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1 **Active tectonics along the Cul-de-Sac - Enriquillo trough and seismic hazard for Port-**
2 **au-Prince, Haiti**

3

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9

10 **Abstract-** The active faults in Haiti were not well known and no detailed mapping of active
11 fault traces was available before the 2010, M7.0 earthquake. The lack of detailed fault
12 mapping hindered the interpretation of the event and the seismic hazard assessment. Here,
13 using high-resolution LIDAR topography, aerial photographs, bathymetric charts, together
14 with geological data complemented with field observations, we carried out a morphotectonic
15 analysis at a variety of scales. We analyzed the drainage network at the northern front of the
16 Massif de la Selle – Sierra de Bahoruco (MSB) by mapping the fans of the main rivers and
17 their associated drainage basins. We found that the areas of all the fans were compatible with
18 the sizes of their drainage basins, except the paleofan of Port-au-Prince. We interpret that this
19 paleofan has been offset by 7.9 ± 0.3 km across the main strike-slip Enriquillo-Plantain Garden
20 Fault (EPGF) and we estimate a minimum horizontal slip rate of ~ 3 mm/yr over the
21 Pleistocene. Moreover, in the Cul-de-Sac – Enriquillo plain, within which the capital city of
22 Port-au-Prince is located, we mapped numerous NW-SE to WNW-ESE-striking Quaternary
23 folds and thrust faults. Some of the thrust faults are north-dipping and located to the southern
24 front of the Matheux-Neiba Lower Miocene fold. Other thrusts, such as those near Ganthier,
25 Jacquet, Nan Cadastre, and Port-au-Prince, are south-dipping and located along the northern

26 front of the MSB Lower Miocene fold. Previously, Saint Fleur *et al.* (2015) showed that the
27 2010 Haiti earthquake activated both one of the young thrusts (Lamentin) and the EPGF,
28 consistent with oblique convergence between the Caribbean and the North American plates.

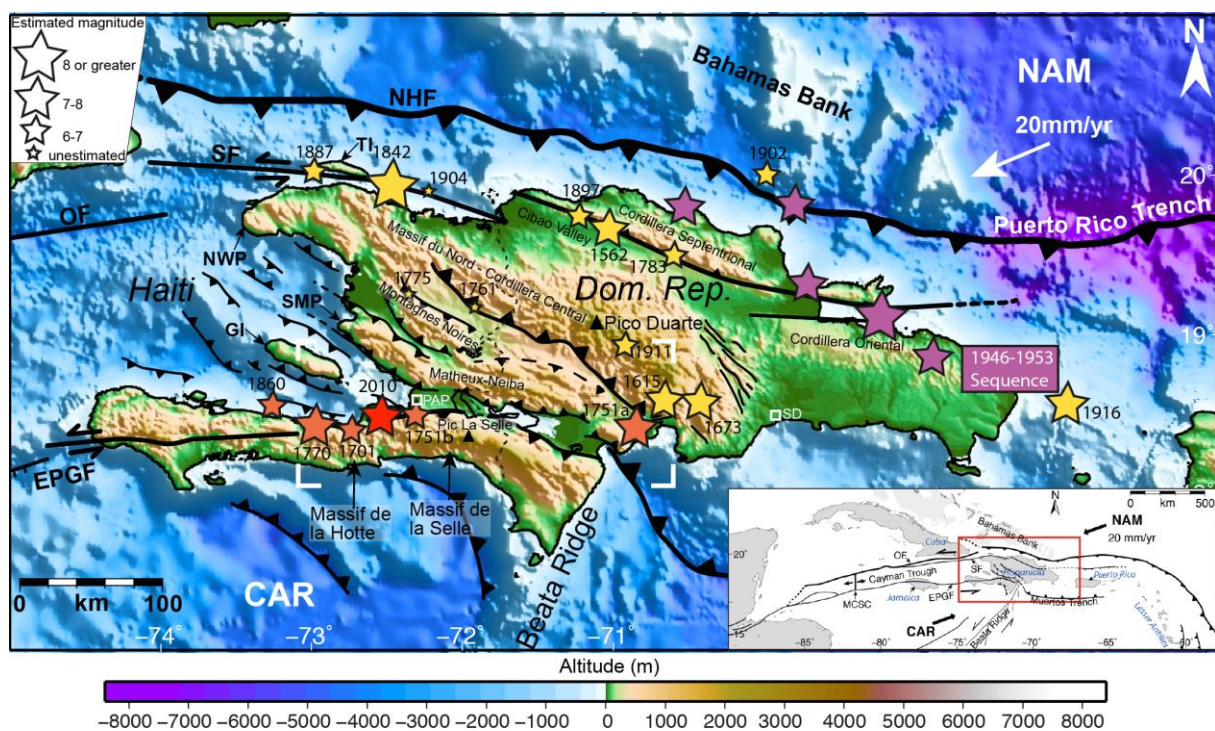
29 **1. Introduction**

30 The northern boundary of the Caribbean plate is curved between the Lesser Antilles
31 arc and Hispaniola (Fig. 1, inset). This curvature implies that the almost-frontal convergence
32 between the Caribbean and the North American plates at the Lesser Antilles becomes oblique
33 near Hispaniola [DeMets *et al.*, 2010; Sykes *et al.*, 1982]. At the longitude of Hispaniola, the
34 plate motion is partitioned between shortening and strike-slip faulting [Dolan *et al.*, 1998].
35 This shortening is accommodated by several folds and thrusts located in the central part of the
36 island and offshore [Pubellier *et al.*, 1991]. Onshore, the compression has produced mountain
37 ranges and valleys. The mountains reach 2680 m high (Pic La Selle) in the Massif de la Selle,
38 in Haiti, and ~3100 m high (Pico Duarte) in the Cordillera Central, in Dominican Republic
39 (Fig. 1). The folds in the central part of Hispaniola are situated in between two major, left-
40 lateral strike-slip faults, the Septentrional Fault (SF) to the north, and the Enriquillo-Plantain
41 Garden Fault (EPGF) to the south.

