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

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Key Points:

- First high-resolution sonar surveys of two actively deforming lakes in Haiti.
- Extreme 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.

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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. Nevertheless, the EPGFZ still formed a major, crustal 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 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 in damage [*Prentice et al.*, 2010; *Bilham*, 2010; *Paultre et al.*, 2013; *Kocel et al.*, 2016] (Figure 1). Multidisciplinary, geological and geophysical studies within the 2010 epicentral area of south-central Haiti include: 1) measurements and fault modeling of coseismic, coral reef uplift along a 50 km-long area of coastline in the epicentral region [*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 a distance of 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° to the EPGFZ [*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 produced by 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 that is buried beneath at least 1 km of overlying undeformed clastic sediment in the area north of the EPGFZ absorbed northeast-southwest shortening related to extreme transpression 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 more

east-west-striking EPGFZ located 5 km to the south (Figure 1B). Previous GPS surveys [*Calais et al.*, 2010, 2016] along this area of the EPGFZ have shown that plate motion is almost at right angles to these obliquely-striking thrusts and consistent with their preferred orientation for reactivation within the area of northeast-to-southwest shortening (Figure 1A, B).

Aftershock studies following the 2010 earthquake by *Douilly et al.* [2013, 2015] showed that the EPGFZ moved locally 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 fault-related, surface ground breaks along the pro-posed 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 for distances of 4-29 km into the more thickly-sedimented basinal areas north of the EPGFZ (Figure 2A). As a result of this distinc-tive 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 northern area 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], is either accommodated by: 1) slip and major earthquakes on the main, strike-slip plate boundary fault; 2) the oblique, *en echelon* thrusts adjacent to the main fault; 3) or 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 would continue to accumulate strain. In an extreme transpression case as observed in Haiti, plate motions become increasingly convergent across the main, strike-slip fault zone (Figure 1A, B). In such a setting, 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 [*Mount and Suppe*, 1987].

These oblique and *en echelon* thrust faults in transpressional settings, that includes large restraining bends such as 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 faults [*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 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 and earthquake potential of oblique *en echelon* thrusts, especially when buried or "blind", can be challenging to assess in transpressional zones [*Frankel et al.*, 2011].

2 Objectives and methods

2.1 Study area

The 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 [*Butterlin*, 1960; *Mann et al.*, 1995; *Bachhuber et al.*, 2010; *Rathje et al.*, 2011; *Terrier et al.*, 2014; *Saint Fleur et al.*, 2015]. In easternmost Haiti, this belt is overlain by 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 twice as large (346 km ^{2}) as Azuey, shallow (52 m-deep), hypersaline, about 40 m below sealevel, and located entirely in the Dominican Republic. Lake Enriquillo is 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).

139   In the western part of our study area, the more transtensional segment of the EPGFZ

140 is overlain by the 42.8 m-deep, 14 km^2, freshwater Lake Miragoâne (Figure 1B). All three

141 of these shallow, inland, lakes experience variations up to 13 m in their surface elevations

142 due to annual to decadal changes in climate and rainfall amounts including extreme rain-

143 fall events associated with hurricanes [*Wright et al.*, 2015; *Piasecki et al.*, 2016; *Moknatian*

144 *et al.*, 2017; *Rico*, 2017].

2.2 Objectives

146   The main goal of this paper is to better integrate the geologic structure of the 120

147 km-long study area, which parallels the trace of the EPGFZ and includes the 2010 epi-

148 central area. Data types that we have integrated for this study include: surficial-geologic

149 mapping, geophysics, GPS, radar interferometry, aftershocks, and modeling studies. Most

150 of these studies were completed in the aftermath of the 2010 earthquake. Our study inte-

151 grates these datasets in order to structurally characterize the 10-15 km-wide, belt of late

152 Holocene, transpressional deformation that forms a laterally-extensive, deformed belt along

153 the inland, Cul-de-Sac intermontane basin in the east and the low-relief coastal plain along

154 Port-au-Prince bay and the Canal du Sud to the west (Figure 1B). In particular, we focus

155 on the identifying a family of *en echelon* thrusts, whose curvilinear strikes area are very

156 similar to the Léogâne thrust now known to be responsible for most of the energy release

157 and coseismic uplift during the 2010 Haiti earthquake [*Calais et al.*, 2010; *Douilly et al.*,

158 2013, 2015] (Figure 1B, Figure 2A).

