from 4 to 17 km beneath the ground surface [*Douilly et al.*, 2013, 2015]. The orientation of the Léogâne thrust based on gravity and uplift of coastal features is east-west and parallel to recent near-surface breaks of the EPGFZ mapped in the shallow, coastal zone adjacent to the Léogâne plain [*Hornbach et al.*, 2010]. Due to its proximity to the EPGFZ, an east-west strike of the Léogâne thrust is predicted as this is the area where *en echelon* folds and faults curve into an asymptotic orientation relative to the main EPGFZ, as shown on Figure 2B.

A radar interferogram compiled on the structure map of Figure 2A revealed that the 2010 earthquake elevated the smaller folds of the Léogâne fan-delta north of the EPGFZ, yet produced coseismic subsidence in the 1.4 km-high, less complexly deformed, mountain range south of the EPGFZ [*Hashimoto et al.*, 2011] (Figure 2A). This paradox can be simply explained by the northward dip of the seismogenic Léogâne fault that elevated the basinal area to the north (hanging wall of the Léogâne fault) and depressed the mountainous area to the south (footwall block of the Léogâne fault (line A–A' in Figure 3).

4.3.2 Geologic structure of the Port-au-Prince urban area compared to the Léogâne epicentral area

A similar pattern of deformation is observed in Port-au-Prince urban area where the central and northern edge of the Cul-de-Sac basin is almost undeformed [*Massoni*, 1955; *Cox et al.*, 2011; *McHugh et al.*, 2011; *Saint Fleur et al.*, 2015] (Line B-B' in Figure 3). The cross section taken from workers, who were mapping 60 years ago when the city was smaller and the geology was less obscured by urbanization, shows two large thrusts, a range-bounding thrust along the southern edge of the city, and a northeast-dipping thrust, the Dumay thrust, that elevates a broad outcrop zone of north-dipping, Neogene sedimentary rocks on which the northern part of the city is built [*Rathje et al.*, 2014]. The 50° northeast dip of the Dumay thrust is similar to the 70° northeast dip of the Léogâne thrust to the west known from aftershocks [*Douilly et al.*, 2013, 2015], although the dip of the Dumay thrust reverses to a southwest dip as it approaches the EPGFZ (Figure 2A, B). On the cross section B–B' in Figure 3, we have schematically indicated areas that are elevated as a result of the northward dip of the Dumay thrust and the depression of the area to the south of the EPGFZ in the highlands south of the EPGFZ. If a future earthquake occurred along the north-dipping, *en echelon* thrust faults in the Port-au-Prince area (Line B–B' in Figure 3) or Lake Azuey area (Line C–C' in Figure 3) a similar uplift phenomenon probably would occur where the lowlands are uplifted and the adjacent mountains subside.

4.3.3 Geologic structure of the Lake Azuey area

In the Lake Azuey area, we mapped a linear and east-west striking fault trace in deformed Holocene sediments along the projected trend of the landward traces of the EPGFZ both east and west of Lake Azuey (Figure 5 and Figure 6A, B). Integrated with previous land mapping of the EPGFZ [*Bourgueil et al.*, 1988; *Mann et al.*, 1995; *Prentice et al.*, 2010; *Cowgill et al.*, 2012], we interpret this linear east-west striking feature in Lake Azuey as a 5 m-wide and continuous trace of the EPGFZ which we can follow westward to the EPGFZ locality at Dumay, about half way between Lake Azuey and Port-au-Prince, which was previously described and dated as a 6 m-long, left-lateral offset of a late Holocene stream channel [*Cowgill et al.*, 2012] (locates at red circle, which is labeled as Dumay in Figure 2A). The structural cross sections in this area taken from the previous studies [*Massoni*, 1955; *Mann et al.*, 1995; *Douilly et al.*, 2015] indicate that the high-angle EPGFZ co-exists with the adjacent thrusts that over-thrust from the south and north (Line B–B' in Figure 3). We project this trace of the EPGFZ along a prominent fault valley at the town of Jimani that separates Lakes Azuey and Enriquillo (Figure 2A and Figure 5). Sonar profiles (Figure 6A, B) show that the most recent rupture of the EPGFZ is covered by about 0.7 m of Holocene sediment, suggesting that there has been late Holocene activity of the EPGFZ along the southern edge of the lake.

From sonar data, we observed late Holocene lake sediments onlapping onto local highs of Eocene limestone of the bounding range along the northern edge of the EPGFZ (Figure 6). The sonar from southern Lake Azuey suggests that the most prominent folds present adjacent to the EPGFZ become less prominent in the central and northern parts of the lake (Figure 2B). These southern folds and thrusts imaged in Lake Azuey define the transpressive belt along the EPGFZ observed in onshore areas to the west. On the cross section in Figure 6C, we have schematically indicated areas that are elevated as a result of the northward dip of the Jimani thrust and the depression of the area to the south of the EPGFZ.

The structural cross-section (Figure 6C) of the Lake Azuey area and the previous works [*Massoni*, 1955; *Bourgueil et al.*, 1988; *Cox et al.*, 2011; *Douilly et al.*, 2015] (Line A–A' and B–B' in Figure 3) along this 120 km-long zone of deformation adjacent to the EPGFZ show that the oblique thrust faults share a similar orientation with other northeast-dipping thrusts along the northern edge of the EPGFZ. All three of these oblique thrust faults (the Léogâne thrust in Line A–A', the Dumay thrust in Line B–B', and the Jimani thrust in Figure 6C) shown on the cross sections deform rocks as young as Pliocene and Quaternary [*Saint Fleur et al.*, 2015].

On a more regional scale, these observations form Lake Azuey are consistent with the multi-channel seismic reflection profile (named as Canadian Superior 2D and shown in Figure 1C), that shows a lack of intensive deformation in the part of Port-au-Prince Bay, that is the offshore, largely un-faulted and folded seaward extension of the Cul-de-Sac basin [*McHugh et al.*, 2011]. *Pubellier et al.* [2000] proposes that the Trans-Haitian fold-and-thrust belt exposed in the Chaine des Matheux range extends beneath the entire Cul-de-Sac and Port-au-Prince basins (Figure 2A, B). In summary, our observations at this scale do not support the previous model by *Pubellier et al.* [2000] and *Calais et al.* [2010] that folds and faults of the northern range are propagating southwestward beneath the zone of *en echelon* faults and folds (Figure 2A, B).