42

43 Based on GPS data, the short-term slip rate along the SF is estimated at 9 ± 2 mm/yr
44 [Benford *et al.*, 2012; Manaker *et al.*, 2008]. Geomorphic analysis and radiocarbon dating
45 suggest a similar longer term slip rate between 6 and 12 mm/yr over the last 5 kyr in central
46 Cibao Valley (Fig. 1) [Prentice *et al.*, 2003]. In the case of the EPGF, the geodetic slip rate
47 over ~10 years, is in the range of 4 to 12 mm/yr [Benford *et al.*, 2012; Calais *et al.*, 2010;
48 Dixon *et al.*, 1998; Mann *et al.*, 2002]. This large uncertainty is likely a result of the relatively
49 sparse GPS network in Haiti, especially for the earlier campaigns [Dixon *et al.*, 1998].

50 Thereafter, the slip rate was estimated at 6 ± 2 mm/yr [Symithe and Calais, 2016]. In addition
 51 to this left-lateral slip, 5.7 ± 1 mm/yr of shortening is estimated, using GPS data, in the
 52 vicinity of the EPGF. This shortening may be accommodated by the fold and thrust belt
 53 bordering the main strike-slip EPGF (Fig. 2) [Benford et al., 2012]. We interpret that the
 54 deformation is mainly compressional at the northern front of the Massif de la Selle and
 55 Bahoruco Mountains. Because ground shaking associated with thrust faults may be twice that
 56 associated with strike-slip faults, these compressional structures imply greater seismic hazard
 57 than previously recognized [Symithe and Calais, 2016].



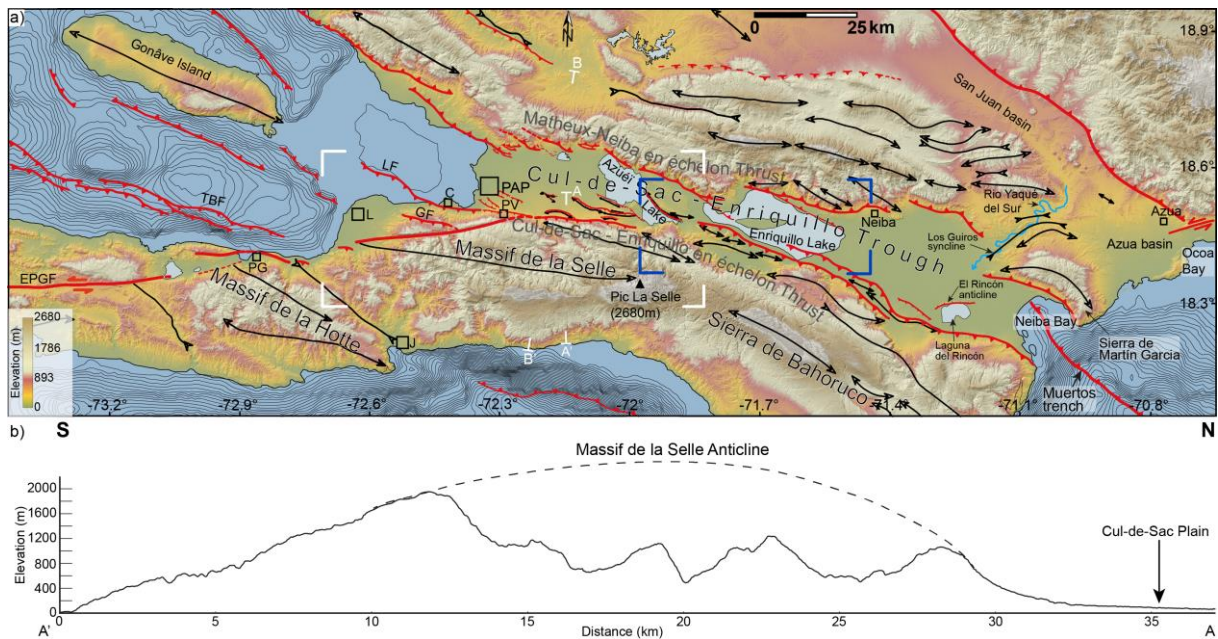
58
 59
 60 Figure 1: Tectonic setting and historical seismicity of Hispaniola. The hyper oblique convergence of 20 mm/yr
 61 (white arrow) between North American (NAM) and Caribbean (CAR) plates is partitioned into 1) two main
 62 strike-slip faults : the Septentrional Fault (SF) to the north and the Enriquillo-Plantain Garden Fault (EPGF) to
 63 the south; and 2) numerous thrust faults forming the Trans-Haitian Belt. This map is obtained using 1)
 64 bathymetric and topographic data: SRTM 30+ (pixel : 900 m) illuminated from the northeast; 2) bathymetric
 65 chart (1/25000) from the Service Hydrographique et Océanographique de la Marine (SHOM); 3) seismic profiles

66 from Mann *et al.* (1995); 4) LIDAR data (pixel 1 m), and 5) geological maps of Hispaniola [e.g., *Momplaisir*
67 *and Boisson*, 1988; *Toloczyki and Ramirez*, 1991]. The stars denote the historical seismicity. The northern and
68 central seismicity (yellow and purple) is from the NOAA database; and the southern seismicity (orange) is from
69 Bakun *et al.* [2012]. The 2010 earthquake is evidenced in red. The white box is the location of Fig. 2. OF :
70 Oriente Fault ; NHF : Northern Hispaniola Fault ; TI : Tortue Island ; NWP : Northwestern Peninsula ; SMP :
71 Saint-Marc Peninsula ; GI : Gonâve Island ; PAP : Port-au-Prince; SD : Santo Domingo. Inset : Tectonic setting
72 of the Northern Caribbean. Main tectonic structures are from Feuillet (2000). MCSC : Mid-Cayman Spreading
73 Center. The ~N70°E convergence direction between Caribbean and North American Plates is from Sykes *et al.*
74 (1982). The red box locates the main map.