2.3 Survey design

160   In order to understand the geologic and structural styles of transpression within this

161 belt, including the age relations between deformation in the north-flanking belt and the

162 EPGFZ itself, we collected a total of 94 km of high-resolution (2-10 kHz) sonar profiles

163 in 2014 from the 138 km^2, brackish Lake Azuey and 37 km of profiles from the 14 km^2,

164 fresh-water Lake Miragoâne (Figure 1B). The EPGFZ strikes through both of the lakes, so

165 80% of our lines on Lake Azuey and 90% of our survey lines on Lake Miragoâne were

166 dedicated to the across fault-strike, north-south profiles.

167   The average speed of the small, outboard, motorboat towing the sonar was 3 knots,

168 with a sonar pulse rate of 4 per second. Our 2-10 kHz sonar frequency range yielded sub-

bottom layer resolution of about 10 cm [*Wang et al.*, 2015]. 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, and therefore provide new con-

straints on the location, structural style, and timing of deformation within both structural

provinces. We integrate these lake data with previous geologic mapping, geophysical ob-

servations related to the 2010 earthquake, and regional information on plate motions in

this region.

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, previously-proposed, 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 transpres-

sion 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). GPS surveys within this 250 km-

wide, transpressional zone [*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 sub-

parallel Septentrional strike-slip fault zone 200 km to the north (which is the plate bound-

ary separating the North Hispaniola microplate and Gonâve microplate) (Figure 1A). As a

result of this oblique collision and restraining bend area, the 3-km-high mountains of cen-

tral Hispaniola have grown since the late Miocene to an elevation of 3 km to the highest

range in the northern Caribbean.

The left-lateral strike-slip rupture of the EPGFZ in the 18th century inferred from

the map pattern of historical earthquakes [*Bakun et al.*, 2012] combined with average late

Holocene, left-lateral offset amounts of 1.3 – 3.3 m as expressed along offset streams of

the EPGFZ [*Prentice et al.*, 2010] and by late Holocene, left-lateral, channel offsets of 7

199 – 8 m along stream channels offset by the Septentrional fault zone [*Prentice et al.*, 1993,

200 2003].

201 The study by *Saint Fleur et al.* [2015] indicates that the folding and thrusting of 10

202 – 15 km-wide belt of Miocene to Quaternary rock was generated by transpression along

203 the EPGFZ. In addition, *Mann et al.* [2002]; *Grindlay et al.* [2005]; *Kroehler et al.* [2011]

204 suggest a strong, southwestward, backthrusting of the southern Hispaniola in Haiti and

205 Dominican Republic to the southwest onto the Caribbean plate (Figure 1B, C). South-

206 westward backthrusting of Hispaniola is manifested by the large accretionary wedge along

207 the Muerto trench south of the Dominican Republic [*Bien-Aimé Momplaisir*, 1986; *Bruña*

208 *et al.*, 2009] (Figure 1A, B) and along the southern margin of Haiti (South Haiti accre-

209 tionary prism [*Bien-Aimé Momplaisir*, 1986] (Figure 1C). A localized, negative gravity

210 anomaly marks the trend of plate flexure of the underthrusting Caribbean plate beneath

211 the overriding area of southern Hispaniola [*Mann et al.*, 2002; *Bruña et al.*, 2009] (Figure

212 1A)).

213 ### 3.1.2 Criticisms of the strike-slip, regional structural model

214 Two criticisms have been proposed for the strike-slip model. First, *Corbeau et al.*

215 [2016] noted that the predictions of the GPS-based block models overestimate the ob-

216 served amounts of transpression-related shortening seen on seismic reflection profiles in

217 the offshore area of the Gulf of Gonâve north of the southern peninsula of Haiti, or in the

218 area of the Jamaica Passage east of Haiti. Second, *Symithe and Calais* [2016] have pro-

219 posed that there is no geologic evidence for a continuation of the EPGFZ east of latitude

220 72.27°W in the eastern Cul-de-Sac Valley, Lake Azuey and Lake Enriquillo in the Do-

221 minican Republic (Figure 1B). Instead, *Symithe and Calais* [2016] propose that the high

222 rates of north-south shortening predicted from GPS block models are accommodated en-

223 tirely by low-angle thrust structures in the eastern Cul-de-Sac and Enriquillo Valleys that

224 were modeled using GPS data as part of their study.