4.4 Subsurface stratigraphy of Lake Azuey and Lake Enriquillo and paleoseismic estimates of the relative timing of recent earthquakes on the EPGFZ and secondary, *en echelon* thrust faults

Our objective is to determine the relative age of the EPGFZ and its adjacent zone of fold-and-thrust deformation using the sonar profiles from Lakes Azuey and Enriquillo (Figure 4A). Previous coring, both in Lake Enriquillo [*Rios et al.*, 2013] (which was tied to the onshore stratigraphic studies [*Taylor et al.*, 1985; *Rios et al.*, 2013]) and in Lake Miragoâne [*Higuera-Gundy et al.*, 1999], has established the late Holocene 5 m and 7 m sedimentary history, respectively.

In Lake Enriquillo, a sonar survey similar to ours was conducted in 2013 [*Rios et al.*, 2013]. Mapping in both lakes revealed the presence of the east-west strands of the EPGFZ that are collinear with online scarps both east and west of Lake Azuey (Figure 2, Figure 4, and Figure 5) and east and west of Lake Enriquillo [*Mann et al.*, 1995; *Rios et al.*, 2013]. These east-west fault strands abruptly truncate the trends of folds in the ranges south of the lake (Figure 5). The sonar events, which are interpreted as stratigraphic features, from Lake Azuey and Lake Enriquillo (Line B1 and Line L19 correlate convincingly (Figure 4B). Given the small distance separating the two lakes (about 4 km); the similarity of the stratigraphic profiles; and the same amount of sediment above the EPGFZ; it is reasonable to suggest that Lake Azuey and Lake Enriquillo share the same sedimentation history as well as the same structural style and seismicity related to the EPGFZ and its oblique, thrust faults.

The EPGFZ in both Lake Enriquillo and Lake Azuey is buried by 0.7 m of sediments. According to coring studies in the Dominican Republic [*Taylor et al.*, 1985; *Rios et al.*, 2013], the 5.2 m thickness of the latest lake stage (2 ka BP to present) gives a recent Holocene average sedimentation rate of 2.6 mm/yr (Figure 4B). Using the average sediment rate, the most recent rupture of the EPGFZ would be dated to some 270 years ago. Given the historical earthquake records [*Bakun et al.*, 2012], we suggest that the most recent rupture of the EPGFZ corresponds to the historical events of October or November 1751, and the deformed sediments in Lake Azuey are of Holocene age.

4.5 Easternmost extent of the EPGFZ trace in Lake Enriquillo, Dominican Republic

Based on both of our lake surveys combined with a previous survey of Lake Enriquillo in the Dominican Republic [*Rios et al.*, 2013], and the previous geologic mapping of the basinal and topographic corridor of the Cul-de-Sac basin in Haiti and the Enriquillo basin in the Dominican Republic [*Mann et al.*, 1995; *Mann*, 1999], a first-order question we pose is whether the EPGFZ extends as a continuous, strike-slip fault along the 120 km-long zone of deformation of Miocene and younger clastic rocks present between the two lakes (Figure 1B and Figure 4A). The previous studies [*Saint Fleur et al.*, 2015; *Symithe and Calais*, 2016] have proposed that the EPGFZ terminates as a strike-slip feature in the area south of Port-au-Prince. These studies further have proposed that transpressional plate motion in the eastern Cul-de-Sac basin and the Enriquillo Valley in the Dominican Republic (Figure 1B and Figure 4A) is entirely accommodated along the low-angle oblique-thrust structures that overthrust the southern edges of Lake Azuey and Lake Enriquillo.

A previous study of Lake Enriquillo by *Rios et al.* [2013] identified the break along the northeastern edge of Cabritos Island in Lake Enriquillo, which aligns exactly with the large east-western lineament extending eastward from our map area in Lake Azuey (Figure 4A). The sonar results from both lakes show that the EPGFZ extends to at least to the eastern tip of Cabritos Island in the center of Lake Enriquillo, Dominican Republic (Figure 4A). This survey revealed a fault penetrating the youngest sediment layer of Holocene age which is consistent with recent activity on this segment of the EPGFZ (Figure 6A, B). Therefore, we conclude that this linear, late Holocene strike-slip fault extends at 55 km (at least) to the eastern edge of Lake Enriquillo, where the previously documented [*Mann et al.*, 1995] uplift of the Holocene reef fringes Lake Enriquillo.

5 Active tectonics of the area west of the 2010 epicentral zone in the western study area: Léogâne plain, Miragoâne basin, and their adjacent offshore area

5.1 The Trois Baies thrust fault, Canal du Sud, as the termination structure for the 2010 earthquake

The 2010 aftershock zone at the western and central part of our study area (Figure 7A) reflects the rupture along the northwest-striking, 20 km-long, submarine, Trois

Baies thrust fault that forms the western extension of the 10 – 15 km-wide, transpressional zone north of the EPGFZ. As the Trois Baies fault is submarine, InSAR cannot be used to assess its 2010 coseismic similarity with folding and thrusting along the Léogâne thrust that affected the onshore, Léogâne plain (Figure 7A).

However, the same basic structural elements of the Léogâne plain are also observed for the Trois Baies thrust fault, which include the short distance (1 km) to the EPGFZ and its steep (45°) but opposite (southwest) dip of the Trois Baies thrust fault (Figure 7). One of the most intense zones of coseismic, aftershock, coastal uplift [*Hashimoto et al.*, 2011], and subsidence [*Prentice et al.*, 2010] separates the oppositely-dipping Léogâne and Trois Baies faults, and may represent complex deformation at a transfer zone between the two faults (Figure 7A, B). The aftershock study of the Trois Baies fault [*Symithe and Calais*, 2016] shows that its thrust character and oblique orientation in map view with the main EPGFZ is comparable to the cross sections of the eastern area in Figure 3. In the map view, the overall structure of this western part of the study area mirrors the same geometrical relationship between the oblique thrusts (such as the Trois Baies thrust fault) and the main EPGFZ as described at the eastern part of the study area (Figure 2).