75

76 Along the southern Haitian peninsula, historical earthquakes occurred (Fig. 1) in 1701,
77 1751 and 1770, causing severe damage in Port-au-Prince [*de St. Méry*, 1803]. On 8 April
78 1860, a tsunamigenic earthquake occurred in southern Haiti that produced waves observed at
79 Anse-à-Veau and Miragoâne [*Bakun et al.*, 2012]. Most earthquakes of the 18th century are
80 generally attributed to the EPGF [e.g., *Ali et al.*, 2008; *Bakun et al.*, 2012; *McCann*, 2006].
81 The 2010 earthquake occurred in the immediate vicinity of EPGF [e.g., *Saint Fleur et al.*,
82 2015; *Douilly et al.*, 2013; *Symithe et al.*, 2013], and included both strike-slip and reverse
83 motion. Most aftershocks were associated with thrust mechanisms [*Mercier de Lépinay et al.*,
84 [2011](#); *Nettles and Hjörleifsdóttir*, [2010](#)], which, along with coastal uplift indicate that this
85 earthquake activated a thrust fault along the southern peninsula, near Port-au-Prince [*Hayes et*
86 *al.*, 2010; *Calais et al.*, 2010; *Prentice et al.*, 2010]. Despite its large magnitude, no
87 significant surface rupture occurred along the EPGF [e.g., *Bilham*, 2010; *Lacassin et al.*,
88 2013; *Prentice et al.*, 2010]. For this study, we carried out a morphotectonic analysis in
89 southern Haiti for a better understanding of this earthquake and conducted detailed fault
90 mapping in the Cul-de-Sac – Enriquillo trough for future seismic hazard assessment in the
91 area. We conducted our fault mapping at several scales, using LIDAR topography (pixel 1 m),
92 aerial photographs (pixel 0.3 m), and bathymetric charts (scale: 1/25000), complemented with

93 field observations and local geological data. This is the first large scale seismotectonic map
 94 presented for southern Haiti. Finally, on the basis of our detailed fault mapping, we discuss
 95 the implications for seismic hazard near significant cities such as Port-au-Prince, Pétion-Ville,
 96 and Carrefour.
 97



98
 99 Figure 2: a) Tectonic map of southeastern Hispaniola. This map mainly evidences the Cul-de-Sac – Enriquillo
 100 trough bounded by two giant fold systems: the Matheux-Neiba and the Massif de la Selle-Sierra de Bahoruco
 101 folds. In the Cul-de-Sac – Enriquillo trough itself, numerous young folds are emerging and connected to the
 102 older Matheux-Neiba and to the Massif de la Selle-Sierra de Bahoruco fold systems. The folds and thrusts are
 103 oriented NW-SE to WNW-ESE. This orientation tends to be disturbed eastward. Fold axes are from Mann *et al.*
 104 (1991, 1995) and this study. White and blue boxes are locations of Fig. 3 and 6, respectively. AA' locates b); BB'
 105 locates Fig. 15b. Topographic data: ASTER (pixel 30 m); Bathymetric data: SRTM 30+ (pixel 900 m), isobaths
 106 are 100 m interval. EPGF: Enriquillo-Plantain Garden Fault; TBF: Trois-Baies Fault; LF: Lamentin Fault; GF:
 107 Gressier fault; L: Léogâne; J: Jacmel; PAP: Port-au-Prince; PV: Pétion-Ville; C: Carrefour; PG: Petit-Goâve. b)
 108 Topographic profile showing the Massif de la Selle Anticline. The two flanks of the anticline have different
 109 morphology. The northern flank is steeper.
 110

111 2. Overall tectonic setting of Southern Haiti

112 Using magnetic data, Pindell *et al.* (1988) suggested that the EPGF initiated in the
113 middle Eocene, propagating eastward from the Mid-Cayman Spreading Center (Fig. 1, inset).
114 The fault seems to have reached the southern peninsula of Haiti in Pliocene time, disrupting
115 Late Miocene terranes [*Calais and Mercier de Lépinay*, 1995; *Calmus*, 1983; *Calmus and*
116 *Vila*, 1988; *Cooper*, 1983; *Heubeck and Mann*, 1991a; b; *Mann et al.*, 1984; *Van Den*
117 *Berghe*, 1983; *van den Bold*, 1975]. The 1100 km-long EPGF crosses the southern peninsula
118 of Haiti in a N85°E direction.

119

120 The morphology of Hispaniola consists of several NW-SE to WNW-ESE subparallel
121 anticlines separated by several kilometer-wide valleys likely related to ramp basins [*Mann et*
122 *al.*, 1991]. One of the largest of these valleys is the Cul-de-Sac – Enriquillo plain or trough
123 (CSE) (Fig. 2a). This basin is bounded to the north by the N100-120°E, ~205 km long, ~25
124 km wide Matheux – Neiba en échelon thrust system and to the south by the N100-130°E,
125 ~180 km long, ~40-50 km wide Massif de la Selle - Sierra de Bahoruco (MSB) northward
126 verging Fold and thrust belt [*Saint Fleur et al.*, 2015] of Miocene age. The region is underlain
127 by Eocene to Miocene limestones that overlie a Campanian-Maastrichtian tholeiitic complex
128 (basalt). The Massif de la Selle anticline is asymmetric with a southern flank that is 12 km
129 wide and dips southward ~18° from 2000 m of elevation to sea level (Fig. 2b). This structural
130 surface is well preserved and only incised by small rivers. Consequently, along the southern
131 coast, the alluvial deposits are small and are only visible at large scale. The northern flank of
132 the anticline is steeper than the southern flank, with about ~800 m of relief over only 3 km.