225 ### 3.1.3 Trans-Haitian fold-and-thrust belt regional structural model

226 The Trans-Haitian fold-and-thrust belt model originated with a study by *Pubellier*

227 *et al.* [2000], who proposed a low-angle southwestward-verging fold-and-thrust belt along

228 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, that is 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 inactive. Increasing amounts of shortening caused the Trans-Haitian fold-and-thrust belt to propagate 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 the Léogâne fault marks 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 GPS data showing 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, as imaged 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 previous interpretation that deformation north of the

261 EPGFZ is the result of southwestward propagation of the Trans-Haitian fold-and-thrust

262 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

266 The presence of a strike-slip fault at any scale is indicated by the presence of *en ech-*

267 *elon* arrays of thrust faults, normal faults, folds, fractures, dikes, and other linear features

268 in narrow, elongate zones [*Sylvester*, 1988]. On Figure 2A, we have compiled geologic in-

269 formation on *en echelon* folds and faults in a 10 – 15 km-wide zone of deformation along

270 both the northern and southern flanks of the EPGFZ. Folds form as fault propagation folds

271 along oblique, thrust faults, vary from 1 to 8 km in lateral spacing, and deform Miocene

272 and younger fine to coarse-grained, basinal, and coastal plain rocks in the belt that is 10

273 – 15 km wide and extends parallel to the EPGFZ for 120 km (Figure 1B and Figure 2A).

274 Folds in Neogene clastic lithologies of the Cul-de-Sac basin contrast with more continuous

275 and longer wavelength, *en echelon* fold axes present in more massively-bedded Cretaceous

276 to Eocene rigid, basaltic, and carbonate lithologies exposed in the 2 km-high range south

277 of the EPGFZ, the Massif de Selle (Figure 2A). The curvilinear trend of fold axes is sim-

278 ilar both to the north and south of the EPGFZ and indicates a genetic relation between

279 left-lateral shearing along that fault and the formation of those *en echelon* features (Fig-

280 ure 2B).

281 The *en echelon* distribution of complex Holocene folding and thrusting in the 10

282 – 15 km wide zone of deformation north of the EPGFZ is also reflected in the complex

283 pattern of 2010 coseismic and vertical deformation recorded by the interferogram from

284 the 2010 epicentral area on the Léogâne plain west of the Cul-de-Sac basin [*Hayes et al.*,

285 2010; *Hashimoto et al.*, 2011; *Bilham and Fielding*, 2013] (Figure 2A). *Douilly et al.* [2013,

286 2015] and *Kocel et al.* [2016] use aftershocks and shallow geophysics to show that the

287 2010 Léogâne thrust fault and sub-parallel faults are overlain by at least one kilometer

288 of undeformed and sub-horizontal strata (cross-section A–A' in Figure 3).

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 present along the southern edge of the Cul-de-Sac basin are 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 mapview 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 observed in claybox experiments of shearing (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 is modified from aftershock data from *Douilly et al.* [2013, 2015] and 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 proxim-

320 ity to the EPGFZ, an east-west strike of the Léogâne thrust is predicted as this is the area

321 where *en echelon* folds and faults curve into an asymptotic orientation relative to the main

322 EPGFZ, as shown on Figure 2B.

323 A radar interferogram compiled on the structure map of Figure 2A revealed that the

324 2010 earthquake elevated the smaller folds of the Léogâne fan-delta north of the EPGFZ,

325 yet produced coseismic subsidence in the 1.4 km-high, less complexly deformed, moun-

326 tain range south of the EPGFZ [*Hashimoto et al.*, 2011] (Figure 2A). This paradox can be

327 simply explained by the northward dip of the seismogenic Léogâne fault that elevated the

328 basinal area to the north (hanging wall of the Léogâne fault) and depressed the mountain-

329 ous 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

332 A similar pattern of deformation is observed in Port-au-Prince urban area where the

333 central and northern edge of the Cul-de-Sac basin is only gently folded and faulted [*Bach-*

334 *huber et al.*, 2010; *Rathje et al.*, 2011; *Cox et al.*, 2011; *McHugh et al.*, 2011; *Saint Fleur*