5.2 Structure of the Miragoâne pull-apart basin

In the onshore part of the western study area, Lake Miragoâne was interpreted as a 14 km^2 pull-part basin developed as a left-stepping, releasing bend on the EPGFZ paired with the adjacent Tapion du Petit Goâve restraining bend 12 km to the east (Figure 7) [*Cowgill et al.*, 2012]. Bathymetry from our sonar data shows the maximum water depth of Lake Miragoâne is 42.8 m (Figure 7B), which makes this lake the deepest [*Higuera-Gundy et al.*, 1999] in the Caribbean region. The 30 m of recognizable stratigraphy (Figure 8B and C) from the sonar survey in Lake Miragoâne reveals a series of deformational features including major east-west normal faults, minor thrust faults at depth (some 20 m), and active folds at the lake bottom (Figure 8). The upper 7 m of the lake sediments were cored and dated at 10 ka at the bottom of the core [*Higuera-Gundy et al.*, 1999]. By applying the average sedimentary rate from the core data to the chirp sonar trace, we can extrapolate the sedimentation rate to the observed thickness of 30 m in the lake and estimate a minimum of 43 ka for the age of the pull-apart basin on the EPGFZ. Core measurements of the E/P (evaporation and precipitation ratio from the δ^{18}O of ostracod shells in the core sample) were undertaken [*Higuera-Gundy et al.*, 1999] in the center of Lake

Miragoâne (Figure 9B). The core reveals that the uppermost part of the sediments are Holocene to the latest Pleistocene in age (Figure 9A). Pollen data from the core indicate alternating dry and wet environments.

5.3 Ages and sedimentary cycles of the Miragoâne pull-apart basin

We applied a low-pass filter on the pollen log data (from the core acquired by *Higuera-Gundy et al.* [1999] in the center of the lake) and found a strong correlation between the pollen and sonar data (red curve in Figure 9B). To further investigate this interesting correlation between the geochemical and geophysical data, we use the filtered E/P log, considered as pseudo-acoustic impedance log, to generate a synthetic sonar response (Figure 9B). The correlation is compelling which suggests that the depositional environment influences the acoustic properties of the sediments and sonar response may be a partial proxy for climatic processes. In another words, the sediment layers from drier climates (higher E/P) have stronger acoustic reflectivity and vice versa. Combining the correlation between the pollen log and the acoustic reflections from the chirp sonar data, we can extend the sedimentary history of the upper 7 m from the log data to the entire sonar data set. In the sonar profile, we find the most recent rupture in the lake is buried by about 0.5 meter sediment (Figure 8B, C). The core dating result from *Higuera-Gundy et al.* [1999] suggests the age of these rupture is about 300 years old. The historical document record [*Bakun et al.*, 2012] indicates a historical earthquake happened in this area in 1770. Considering the historical document record [*Bakun et al.*, 2012], the dating of the core, and the sonar interpretation in Lake Miragoâne suggest that the most recent rupture in this lake is likely related to the historic earthquake in 1770 [*Bakun et al.*, 2012].

6 Discussion

6.1 Proposed 3D structural model for the 10 – 15 km-wide belt of transpressional deformation along the northern edge of the EPGFZ

In summary, our lake studies, along with previous work, favor a model of a 10 – 15 km-wide transpressional zone that deforms thick, loosely-consolidated, Miocene to recent clastic rocks in coastal, marine, and lake settings as illustrated in three-dimensional block diagram (Figure 10). Moving from Lake Azuey in the east to Lake Miragoâne in the west, the block diagram illustrates along-strike changes observed in the dips of the thrust faults and obliquely orientation to the EPGFZ. Fold axes north of the EPGFZ range from 3 to 20 km in length, and are sigmoidally related to the EPGFZ in map view (Figure 2A, B). Dip direction and amounts on these thrust faults vary from north-dipping at 21° on the Jimani fault (Figure 6C and Figure 10), south-dipping on the Lamentine fault [*Saint Fleur et al.*, 2015] at 40°, north-dipping at 70° on the Léogâne fault active during the 2010 earthquake (A–A' in Figure 3, Figure 10), and south-dipping on the Trois Baies fault at 45° (Figure 10).

South of the EPGFZ, transpressional folding in more rigid Cretaceous basalts and overlying Eocene limestone have broader folding wavelengths from 1 to 8 km and a weak seismogenic deformation. On the other hand, InSAR images of the 2010 earthquake indicate smaller folds and more seismogenic deformation in the 10 – 15 km belt north of the EPGFZ. This contrast is likely related to rock type with poorly consolidated sedimentary rocks up to several kilometers north of the EPGFZ and more consolidated carbonate rocks and basalts exposed in the highlands south of the EPGFZ [*Mann et al.*, 1991] (Figure 2).

We propose that the folds north of the EPGFZ formed originally as conjugate thrust faults, reflecting the northeast to southwest convergence indicated by GPS vectors and highly transpressional character of the EPGFZ [*Calais et al.*, 2010]. Conjugate thrust faults are common in thick, clastic sedimentary basins undergoing active, sub-horizontal shortening [*Sibson*, 2012], as documented in the M_w 7.6 Chi-Chi Taiwan earthquake in 1999 [*Chen et al.*, 2002] or the M_w 7.1 Kumamoto Japan earthquake in 2016 [*Lin and Chiba*, 2017]. Aftershocks north of the EPGFZ reflect the most recent phase of NE-SW shortening on the 70° dipping reverse fault planes [*Nettles and Hjörleifsdóttir*, 2010], along the deeply buried Léogâne thrust fault, as shown in the cross-section of A–A' in Figure 3.