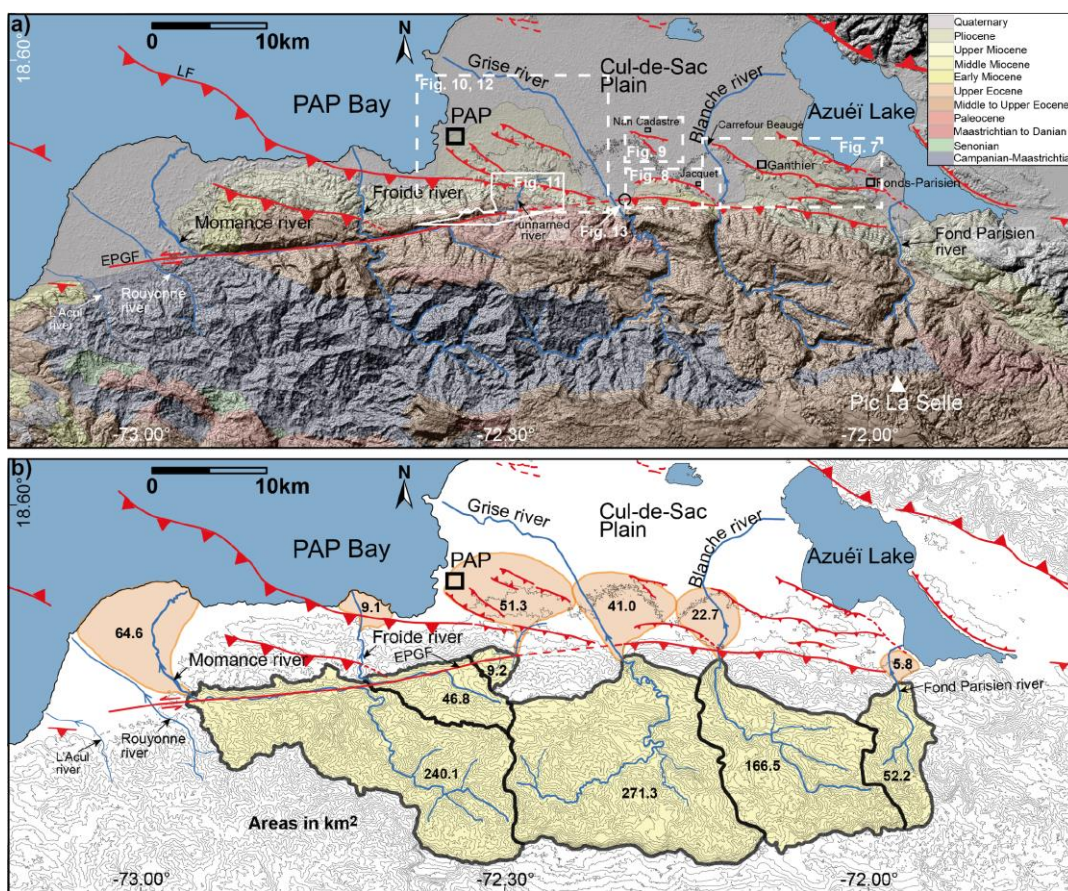
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136 **3. Drainage network analysis and offset of the EPGF in Port-au-Prince**

137 In contrast to the southern flank of the Massif de la Selle anticline, the northern flank
 138 is incised by a dense drainage network of significant north-flowing rivers (e.g., Momance
 139 river, Grise river) (Fig. 3a). These rivers flow either to the bay of Port-au-Prince or to Azuéli
 140 lake, and have deposited large alluvial fans along the northern piedmont of the Massif de la
 141 Selle. From east to west, these alluvial fans are mainly the fans of Fond Parisien, Blanche,
 142 Grise, Froide, and Momance rivers, and the Port-au-Prince fan.



155

156 Figure 3: a) The Cul-de-Sac Plio-Quaternary folds and thrusts that disturb the gentle topography of the plain.
 157 Topographic data: ASTER (pixel: 30 m). Contours are 50-m interval. The geological map overlain on the
 158 topographic data has been redrawn from the original map of Momplaisir and Boisson (1988). Note the locations
 159 of Fig. 7-12. PAP: Port-au-Prince; LF: Lamentin Fault. b) Map of the alluvial fans (shaded orange) of the
 160 northern piedmont of the Massif de la Selle, including the paleofan of Port-au-Prince, with respect to their
 161 related catchments or drainage basins (shaded yellow). On the map, the paleofan of Port-au-Prince, compared to

162 the other fans, is abnormally too big (~51.3 km²) with respect to its catchment (9.2 km²). The latter catchment
163 does not correspond to the one that should have generated the paleofan. This pattern may evidence the offset of
164 the paleofan by the Enriquillo-Plantain Garden Fault (EPGF). Values are areas in km². Once the mapping was
165 done, the area values were obtained using the measurement tools of ArcGIS. PAP: Port-au-Prince. Topographic
166 data: ASTER (pixel: 30 m); contours: 100-m interval.