335 *et al.*, 2015] (Line B-B' in Figure 3). The cross section taken from workers, who were

336 mapping 60 years ago when Port-au-Prince was smaller and the geology was less obscured

337 by urbanization, shows two large thrusts, a range-bounding thrust along the southern edge

338 of the city, and a northeast-dipping thrust, the Dumay thrust, that elevates a broad out-

339 crop zone of north-dipping, Neogene sedimentary rocks on which the northern area of

340 Port-au-Prince is built [*Rathje et al.*, 2014]. The 50° northeast dip of the Dumay thrust is

341 similar to the 70° northeast dip of the Léogâne thrust to the west known from aftershocks

342 [*Douilly et al.*, 2013, 2015], although the dip of the Dumay thrust reverses to a southwest

343 dip as it approaches the EPGFZ (Figure 2A, B).

344 On the cross section B–B' in Figure 3, we have indicated areas that are elevated as

345 a result of the northward dip of the Dumay thrust and the depression of the area to the

346 south of the EPGFZ in the highlands south of the EPGFZ. If a future earthquake occurred

347 along the north-dipping, *en echelon* thrust faults in the Port-au-Prince area (Line B–B'

348 in Figure 2) or Lake Azuey area (Line C–C' in Figure 2) a similar uplift phenomenon

349 is likely to occur where the lowlands north of the EPGFZ are uplifted and the adjacent

350 mountains south of the EPGFZ subside.

4.3.3 Geologic structure of the Lake Azuey area

In the Lake Azuey area, we mapped a linear, 250–500 m-wide, and east-west strik-
ing 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 4 and Figure 5A – D).
The fault is marked by a 250–500 m-wide, graben-like feature that disrupts the uppermost
late Holocene, lake stratigraphy. 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 250–500 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). A
similar, 500 m-wide, graben-like structure was described by *Hornbach et al.* [2010] along
the trace of EPGFZ where it enters the Baie de Grand Goâve 75 km west of Lake Azuey
(Figure 2A).

The structural cross sections in this area were compiled from previous studies [*Mann
et al.*, 1995; *Bachhuber et al.*, 2010; *Rathje et al.*, 2011; *Saint Fleur et al.*, 2015; *Douilly
et al.*, 2015] and 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 4). Sonar profiles (Figure 5A – D) 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,
indicating that this margin is not controlled by late Holocene faulting (Figure 5C, E). 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 (Fig-
ure 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 Fig-

ure 5E, we have schematically indicated areas that are elevated as a result of the north-

ward dip of the Jimani thrust and the depression of the area to the south of the EPGFZ.

The structural cross-section (Figure 5E) of the Lake Azuey area and the previous works [*Bourgueil et al.*, 1988; *Rathje et al.*, 2011; *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 5E) 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 from 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 6A). 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 history in the upper 5 m and 7 m sediment, 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, sub-parallel

strands of the EPGFZ that are collinear with onland scarps both east and west of Lake

Azuey (Figure 2 and Figure 4) and east and west of Lake Enriquillo [*Mann et al.*, 1995;

Rios et al., 2013] (Figure 6A). These east-west fault strands abruptly truncate the trends of

folds in the ranges south of the lake (Figure 4). The sonar events, which are interpreted as

stratigraphic features, from Lake Azuey and Lake Enriquillo (Line B1 and Line L19 cor-

relate convincingly (Figure 6B). *Schwartz* [1980] suggested that both of the lakes were the

results of the closure of former marine strait. Due to the small distance separating the two

lakes (about 4 km), the two lakes merged during heavy rainfall years [*Greer and Swart*,

2006; *Medley et al.*, 2007; *Romero Luna and Poteau*, 2011]. Given 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 similar sedimentation history

as well as the same structural style and seismicity related to the EPGFZ and its oblique,

thrust faults. However, this hypothesis remains speculative pending more coring in Lake

Azuey.

The EPGFZ in both Lake Enriquillo and Lake Azuey is buried by 0.7 m of sedi-

ments. 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 re-

cent Holocene average sedimentation rate of 2.6 mm/yr (Figure 6B). 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 (267 years ago), and that the deformed sediments in Lake Azuey are of Holocene

age [*Rios et al.*, 2013].