6.2 Analogy between the 2010 coseismic transpressional deformation in Haiti and the 1989 Loma Prieta earthquake in northern California

A similar pattern of transpression in a restraining bend setting to Haiti has been described for 1989 M_w 6.9 Loma Prieta earthquake [*Marshall et al.*, 1991] (Figure 11). The selected GPS vectors relative to a fixed North America plate [*UNAVCO (University Navstar Consortium)*, 2009] indicate the transpressional setting in a gentle restraining bend setting. In the inset map of Figure 11, the 1989 hypocentral area [*Marshall et al.*, 1991] shows the steep (~ 61°) dip of oblique-reverse faults of the collective Sargent and San Andreas faults. Also, the 1989 coseismic elevation uplifted 0.55 m on the southwestern hanging wall of the San Andreas and Sargent faults, and subsided 0.1 m on the northeastern footwall block [*Marshall et al.*, 1991]. The thrusting was blind with the M_w 7.1 earthquake not being accompanied by coseismic, surface breaks. These aftershocks define a conjugate pair of reverse faults with the dominant motion on the south-dipping fault plane.

As in the 2010 M_w 7.0 Haiti earthquake, a secondary, blind thrust fault [*Olson*, 1990] beneath the surface trace of the Sargent fault that, and oblique to the main San Andreas strike-slip fault (shown in inset map of Figure 11), played a major role in the 1989 fault rupture and resulting pattern of regional uplift shown in red color to the southwest and regional subsidence shown in blue color to the northeast (Figure 11).

While the oblique thrust planes form smaller fault segments ranging in length from 3 to 11 km (Figure 2A), the 2010 earthquake demonstrates that oblique thrusts like the Léogâne fault are capable of producing a M_w 7.0 earthquake with devastating results, especially when coupled with inadequate construction practices [*Symithe and Calais*, 2016]. Paleoseismic estimates of the age of the most recent deformation of Lake Azuey, eastern Haiti, suggests that the latest activity of the EPGFZ in this area was in 1751 [*Prentice et al.*, 2010; *Bakun et al.*, 2012]. Similar analysis indicates that the latest earthquake event in the Lake Miragoâne area, western Haiti, was in 1770 [*Bakun et al.*, 2012]. This, agreeing the previous study by *Bakun et al.* [2012], suggest the earthquake recurrence cycle along the EPGFZ is about 250 years. Therefore, in this transpressional setting, the earthquake cycle may consist of an interplay between ruptures on the EPGFZ and ruptures on the oblique thrusts and related folds.

The 2010 M_w 7.0 earthquake released part of the stress of the region, but as the oblique thrusts may not be directly linked to the EPGFZ, it is possible that stresses on the EPGFZ have continued to accumulate since the 18th century [*Prentice et al.*, 2010]. Integrated paleoseismic study of the EPGFZ with the commonly buried oblique thrust faults, using geophysical and geologic methods, can help to inform the critical social issue of how future earthquakes will be partitioned between the larger EPGFZ and other more obscure, oblique faults

7 Conclusions

The main conclusions of the study are as follows:

1. High-resolution sonar data from two Haitian lakes that straddle the EPGFZ and its northern flank demonstrates the presence of a 10 – 15 km-wide, 120 km-long, late Holocene, fold-and-thrust belt, which is deforming both the clastic lowland basins along the northern edge of the EPGFZ and the steep topographic highlands to the south.

2. In the eastern part of the study area, sonar results from Lake Azuey show that the EPGFZ is more deeply buried and less active than the adjacent, newly discovered, northwest-striking, northeast-dipping Jimani thrust fault. This structural relationship between the two faults is identical to the 2010 epicentral area 70 km to the west: the 2010 seismogenic, Léogâne blind thrust fault is northwest-to-east-striking, and the quiescent fault to the south during the 2010 earthquake is the east-west-striking, sub-vertical EPGFZ.

3. The geographic distribution of 2010 aftershocks revealed that the seismogenic motions of the Léogâne thrust fault and smaller motions on the EPGFZ terminated on a similar northwest-striking fault: the submarine Trois Bains thrust fault. In the westernmost part of the study area, sonar results from Lake Mirogoâne show two overlapping and active strands of the EPGFZ, and was instead diverted onto the Trois Bains thrust fault.

4. Our survey confirmed the pull-apart origin of Lake Mirogoâne and the lack of deformation on this western segment of the EPGFZ during the 2010 M_w 7.0 earthquake. Integration of the geologic data across the study area show an alternation in dip along nine northwest-striking, thrust faults at spacing of 5 to 40 km.

5. We interpret this zone of late Holocene deformation in clastic basins north of the EPGFZ as the accommodation of transpressional strain supported by highly-oblique GPS vectors across the study area. In this transpressional zone, coseismic deformation alternates at recurrence intervals of centuries between oblique shortening structures, such as Léogâne thrusts, Jimani thrusts, and Trois Bains thrusts, and strike-slip ruptures along the narrow and well defined main trace of the EPGFZ.

6. Our results, including the eastward extension of the EPGFZ into Dominican Republic, support the “thick-skinned” strike-slip model along a 10-15 km-wide corridor of left-lateral shearing centered on the EPGFZ as opposed to the southwestward propagation of the Trans-Haitian fold-and-thrust belt proposed by *Pubellier et al.* [2000].

Acknowledgments

We would like to thank the Society of Exploration Geophysicists' Geoscientists Without Borders program for supporting this project along with our earlier shallow-geophysical imaging of the epicentral region on the Léogâne fan [*Kocel et al.*, 2016]. We also express our appreciation to Alex von Lignau (Haiti Department of Finance), Alfredo Lo Cicero (Oxfam Italia in Haiti) for financial and logistical support on Lake Azuey. Ludner Remarais, and Jean Robert Altidor of the Haiti Bureau of Mines and Energy for their assistance with fieldwork, permissions, and importation of equipment. Eric Fielding of NASA Jet Propulsion Laboratory (JPL)/Caltech for kindly providing the InSAR imagery. Roby Douilly of Purdue University for generously providing location information for aftershock data. We are grateful to Allied Geophysical Laboratories (AGL) and William Sager at University of Houston for assisting with equipment and fieldwork preparation. Last but not least, we sincerely thank Jean-Francois Ritz, an anonymous reviewer, and Marc Jolivet, Tectonics Associate Editor, for their valuable comments and suggestions to improve the quality of the paper. The chirp sonar data used in this paper are available on AGL datastation (http://www.agl.uh.edu/resources-data.php) or by contacting the corresponding author.