167

168

169 The Grise river, which is about 60 km long, is the most prominent river that crosses
170 the Cul-de-Sac plain (Fig. 3). The river's source is in the Paleogene carbonates of the northern
171 flank of the Massif de la Selle anticline, and most of the drainage area is within the
172 Campanian-Maastrichtian basalt unit exposed at the crest of the anticline. The river meanders
173 over about half of its length, along its upstream and then flows in a roughly straight, ~N150°E
174 direction for ~12 km through the Cul-de-Sac plain. Finally, it changes course to N115±20°E
175 and bounds northern Port-au-Prince before flowing into the bay of Port-au-Prince. This
176 configuration suggests that the paleofan of Port-au-Prince creates sufficient topography to
177 force the Grise river to flow around it.

178 The drainage basin of Grise river has a total area of 271.3 km² and is the largest of the
179 Massif de la Selle. The southern boundary of the drainage basin is close to the geological
180 contact between the tholeiitic complex of the anticlinal crest and the Eocene limestone of the
181 southern flank of the anticline (Fig. 3). Immediately above the contact the limestone forms a
182 cliff that is 630 to 1070 m high (Supplementary Fig. S1) and more than 20 km long. The Grise
183 river fan is ~41 km² in area and is located where the river flows out of the Massif de la Selle
184 into the Cul-de-Sac plain (Fig. 3b).

185

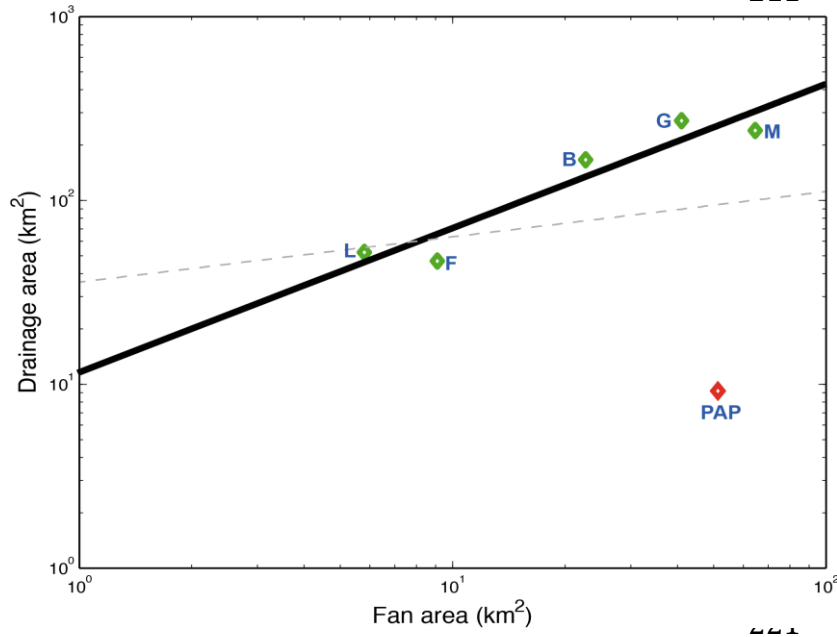
186 **3.1. Offset of the Paleofan of Port-au-Prince**

187 The densely populated city of Port-au-Prince (PaP) is located at the western edge of
188 the Cul-de-Sac plain. It is built on a paleofan, which we refer to as the PaP paleofan, and on

189 surrounding alluvial deposits. The EPGF is located immediately south of the PaP paleofan.
190 We identified an unnamed river that flows N80°E along the EPGF and abruptly changes
191 direction to N45°E at the apex of the PaP paleofan where it crosses the fault and flows along
192 the southeastern edge of the fan (Fig. 3 and 11). The source of the unnamed river is in the
193 Paleogene carbonate rocks of the northern flank of the Massif de la Selle and is fed by a small
194 catchment of 9.2 km².

195

196 Most of the large fans shown in Figure 3b correspond to large drainage basins,
197 consistent with numerous studies carried out in different climatic, lithologic and tectonic
198 contexts [e.g., *Bull*, 1962; *Bull*, 1977; *Fraser and DeCelles*, 1992; *Giles*, 2010; *Guérit*, 2014;
199 *Harvey*, 1997; *Mather et al.*, 2000; *Weissmann and Fogg*, 1999; *Whipple and Trayler*, 1996].
200 However, an exception is the large PaP paleofan (51.3 km²), which is situated in front of the
201 small catchment (9.2 km²) of the unnamed river. Following Bull [1962; 1977], we plot our
202 drainage areas as a function of their associated fan areas (Fig. 4). The PaP paleofan is clearly
203 an outlier, and we therefore exclude it in our initial analysis. The five points (in green) are
204 well correlated (black heavy line). In this case, the PaP paleofan, shown in red, plots
205 significantly below the trend. When we include it in the fit (grey dotted line), the five green
206 points are less well correlated because the fit is influenced by the paleofan. But, the PaP
207 paleofan still does not lie near the trend. Thus, we conclude that the drainage basin of the
208 unnamed river that is currently in front of the paleofan is too small be the original source of
209 this fan. We propose that the Grise river, because of its size and location, is the original source
210 of the paleofan, and that the PaP paleofan has been left-laterally offset across the EPGF.