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 En-

riquillo 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 basic 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 6A). 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 6A) 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 prominent, east-western lineament extending eastward from our map area in Lake Azuey (Figure 6A). 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 6A). 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 5A – D). 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 [*Mercier de Lépinay et al.*, 2011]. As the Trois Baies fault is is a submarine fault, 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).

Nevertheless, the same basic structural elements of the Léogâne plain are also observed for the offshore Trois Baies thrust fault, which include its proximity (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 2010 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, oppositely-dipping thrust 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) [*Mann et al.*, 1995; *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 entire 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 formation for the pull-apart basin along 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 carried out [*Higuera-Gundy et al.*, 1999] (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 cor-

relation between the paleoenvironmental 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 suggests that the paleodepositional environment influences

the acoustic properties of the sediments and sonar response may serve as a partial proxy

for climatic processes with the sediment layers from drier climates (higher E/P) having

stronger acoustic reflectivity and layers from wetter climates having weaker acoustic re-

flectivity. 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 dataset.

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,

or 248 years ago. Considering the historical earthquake record [*Bakun et al.*, 2012], the

dating of the core, and the sonar interpretation in Lake Miragoâne all indicate that the

most recent rupture in this lake is likely related to the historic earthquake of 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 geologic and geophysical studies

that we have compiled here 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 shown schematically in our three-dimensional block diagram (Figure 10).

Moving from Lake Azuey in the east to Lake Miragoâne in the west, the block diagram

illustrates the along-strike alternations in the dips observed in the dips of the thrust faults

that are oriented in an oblique and *en echelon* arrangement with the EPGFZ (Figure 10).

EPGFZ. Fold axes north of the EPGFZ range from 3 to 20 km in length, and are sig-

moidal in trend with respect to the trace of 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 5E and Figure 10), south-dipping on the Lamentin fault [*Saint Fleur et al.*,

538   2015] at 40°, north-dipping at 70° on the Léogâne fault active during the 2010 earth-

539   quake (A–A' in Figure 3, Figure 10), and south-dipping on the Trois Baies fault at 45°

540   (Figure 10).

541   South of the EPGFZ, transpressional folding in more rigid Cretaceous basalts and

542   overlying Eocene limestone have broader folding wavelengths from 1 to 8 km and exhibit

543   minor seismicity during and after the 2010 earthquake. In contrast, InSAR images of the

544   2010 earthquake indicate smaller folds and much more seismogenic deformation in the

545   10 – 15 km belt north of the EPGFZ. This deformational and seismogenic contrast north

546   and south of the EPGFZ is likely related to rock type with weaker, poorly-consolidated

547   sedimentary rocks up to several kilometers north of the EPGFZ and stronger, more con-

548   solidated Paleocene limestone and Cretaceous basalt exposed in the highlands south of the

549   EPGFZ [*Mann et al.*, 1991] (Figure 2).

550   We propose that the folds north of the EPGFZ formed originally as conjugate thrust

551   faults within a highly transpressional, tectonic setting indicated by GPS vectors [*Calais*

552   *et al.*, 2010]. Conjugate thrust faults are common in thick, clastic sedimentary basins un-

553   dergoing active, sub-horizontal shortening [*Sibson*, 2012], as documented in the M_w 7.6

554   Chi-Chi Taiwan earthquake in 1999 [*Chen et al.*, 2002] or the M_w 7.1 Kumamoto Japan

555   earthquake in 2016 [*Lin and Chiba*, 2017]. Aftershocks north of the EPGFZ reflect the

556   most recent phase of NE-SW shortening on the 70° dipping, conjugate reverse fault planes

557   [*Nettles and Hjörleifsdóttir*, 2010], of the deeply buried Léogâne thrust fault, as shown in

558   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

561   A similar pattern of transpression in a restraining bend setting to Haiti has been de-

562   scribed for 1989 M_w 6.9 Loma Prieta earthquake [*Marshall et al.*, 1991] (Figure 11). The

563   selected GPS vectors relative to a fixed North America plate [*UNAVCO (University Navstar*

564   *Consortium)*, 2009] indicate the transpressional setting within a gentle restraining bend

565   setting. In the inset map of Figure 11, the 1989 hypocentral area maps of aftershocks

566   [*Marshall et al.*, 1991] reveal the steep (~ 61°) dip of oblique-reverse faults of the collec-