References

Bakun, W. H., C. H. Flores, and S. Uri (2012), Significant earthquakes on the Enriquillo fault system, Hispaniola, 1500–2010: Implications for seismic hazard, *Bulletin of the Seismological Society of America*, *102*(1), 18–30.

Benford, B., C. DeMets, and E. Calais (2012), GPS estimates of microplate motions, northern Caribbean: evidence for a Hispaniola microplate and implications for earthquake hazard, *Geophysical Journal International*, *191*(2), 481–490.

Bien-Aimé Momplaisir, R. (1986), Contribution à l?étude géologique de la partie orientale du Massif de la Hotte (Presqu?île du Sud d?Haïti): Synthèse structurale des marges de la presqu?île à partir de données sismiques, *PhD thesis*, p. 210.

Bilham, R. (2010), Lessons from the Haiti earthquake, *Nature*, *463*(7283), 878–879.

Bilham, R., and E. Fielding (2013), Remote sensing and the search for surface rupture, haiti 2010, *Natural hazards*, *68*(1), 213–217.

Bourgueil, B., P. Andreieff, J. Lasnier, R. Gonnard, J. Le Metour, and J.-P. Rancon (1988), Synthèse géologique de la République d?Haïti, in *Technical report, Bureau des Mines et de l'Energie*, Haiti Port-au-Prince.

Bruña, J. G., U. S. Ten Brink, A. Carbó-Gorosabel, A. Muñoz-Martín, and M. G. Ballesteros (2009), Morphotectonics of the central Muertos thrust belt and Muertos Trough (northeastern Caribbean), *Marine geology*, *263*(1), 7–33.

Calais, E., Y. Mazabraud, B. Mercier de Lépinay, P. Mann, G. Mattioli, and P. Jansma (2002), Strain partitioning and fault slip rates in the northeastern Caribbean from GPS measurements, *Geophysical Research Letters*, *29*(18).

Calais, E., A. Freed, G. Mattioli, F. Amelung, S. Jónsson, P. Jansma, S.-H. Hong, T. Dixon, C. Prépetit, and R. Momplaisir (2010), Transpressional rupture of an unmapped fault during the 2010 Haiti earthquake, *Nature Geoscience*, *3*(11), 794–799.

Calais, É., S. Symithe, B. M. de Lépinay, and C. Prépetit (2016), Plate boundary segmentation in the northeastern Caribbean from geodetic measurements and Neogene geological observations, *Comptes Rendus Geoscience*, *348*(1), 42–51.

Chen, K.-C., B.-S. Huang, J.-H. Wang, and H.-Y. Yen (2002), Conjugate thrust faulting associated with the 1999 Chi-Chi, Taiwan, earthquake sequence, *Geophysical Research Letters*, *29*(8).

Corbeau, J., F. Rolandone, S. Leroy, B. Meyer, B. Mercier de Lépinay, N. Ellouz-Zimmermann, and R. Momplaisir (2016), How transpressive is the northern Caribbean plate boundary?, *Tectonics*, *35*(4), 1032–1046.

Cowgill, E., T. S. Bernardin, M. E. Oskin, C. Bowles, M. B. Yıkılmaz, O. Kreylos, A. J. Elliott, S. Bishop, R. D. Gold, A. Morelan, et al. (2012), Interactive terrain visualization enables virtual field work during rapid scientific response to the 2010 Haiti earthquake, *Geosphere*, *8*(4), 787–804.

Cox, B. R., J. Bachhuber, E. Rathje, C. M. Wood, R. Dulberg, A. Kottke, R. A. Green, and S. M. Olson (2011), Shear wave velocity-and geology-based seismic microzonation of Port-au-Prince, Haiti, *Earthquake Spectra*, *27*(S1), S67–S92.

Dolan, J. F., H. T. Mullins, and D. J. Wald (1998), Active tectonics of the north-central Caribbean: Oblique collision, strain partitioning, and opposing subducted slabs, *SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA*, pp. 1–62.

Douilly, R., J. S. Haase, W. L. Ellsworth, M.-P. Bouin, E. Calais, S. J. Symithe, J. G. Armbruster, B. M. de Lépinay, A. Deschamps, S.-L. Mildor, et al. (2013), Crustal structure and fault geometry of the 2010 Haiti earthquake from temporary seismometer deployments, *Bulletin of the Seismological Society of America*, *103*(4), 2305–2325.

Douilly, R., H. Aochi, E. Calais, and A. Freed (2015), Three-dimensional dynamic rupture simulations across interacting faults: The mw7. 0, 2010, haiti earthquake, *Journal of Geophysical Research: Solid Earth*, *120*(2), 1108–1128.

Fielding, E. J., A. Sladen, Z. Li, J.-P. Avouac, R. Bürgmann, and I. Ryder (2013), Kinematic fault slip evolution source models of the 2008 M7.9 Wenchuan earthquake in China from SAR interferometry, GPS and teleseismic analysis and implications for Longmen Shan tectonics, *Geophysical Journal International*, *194*(2), 1138–1166, doi: 10.1093/gji/ggt155.

Frankel, A., S. Harmsen, C. Mueller, E. Calais, and J. Haase (2011), Seismic hazard maps for Haiti, *Earthquake Spectra*, *27*(S1), S23–S41.

Grindlay, N. R., M. Hearne, and P. Mann (2005), High risk of tsunami in the northern Caribbean, *Eos, Transactions American Geophysical Union*, *86*(12), 121–126.

Hashimoto, M., Y. Fukushima, and Y. Fukahata (2011), Fan-delta uplift and mountain subsidence during the haiti 2010 earthquake, *Nature Geoscience*, *4*(4), 255–259.

Hayes, G., R. Briggs, A. Sladen, E. Fielding, C. Prentice, K. Hudnut, P. Mann, F. Taylor, A. Crone, R. Gold, et al. (2010), Complex rupture during the 12 January 2010 Haiti earthquake, *Nature Geoscience*, *3*(11), 800–805.