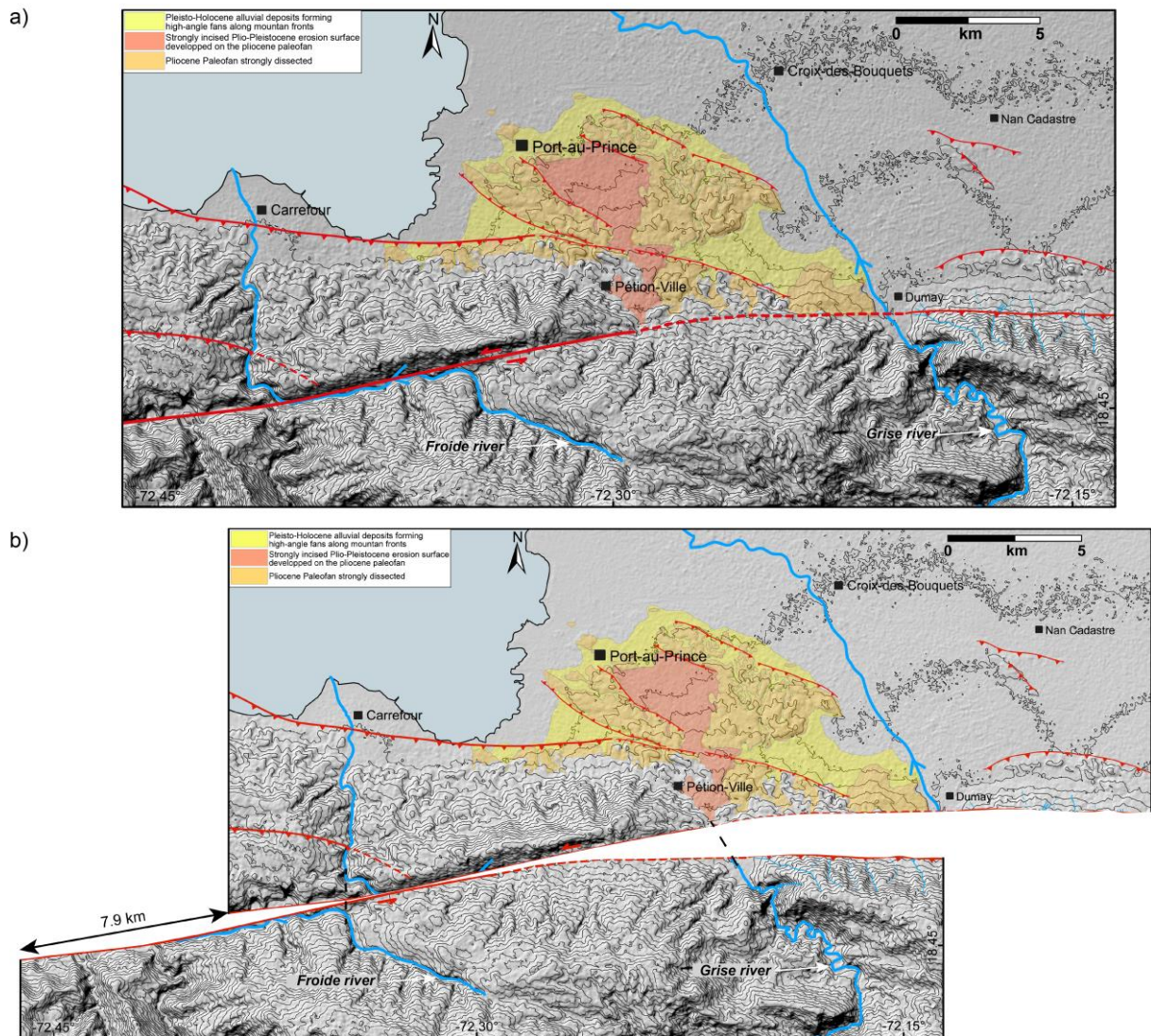


222 Figure 4: Plot showing correlation between fan areas and drainage areas. The green points are for the fans that
 223 relatively follow the correlation. The Port-au-Prince paleofan (red point) does not follow the correlation law
 224 between its present-day area and its drainage area. The black heavy line is the regression line for the five green
 225 points alone. The grey dotted line is the regression line when the paleofan of Port-au-Prince is included in the fit.
 226 In both cases, the paleofan is out of the tendency. L: the fan of Lèwòch river or Fond Parisien river; B: the fan of
 227 Blanche river; G: the fan of Grise river; PAP: Port-au-Prince paleofan; F: the fan of Froide river; M: the fan of
 228 Momance river.

229 3.1.2.- Tectonic reconstruction of the paleofan of Port-au-Prince

230 In order to estimate the amount of offset, we first overlay the detailed geological map
 231 of Port-au-Prince area [[Cox et al., 2011](#)] on a shaded ASTER DEM (pixel: 30 m) (Fig. 5a).
 232 We then reconstruct the paleofan by moving it eastward with respect to the EPGF in order to
 233 estimate its original position in front of the present-day Grise river. Between Pétion-Ville and
 234 Dumay (western bank of Grise river), the EPGF trace is poorly expressed geomorphically. A
 235 fault zone is exposed near Dumay in the eastern bank of Grise river where several of the
 236 exposed fault strands have a component of reverse displacement (Fig. 13). We refer to these
 237 reverse faults as the Dumay Fault zone, and suggest that it may be independent of the EPGF.

238 If this interpretation is correct, and the EPGF continues eastward with the same azimuth as in
239 the Léogâne – Pétion-Ville section, we estimate that the paleofan is offset 9 ± 0.5 km
240 (Supplementary S2). We estimate the uncertainty based on the sweep angle of the river. In the
241 past, the river could have flowed along the eastern edge of the valley, yielding a maximum
242 offset of 9.5 km, or along the western rim, yielding a minimum offset of 8.5 km. If, instead of
243 projecting the EPGF N80°E from Pétion-Ville we project it to the exposure of the Dumay
244 Fault in the eastern cutbank of the Grise river, we find the same offset of 9 ± 0.5 km
245 (Supplementary S2). For these two scenarios, we projected the upstream course of the Grise
246 river to the apex of the reconstructed paleofan perpendicular to the fault trace. An alternative
247 reconstruction is to use the overall NW-SE orientation of the Grise river to project the river to
248 the apex of the paleofan. In this case, using the same sweep angle criterion, we obtained a
249 maximum offset of 8.2 km and a minimum one of 7.6 km by projecting the eastern and the
250 western edges of the Grise river valley, respectively, to the apex of the paleofan. If instead, we
251 use the orientation of the present-day active riverbed to project the river to the apex of the
252 paleofan (Fig. 5b), we find an offset of 7.9 km. Because the 7.9 km reconstruction also brings
253 the offset Froide river into alignment, we consider 7.9 km to be our best solution (Fig. 5).
254