567   tive Sargent and San Andreas faults. As observed during the 1989 earthquake, the south-

568   westward dip of the *en echelon* reverse faults produced coseismic uplift up to 0.55 m of

the lowland areas southwest of the San Andrea fault and depression by up to 0.1 m of the mountainous area to the northeast of the San Andreas fault [*Marshall et al.*, 1991]. The thrusting was blind with the M_w 7.1 earthquake not being accompanied by coseismic, surface breaks. The pattern of aftershocks (seen on the cross section in Figure 11) suggest a conjugate pair of reverse faults with the dominant motion on the south-dipping fault plane, similar to the conjugate pair seen on the cross section of the Léogâne fault as defined by its 2010 aftershocks (cross-section A–A' in Figure 3).

As in the 2010 M_w 7.0 Haiti earthquake on the previously unknown Léogâne thrust, a secondary, blind thrust fault [*Olson*, 1990] beneath the surface trace of the Sargent fault, 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 and *en echelon* thrust planes form smaller fault segments ranging in length from 3 to 11 km (Figure 2A), the 2010 Haiti 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]. *Bakun et al.* [2012] conclude that the earthquake recurrence cycle along the EPGFZ is about 250 years. Therefore, in the highly transpressional setting of Hispaniola, the earthquake cycle may consist of a complex alternation between ruptures on the EPGFZ and ruptures on the oblique, *en echelon* thrusts and related folds.

The 2010 M_w 7.0 earthquake released part of a centuries-long accumulation of stress in the region, but as the oblique thrusts may not be directly linked to the EPGFZ, it is likely 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 completely 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 250–500 m-wide 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 more deeply buried EPGFZ and more active Jimani thrust fault in Lake Azuey is identical to the epicentral area of the 2010 Haiti earthquake 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 Baies 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 Baies 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 10-15 km-wide, belt of late Holocene deformation in clastic basins north of the EPGFZ, with 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, 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 Baies thrusts, and strike-slip ruptures along the narrow and well defined main trace of the EPGFZ.

6. The presence of *en echelon* thrust faults north of the EPGFZ with spacings of 1–8 km and alternating dips are proposed to have formed as a conjugate thrust and reverse faults. The Léogâne thrust dips to the north along with the newly described Jimani thrust fault dip northeast while other faults like the Trois Baies and Lamartin thrust faults dip to the southwest.

7. 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].

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852 **Figure 1.   Tectonic setting of the northeastern Caribbean and Enriquillo-Plantain Garden fault zone**

853 **(EPGFZ) in southern Haiti. A:** Free-air gravity anomaly map of the Greater Antilles (Cuba, Jamaica, His-

854 paniola, Puerto Rico) in the northeastern Caribbean (http://topex.ucsd.edu) with gravity lows marking zones

855 of subduction or thrusting along major faults (black lines) of the North America-Caribbean plate boundary.

856 Arrows with error ellipses from *Calais et al.* [2010] are GPS vectors showing the direction and velocity

857 of the large North American plate, the Bahamas platform, and intervening microplates relative to a fixed

858 Caribbean plate. Microplates with variable relative motions occupy the 200 km-wide, transpressional, plate

859 boundary zone and include: **NHM** = North Hispaniola microplate; **HM** = Hispaniola microplate; **GM** =

860 Gonâve microplate; **PRVIM** = Puerto Rico-Virgin Islands microplate. Box shows more detailed map of the

861 EPGFZ shown in B. **B:** Regional structure map of the southern peninsula of Haiti with the active, left-lateral

862 Enriquillo-Plantain Garden fault zone (EPGFZ) from the Lake Enriquillo in the east to the western tip of the

863 southern peninsula. The centroid moment tensor (CMT) mechanism is from *Douilly et al.* [2013]. From east

864 to west, key lakes and marine embayments aligned parallel and overlying the EPGFZ include: **LE** = Lake

865 Enriquillo, Dominican Republic; **LA** = Lake Azuey, Haiti; **PAPB** = Port-au-Prince Bay; **CS** = Canal du Sud;

866 **TBF** = Trois Baies fault; and **LM** = Lake Miragoâne; **LF** = Léogâne fault. Boxes shows more detailed maps

867 of the structure of the EPGFZ and its secondary faults shown in Figure 2A and Figure 7A. **C:** Composite,

868 multichannel seismic reflection line (acquired by Canadian Superior Energy Inc.) located as the red line X-X'

869 in B that shows an unfolded area of high-angle faults in the Canal du Sud tied to the offshore Cul-de-Sac-1

870 well, the Trois Baies fault, the EPGFZ, the anticlinal structure of the southern peninsula, and a large, south-

871 verging accretionary prism along the south coast of the southern peninsula. The depth scale for this section is

872 in two-way, travel time.