Higuera-Gundy, A., M. Brenner, D. A. Hodell, J. H. Curtis, B. W. Leyden, and M. W. Binford (1999), A 10,300 14 C yr record of climate and vegetation change from Haiti, *Quaternary Research*, *52*(2), 159–170.

Hornbach, M. J., N. Braudy, R. W. Briggs, M.-H. Cormier, M. B. Davis, J. B. Diebold, N. Dieudonne, R. Douilly, C. Frohlich, S. P. Gulick, et al. (2010), High tsunami frequency as a result of combined strike-slip faulting and coastal landslides, *Nature Geoscience*, *3*(11), 783–788.

Kocel, E., R. R. Stewart, P. Mann, and L. Chang (2016), Near-surface geophysical investigation of the 2010 Haiti earthquake epicentral area: Léogâne, Haiti, *Interpretation*, *4*(1), T49–T61.

Koehler, R., and P. Mann (2011), Field observations from the January 12, 2010, Haiti earthquake: Implications for seismic hazards and future post-earthquake reconnaissance investigations in Alaska, *Report of Investigations*, *2*, 24.

Kroehler, M. E., P. Mann, A. Escalona, G. Christeson, et al. (2011), Late Cretaceous-Miocene diachronous onset of back thrusting along the South Caribbean deformed belt and its importance for understanding processes of arc collision and crustal growth, *Tectonics*, *30*(6).

Leroy, S., N. Ellouz-Zimmermann, J. Corbeau, F. Rolandone, B. M. Lépinay, B. Meyer, R. Momplaisir, J.-L. Granja Bruña, A. Battani, C. Baurion, et al. (2015), Segmentation and kinematics of the North America-Caribbean plate boundary offshore Hispaniola, *Terra Nova*, *27*(6), 467–478.

Lin, A., and T. Chiba (2017), Coseismic conjugate faulting structures produced by the 2016 m w 7.1 kumamoto earthquake, japan, *Journal of Structural Geology*, *99*, 20–30.

Mann, P. (1999), Caribbean sedimentary basins: Classification and tectonic setting from Jurassic to present, *Sedimentary Basins of the World*, *4*, 3–31.

Mann, P., G. Draper, J. F. Lewis, et al. (1991), An overview of the geologic and tectonic development of hispaniola, *Geologic and tectonic development of the North America-Caribbean plate boundary in Hispaniola. Geological Society of America Special Paper*, *262*, 1–28.

Mann, P., F. Taylor, R. L. Edwards, and T.-L. Ku (1995), Actively evolving microplate formation by oblique collision and sideways motion along strike-slip faults: An example from the northeastern Caribbean plate margin, *Tectonophysics*, *246*(1), 1–69.

Mann, P., E. Calais, J.-C. Ruegg, C. DeMets, P. E. Jansma, and G. S. Mattioli (2002), Oblique collision in the northeastern Caribbean from GPS measurements and geological observations, *Tectonics*, *21*(6).

Marshall, G. A., R. S. Stein, and W. Thatcher (1991), Faulting geometry and slip from coseismic elevation changes: the 18 October 1989, Loma Prieta, California, earthquake, *Bulletin of the Seismological Society of America*, *81*(5), 1660–1693.

Massoni, P. (1955), *Haïti: reine des Antilles*, Nouvelles Editions Latines.

McHugh, C. M., L. Seeber, N. Braudy, M.-H. Cormier, M. B. Davis, J. B. Diebold, N. Dieudonne, R. Douilly, S. P. Gulick, M. J. Hornbach, et al. (2011), Offshore sedimentary effects of the 12 January 2010 Haiti earthquake, *Geology*, *39*(8), 723–726.

Mercier de Lépinay, B., A. Deschamps, F. Klingelhoefer, Y. Mazabraud, B. Delouis, V. Clouard, Y. Hello, J. Crozon, B. Marcaillou, D. Graindorge, et al. (2011), The 2010 Haiti earthquake: A complex fault pattern constrained by seismologic and tectonic observations, *Geophysical Research Letters*, *38*(22).

Moknatian, M., M. Piasecki, and J. Gonzalez (2017), Development of Geospatial and Temporal Characteristics for Hispaniola?s Lake Azuei and Enriquillo Using Landsat Imagery, *Remote Sensing*, *9*(6), 510.

Nettles, M., and V. Hjörleifsdóttir (2010), Earthquake source parameters for the 2010 January Haiti main shock and aftershock sequence, *Geophysical Journal International*, *183*(1), 375–380.

Odonne, F., and P. Vialon (1983), Analogue models of folds above a wrench fault, *Tectonophysics*, *99*(1), 31–46.

Olson, J. A. (1990), Seismicity in the twenty years preceding the loma prieta california earthquake, *Geophysical Research Letters*, *17*(9), 1429–1432.

Paultre, P., É. Calais, J. Proulx, C. Prépetit, and S. Ambroise (2013), Damage to engineered structures during the 12 January 2010, Haiti (Léogâne) earthquake, *Canadian Journal of Civil Engineering*, *40*(8), 777–790.

Piasecki, M., M. Moknatian, F. Moshary, J. Cleto, Y. Leon, J. Gonzalez, and D. Comarazamy (2016), Report: Bathymetric Survey for Lakes Azuei and Enriquillo, Hispaniola, *Tech. rep.*, City University of New York (CUNY).

Prentice, C., P. Mann, A. Crone, R. Gold, K. Hudnut, R. Briggs, R. Koehler, and P. Jean (2010), Seismic hazard of the Enriquillo-Plantain Garden fault in Haiti inferred from palaeoseismology, *Nature Geoscience*, *3*(11), 789–793.

Prentice, C. S., P. Mann, F. Taylor, G. Burr, and S. Valastro (1993), Paleoseismicity of the north american-caribbean plate boundary (septentrional fault), dominican republic, *Geology*, *21*(1), 49–52.

Pubellier, M., A. Mauffret, S. Leroy, J. M. Vila, and H. Amilcar (2000), Plate boundary readjustment in oblique convergence: Example of the Neogene of Hispaniola, Greater Antilles, *Tectonics*, *19*(4), 630–648.