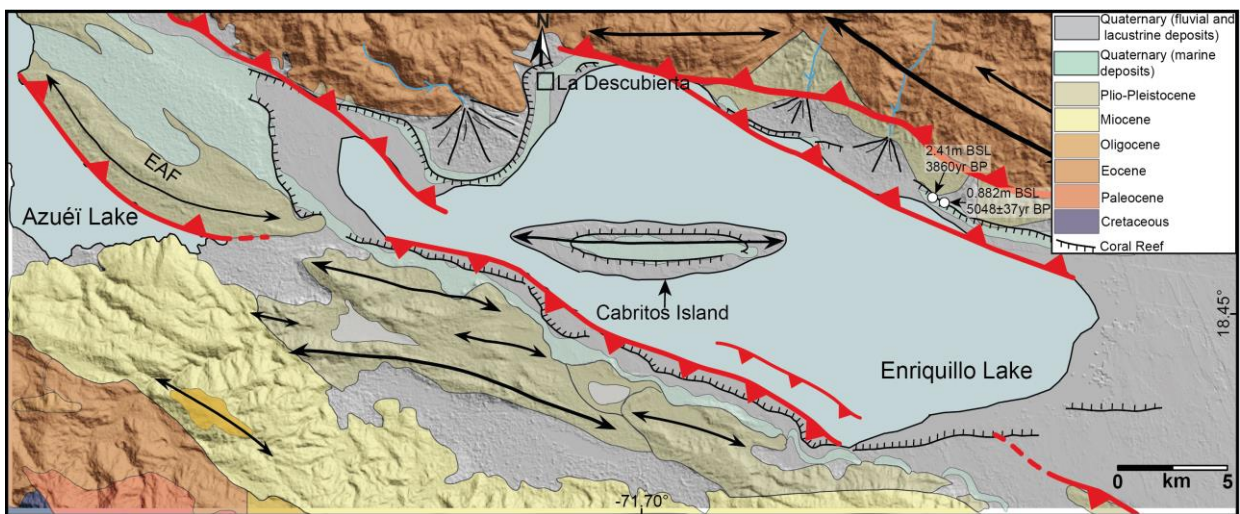
255 Figure 5: a) The paleofan of Port-au-Prince between Froide and Grise rivers. The Grise river is, by its position,
 256 the best candidate to have generated the paleofan. Topographic data: ASTER (pixel: 30 m). Contours are 50 m
 257 interval. Geological information is from Cox *et al.* (2011). b) Tectonic reconstruction of the paleofan of Port-au-
 258 Prince. The paleofan has been displaced by 7.9 ± 0.3 km (see text for discussion). This reconstruction also enables
 259 us to reconstruct the course of the Froide river.

260

261 4. Active thrusting in the Cul-de-Sac – Enriquillo plain

262 The CSE is a set of basins that encompasses the Cul-de-Sac plain and the Enriquillo
 263 valley. The CSE is separated from the Azua basin by the Sierra de Martín Garcia (Fig. 2a).
 264 The entire CSE extends from the bay of Port-au-Prince to the bay of Neiba. It is 135 km long
 265 and up to 25 km wide and bounded by mountains to the north and south.

266 The CSE plain is relatively flat (no higher than a few tens of meters) and is underlain
 267 by Pliocene-Quaternary fluvial and marine sediments [Mann *et al.*, 1991; Taylor *et al.*, 1985].
 268 Near the southern edge of the CSE is a series of ~N115°E elongate low hills that are underlain
 269 by folded sediments and have been interpreted as being the surface expression of young
 270 anticlines (Fig. 6) (Briggs *et al.*, 2012; This study). The flat topography of the CSE is thus
 271 disturbed by active folding mostly associated with blind thrust faults.
 272



273 Figure 6: Morphotectonic map of the Enriquillo Lake area revisited from Mann *et al.* (1995). The lake is
 274 bounded by Plio-Quaternary folds and coral reefs. White-filled circles are uplifted coral reefs sampled and dated
 275 by Taylor *et al.* (1985) and Mann *et al.* (1995). Topographic data: ASTER (pixel: 30 m); geologic contacts are
 276 redrawn from the 1/250000 geological maps of Haiti and Dominican Republic [Toloczyki and Ramirez, 1991].
 277 EAF: Eastern Azuéli Fold.