873 **Figure 2.   Structure of the EPGFZ in eastern Haiti. A:** Faults and folds along a 15 km-wide corridor par-

874 allel to the EPGFZ superimposed on a modified DEM and InSAR surface deformation map (courtesy of Eric

875 Fielding at JPL) [*Hayes et al.*, 2010]. Chirp bathymetry of the Lake Azuey is also shown. GPS vectors are

876 from *Calais et al.* [2010]. **PFZ** = Port-au-Prince fault zone; **DFZ** = Dumay fault zone; **DT** = Dumay thrust;

877 **NaC** = Nan Cadastre thrust; **JFZ** = Jacquet fault zone; **GFZ** = Ganthier fault zone; **LF** = Léogâne fault. Line

878 A – A': Cross-section along the blind Léogâne thrust fault (shown in Figure 3); Line B – B': Cross-section of

879 north Port-au-Prince urban area (shown in Figure 3). **B:** Shaded DEM of the northern deformed belt in the

880 Cul-de-Sac basin with North-Eastern illumination from Figure 2A showing *en echelon* and curvilinear folds

881 striking west-northwest obliquely with respect to the EPGFZ and plunging beneath undeformed sediments

882 occupying the center of the Cul-de-Sac Valley. The inset schematic diagram of shearing along a strike-slip

883 fault is from *Odonne and Vialon* [1983].

884 **Figure 3. Style of late Neogene, transpressional deformation in the northern belt along two transects**

885 **shown in Figure 2. A-A':** Aftershocks of the 2010 earthquake [*Douilly et al.*, 2013, 2015] along the blind

886 Léogâne thrust fault reveals conjugate reverse faults with the dominant slip occurring on the north-dipping

887 fault. The red triangle indicates the location of Léogâne city. Coseismic uplift during the 2010 earthquake

888 elevated the northern basinal area and depressed the mountains south of the EPGFZ. **B-B':** Cross section

889 based on surface mapping [*Bachhuber et al.*, 2010; *Rathje et al.*, 2011; *Cox et al.*, 2011; *McHugh et al.*, 2011;

890 *Saint Fleur et al.*, 2015] showing both north- and south-dipping reverse faults deforming Plio-Pleistocene

891 sedimentary rocks.

892 **Figure 4. Geologic setting of Lake Azuey, Haiti. A:** To the south, the green-colored, brackish waters of

893 Lake Azuey are bound by the EPGFZ which forms a sharp boundary with 2 km-high, folded limestone of Pa-

894 leogene age that forms the smooth surfaces on the skyline. A fault strand of the EPGFZ marks the south edge

895 of Lake Azuey while other parallel strands of the EPGFZ underlie the southern part of the lake as schemat-

896 ically shown. **B:** To the north of the lake folded, Plio-Pleistocene strata form the uplifted, 0 – 30 m-high

897 isthmus that separates Lake Azuey (15 m ASL) from Lake Enriquillo (46 m BSL) located 1 km to the east.

898 Approximate locations of the EPGFZ and the Jimani thrust fault are shown.

899 **Figure 5. Chirp sonar profiles showing the trace of the EPGFZ in the southern part of Lake Azuey**

900 **and its relationship with a newly described thrust we have named the Jimani thrust.** Cross sections of

901 A, B, C, and D are indicated in Figure 2A. The EPGFZ beneath Lake Azuey forms a 250–500 m-wide zone

902 that can be traced as a lineament to the east and west of Lake Azuey (Figure 2). The green and red horizons

903 represent two distinguish stratigraphic layers. The two strands of the EPGFZ are buried by 0.7 m of Holocene

904 sediment and are extrapolated to be 270 years old since their last rupture when an average sedimentation rate

905 of 2.6 mm/yr based on cores from Lake Enriquillo is assumed. Folds associate with the Jimani thrust are

906 interpreted as fault propagation folds above northeast-dipping thrust faults. **E:** Cross section based on both

907 sonar survey and the surface mapping [*Mann et al.*, 1991] showing north- and south-dipping, reverse faults

908 deforming Plio-Pleistocene sedimentary rocks.