Rathje, E., J. Bachhuber, B. Cox, J. French, R. Green, S. Olson, G. Rix, D. Wells, O. Suncar, E. Harp, et al. (2014), Geotechnical reconnaissance of the 2010 Haiti earthquake: GEER (Geotechnical Extreme Events Reconnaissance).

Rico, P. (2017), Hydrodynamic Study of Lake Enriquillo in Dominican Republic, *Journal of Geoscience and Environment Protection*, *5*, 115–124.

Rios, J., C. McHugh, M. Hornbach, P. Mann, V. Wright, and D. Gurung (2013), Holocene activity of the Enriquillo-Plantain Garden Fault in Lake Enriquillo derived from seismic stratigraphy, in *AGU Fall Meeting Abstracts*, vol. 1, p. 2629.

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 M7. 0 earthquake, *Geophysical Research Letters*, *42*(23).

Segall, P., and M. Lisowski (1990), Surface displacements in the 1906 San Francisco and 1989 Loma Prieta earthquakes, *Science*, *250*(4985), 1241–1244.

Sibson, R. (2012), Reverse fault rupturing: competition between non-optimal and optimal fault orientations, *Geological Society, London, Special Publications*, *367*(1), 39–50.

Sylvester, A. G. (1988), Strike-slip faults, *Geological Society of America Bulletin*, *100*(11), 1666–1703.

Symithe, S., and E. Calais (2016), Present-day shortening in Southern Haiti from GPS measurements and implications for seismic hazard, *Tectonophysics*, *679*, 117–124.

Symithe, S. J., E. Calais, J. S. Haase, A. M. Freed, and R. Douilly (2013), Coseismic slip distribution of the 2010 M 7.0 Haiti earthquake and resulting stress changes on regional faults, *Bulletin of the Seismological Society of America*, *103*(4), 2326–2343.

Taylor, F., P. Mann, S. Valastro Jr, and K. Burke (1985), Stratigraphy and radiocarbon chronology of a subaerially exposed Holocene coral reef, Dominican Republic, *The Journal of Geology*, *93*(3), 311–332.

Terrier, M., A. Bialkowski, A. Nachbaur, C. Prépetit, and Y. Joseph (2014), Revision of the geological context of the port-au-prince metropolitan area, haiti: implications for slope failures and seismic hazard assessment, *Natural Hazards and Earth System Sciences*, *14*(9), 2577.

UNAVCO (University Navstar Consortium) (2009), PBO GPS velocities in southern California.

Wright, V. D., M. J. Hornbach, C. Mchugh, and P. Mann (2015), Factors contributing to the 2005-present, rapid rise in lake levels, dominican republic and haiti (hispaniola), *Natural Resources*, *6*(08), 465.

Figure 1. Tectonic setting of the northeastern Caribbean and EPGFZ in southern Haiti. A: Free-air gravity anomaly map of the Greater Antilles (Cuba, Jamaica, Hispaniola, Puerto Rico) in the northeastern Caribbean (http://topex.ucsd.edu) with gravity lows marking zones of subduction or thrusting along major faults (black lines) of the North America-Caribbean plate boundary. Arrows with error ellipses from *Calais et al.* [2010] are GPS vectors showing the direction and velocity of the large North American plate, the Bahamas platform (**BP**), and intervening microplates relative to a fixed Caribbean plate. Microplates with variable relative motions occupy the 200 km-wide plate boundary zone and include: **NHM** = North Hispaniola microplate; **HM** = Hispaniola microplate; **GM** = Gonâve microplate; **PRVIM** = Puerto Rico-Virgin Islands microplate. Box shows more detailed map of the EPGFZ shown in B. **B:** Regional structure map of the southern peninsula of Haiti with the active, left-lateral Enriquillo-Plantain Garden fault zone (EPGFZ) from the Lake Enriquillo in the east to the western tip of the southern peninsula. The centroid moment tensor (CMT) mechanism is from *Douilly et al.* [2013]. From east to west, key lakes and marine embayments aligned parallel and overlying the EPGFZ include: **LE** = Lake Enriquillo, Dominican Republic; **LA** = Lake Azuey, Haiti; **PAPB** = Port-au-Prince Bay; **CS** = Canal du Sud; and **LM** = Lake Miragoâne; **LF** = Léogâne fault. Boxes shows more detailed maps of the structure of the EPGFZ and its secondary faults shown in Figure 2A and Figure 7A. **C:** Composite, multichannel seismic reflection line (acquired by Canadian Superior Energy Inc.) located as the red line X-X' in B that shows an unfolded area of high-angle faults in the Canal du Sud tied to the offshore Cul-de-Sac-1 well, the TBFZ, the EPGFZ, the anticlinal structure of the southern peninsula, and a large, south-verging accretionary prism along the south coast of the southern peninsula. The depth scale for this section is in two-way, travel time.

Figure 2. Structure of the EPGFZ in eastern Haiti. A: Geologic faults and folds along a 15 km-wide corridor parallel to the EPGFZ superimposed on a modified DEM and InSAR surface deformation map (courtesy of Eric Fielding at JPL) [*Hayes et al.*, 2010]. Chirp bathymetry of the Lake Azuey is also shown. GPS vectors are from *Calais et al.* [2010]. **PFZ** = Port-au-Prince fault zone; **DFZ** = Dumay fault zone; **DT** = Dumay thrust; **NaC** = Nan Cadastre thrust; **JFZ** = Jacquet fault zone; **GFZ** = Ganthier fault zone; **LF** = Léogâne fault. Line A – A': Cross-section along the blind Léogâne thrust fault (shown in Figure 3); Line B – B': Cross-section of north Port-au-Prince urban area (shown in Figure 3). **B:** Shaded DEM of the northern deformed belt in the Cul-de-Sac basin with illumination from the Figure 2A showing *en echelon* and curvilinear folds striking west-northwest obliquely with respect to the EPGFZ and plunging beneath undeformed sediments occupying the center of the Cul-de-Sac Valley. The inserted schematic diagram is from *Odonne and Vialon* [1983]

.