909 **Figure 6. Structure of the EPGFZ in eastern Haiti and western-most Dominican Republic. A:** Struc-

910 tural map of Lakes Azuey (surface 15 m ASL) and Lake Enriquillo (surface 46 m BSL) are presently sepa-

911 rated by a shallow sill 30 m ASL in the isthmus near the town of Jimani. **B:** Comparison of two Chirp lines

912 from Lake Enriquillo by *Rios et al.* [2013] (3 km-long Line L19) and from our study of Lake Azuey (4 km-

913 long Line B6). Chirp profiles from both lakes show similar sequences. Ages of units are known from Lake

914 Enriquillo through both exposures around the sub-sea level lake and from lake coring by *Rios et al.* [2013].

915   **Figure 7.**   **Structure and 2010 coseismic surface deformation of the western segments of the EPGFZ.**

916   **A:** Fault map [*Prentice et al.*, 2010; *Cowgill et al.*, 2012] and map of 2010 aftershocks [*Douilly et al.*, 2013]

917   in Miragoâne-Léogâne region overlain with an InSAR image (courtesy of Eric Fielding at JPL) [*Hayes et al.*,

918   2010]. **B:** Zoom of the area of Petit Goave and Lake Miragoâne showing the structure and bathymetry of the

919   14 km^2, pull-apart basin underlying Lake Miragoâne during this study and details of the 2010 surface frac-

920   turing and coseismic subsidence in the Petit Goâve Bay [*Prentice et al.*, 2010; *Hornbach et al.*, 2010]. **LM =**

921   Lake Miragoâne; **PG** = Petit Goâve.

922   **Figure 8.**   **Geologic setting and sonar profiles from Lake Miragoâne. A:** View looking south across

923   the 12 km-wide and 42.8 m deep, freshwater lake. The 2 km-high, ridge along the southern edge of the lake

924   is the cumulative topographic scarp associated with the southernmost strand of the EPGFZ. The 7 m-long

925   core was taken by *Higuera-Gundy et al.* [1999], but was not collected from the deepest part of the lake. **B:**

926   North-south trending line M1 (location shown on Figure 7B). **C:** East-west trending line M5 (location shown

927   on Figure 7B). In the lines shown in **B** and **C**, the strands of the EPGFZ are both buried by 0.5 m of sediment.

928   **Figure 9.**   **Core data from Lake Miragoâne. A:** Tie between chirp sonar and core with radiocarbon age

929   control back to 10,230 years BP. [*Higuera-Gundy et al.*, 1999] Cyclicity is related to changes in lithology

930   related to alternating wet and dry periods as shown. Yellow areas are shallow marine to freshwater and green

931   areas contain wood debris and may mark a period when the lake was dry. **B:** Low-pass filtered E/P log (red)

932   and the synthetic sonar profile generated from the low-pass filtered E/P log used as an acoustic impedance.

933   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 the southwest direction of the GPS vectors relative to the Caribbean plate [*Calais et al.*, 2010]. The 2010 InSAR-derived surface deformation map (provided by Eric Fielding at JPL) [*Hayes et al.*, 2010] shows a large component of shortening accommodated on a 40 km-wide zone of oblique thrusts and folds north of the EPGFZ. Aftershock pattern shown in the cross section show that the northeastward dip of the *en echelon*. Léogâne thrust adjacent to the EPGFZ uplifted the topographically-lower, basinal area to the north of the EPGFZ and depressed the mountainous area to the south of the EPGFZ. The alternating dip of the *en echelon* thrusts is related to their origin as conjugate thrust faults in a highly transpressional setting. **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 co-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 coseismic elevation change and aftershock cross-section are modified from *Marshall et al.* [1991]. **SAF**: San Andreas Fault; **SF**: Sargent Fault. Aftershock pattern in the cross-section shows that the southwest dip of the *en echelon* thrust adjacent to the San Andreas fault uplifted the topographically-lower basinal area and depressed the mountainous area to the northeast of the San Andreas fault.