Figure 3. Style of late Neogene deformation in the northern belt along three transects shown in Figure 2. A-A': Aftershocks of the 2010 earthquake [*Douilly et al.*, 2013, 2015] along the blind Léogâne thrust fault reveals conjugate reverse faults with the dominant slip occurring on the north-dipping fault. The red triangle indicates Léogâne city. **B-B':** Cross section based on surface mapping [*Massoni*, 1955; *Cox et al.*, 2011; *McHugh et al.*, 2011; *Saint Fleur et al.*, 2015] showing north- and south-dipping reverse faults deforming Plio-Pleistocene sedimentary rocks.

Figure 4. Structure of the EPGFZ in eastern Haiti and western-most Dominican Republic. A: Structural map of Lakes Azuey (surface 15 m ASL) and Lake Enriquillo (surface 46 m BSL) are presently separated by a shallow sill 30 m ASL in the isthmus near the town of Jimani. **B:** Comparison of two Chirp lines from Lake Enriquillo by *Rios et al.* [2013] (3 km-long Line L19) and from our study of Lake Azuey (4 km-long Line B6). Identical sequences present on both lines suggest that the two lakes were once part of a single lake that has been recently separated by crustal movements related to the EPGFZ near the Jimani area. Ages of units are known from Lake Enriquillo through both exposures around the sub-sea level lake and from coring by *Rios et al.* [2013].

Figure 5. Geologic setting of Lake Azuey, Haiti. A: To the south, the green brackish waters of Lake Azuey are bound by the EPGFZ which forms a sharp boundary with 2 km-high, folded limestone of Paleogene age that forms the smooth surfaces on the skyline. One scarp is present along the edge of the lake while other parallel strands of the EPGFZ are beneath the southern part of the lake as schematically shown. **B:** To the north of the lake folded, Plio-Pleistocene strata form the uplifted, 0 – 30 m-high isthmus separating the two lakes. Approximate locations of the EPGFZ and the Jimani thrust fault are shown.

Figure 6. Chirp sonar profiles showing the relationship of the trace of the EPGFZ and a newly described thrust we have named the Jimani thrust. Cross sections of A, and B are indicated in Figure 2A. The EPGFZ beneath Lake Azuey forms a 10 m-wide zone that can be traced as a lineament to the east and west of Lake Azuey (Figure 2). The green and red horizons represent two distinguish stratigraphic layers. The two strands of the EPGFZ are buried by 0.7 m of Holocene sediment and are extrapolated to be 270 years old since their last rupture when a sedimentation rate of 2.6 mm/yr is assumed. Folds associate with the Jimani thrust are interpreted as fault propagation folds. **C:** Cross section based on both sonar survey and the surface mapping [*Mann et al.*, 1991] showing north- and south-dipping, reverse faults deforming Plio-Pleistocene sedimentary rocks.

Figure 7. Structure and 2010 coseismic surface deformation of the western segments of the EPGFZ. **A:** Structure [*Prentice et al.*, 2010; *Cowgill et al.*, 2012] and aftershock [*Douilly et al.*, 2013] map of Miragoâne-Léogâne region overlain with an InSAR image (courtesy of Eric Fielding at JPL) [*Hayes et al.*, 2010]. **B:** Zoom of the area of Petit Goave and Lake Miragoâne showing the structure and bathymetry of the 14 km^2, pull-apart basin mapped beneath Lake Miragoâne during this study and details of the 2010 surface fracturing and coseismic subsidence in the Petit Goâve Bay [*Prentice et al.*, 2010]. **LM** = Lake Miragoâne; **PG** = Petit Goâve.

Figure 8. Geologic setting and sonar profiles from Lake Miragoâne. **A:** View looking south across the 12 km-wide and 42.8 m deep, freshwater lake. The 2 km-high, ridge along the southern edge of the lake is the cumulative topographic scarp associated to the southernmost strand of the EPGFZ. The core was taken by *Higuera-Gundy et al.* [1999] and was not collected from the deepest part of the lake. **B:** North-south trending line M1 (location shown on Figure 7B). **C:** East-west trending line M5 (location shown on Figure 7B).

Figure 9. Core data from Lake Miragoâne. **A:** Tie between chirp sonar and core [*Higuera-Gundy et al.*, 1999] extending to lacustrine sediments deformed by the EPGFZ in 1770 A.D.. **B:** Low-pass filtered E/P log (red) and the synthetic sonar profile generated from the low-pass filtered E/P log used as an acoustic impedance. The chirp sonar profiles are from the location of the red bar in the Figure 8B, C.

Figure 10. Schematic diagram of the conjugate-thrust-fault model for the 10 – 15 km-wide belt of transpressional deformation along the northern edge of the EPGFZ. **A:** Three-dimensional block diagram showing the structural, aftershocks, and the late Holocene strain partitioning in a 40-km-wide zone along a 120 km-long segment of the EPGFZ. Black arrows show southwest direction of the Gonâve microplate relative to the Caribbean plate [*Calais et al.*, 2010]. The 2010 InSAR-derived surface deformation map (courtesy of Eric Fielding at JPL) [*Hayes et al.*, 2010] show a large component of shortening accommodated on a 40 km-wide zone of oblique thrusts and folds north of the EPGFZ. **PaP** = Port-au-Prince; **PG** = Petit Goave; **LA** = Lake Azuey; **LM** = Lake Miragoâne-Léogâne; **JF** = Jimani thrust fault; **DT** = Dumay thrust; **PFZ** = Port-au-Prince fault zone; **LMF** = Lamartin thrust fault; **TBF** = Trois Baies thrust fault; **LF** = Léogâne fault. **B:** Schematic diagram, modified from *Sibson* [2012], of the conjugate thrust faults.

Figure 11. Structural map of the southern San Francisco Bay region, the cos-seismic elevation and the aftershock cross-section of 1989 M_w 6.9 Loma Prieta earthquake. The selected GPS vectors relative to a fixed North America plate are from *UNAVCO (University Navstar Consortium)* [2009]. The cos-seismic elevation change and aftershock cross-section are modified from *Marshall et al.* [1991]. **SAF**: San Andreas Fault; **SF**: Sargent Fault.