278

279 4.1. The area of the Enriquillo Lake

280

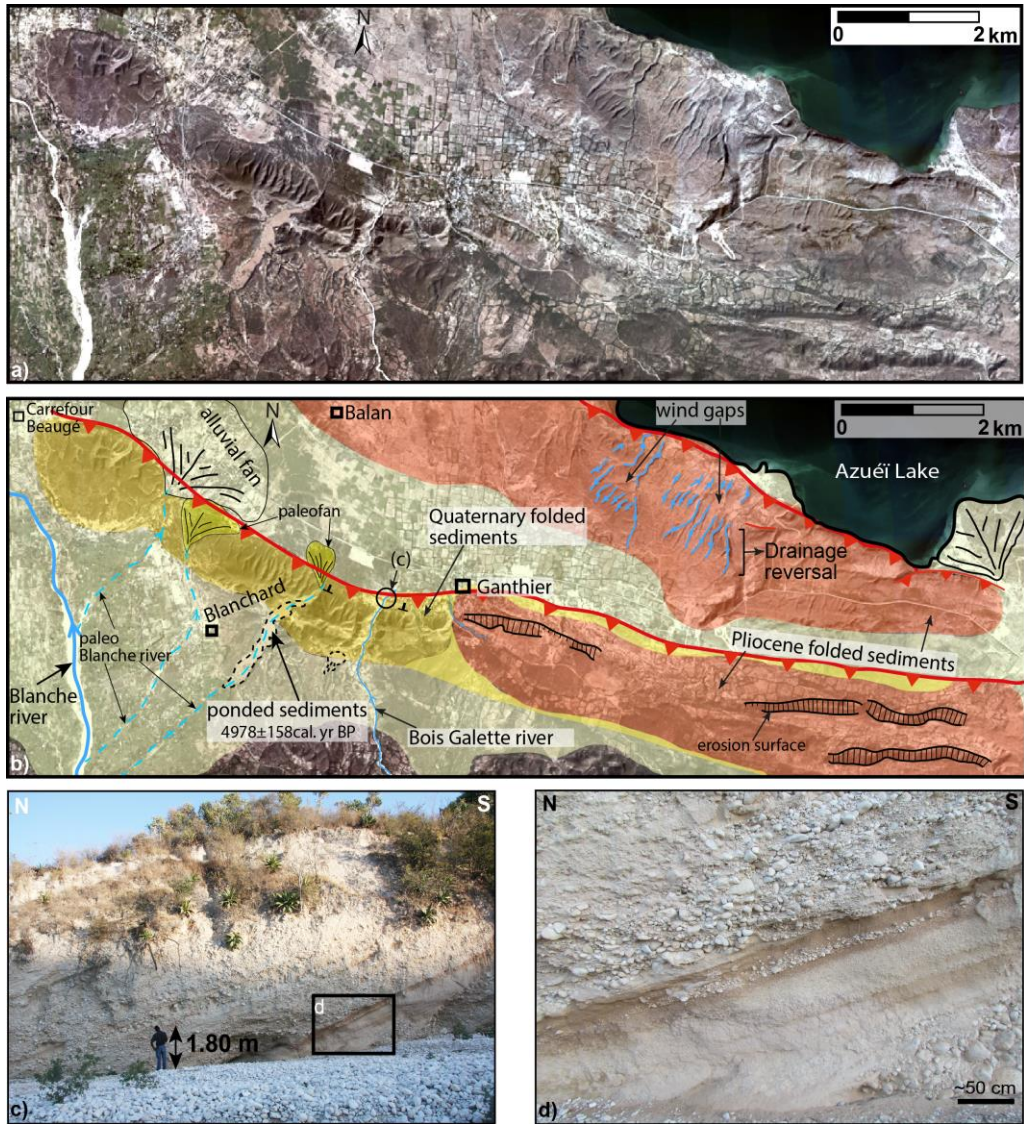
281 Enriquillo Lake lies within the Enriquillo Valley in the eastern part of the CSE. The
 282 lake is ~40 km long and ~12 km wide, with its long axis oriented N105°E (Fig. 6). The lake is
 283 below sea level (-42 m), and this part of the CSE experienced a marine transgression about 10

284 kyr ago [*Taylor et al.*, 1985]. The E-W-striking, ~12 km long and less than 2 km wide
285 Cabritos Island lies in the middle of the lake. This elongate island is bordered by fossil coral
286 reefs that are uplifted, probably due to active folding [*Mann et al.*, 1995]. Mobil multichannel
287 seismic data acquired to the east of Cabritos Island show that the lacustrine sediments are
288 folded, indicating that the Cabritos anticline continues below the lake [*Mann et al.*, 1995].
289 Fossil Holocene coral reefs were also identified and mapped around the periphery of the lake,
290 and record Holocene eustatic variations of sea level [*Mann et al.*, 1995; *Taylor et al.*, 1985].
291 Fossil reefs are uplifted in two locations (Fig. 6) and indicate uplift at a rate of 0.5 mm/yr over
292 the last ~5 kyr [*Mann et al.*, 1995]. To the west of Enriquillo Lake, we observe an arc-shaped
293 fold (Fig. 6). This fold, which we call the Eastern Azu ei Fold (EAF), appears to control the
294 morphology of the eastern border of Azu ei Lake, which is oriented ~N135 E, ~25 km long
295 and up to 10 km wide. The fold is oriented N120   15 E (Fig. 6) and deforms Plio-Quaternary
296 fluvial, lacustrine, and marine deposits. The fold is ~15 km long, ~7 km wide and up to 185 m
297 high above sea level between the Azu ei and Enriquillo lakes (Supplementary Fig. S3).

298

299 In this area, additional young folds and thrusts are found along the northern margin of
300 the Sierra de Bahoruco [*Mann et al.*, 1991; and detailed mapping in this study], and in the
301 Cul-de-Sac plain along the northern margin of the Massif de la Selle (Fig. 7).

302



321

322 Figure 7: a) and b) Aerial photograph (pixel: 30 cm resized into 15 m) and interpretation of the Ganthier Fold
 323 area showing two distinct parts: a western one (dark yellow) exhibiting a youthful morphology and an eroded
 324 older eastern one (orange). Dating of the ponded sediments is from Briggs *et al.* (2012). The activity of the fold
 325 appears to have diverted the Blanche river several times. Note also the Balan Fold to the north along the western
 326 border of the Azuéli Lake. c) and d) Field photographs of the eastern wall of the Bois Galette river showing the
 327 folded interbedded lacustrine and fluvial deposits (see (b) for location). In this area, the layers dip ~33° to the
 328 north.

329

330

331 4.2.- Ganthier and Balan Folds and Thrusts

332

333 The ~N115°E Ganthier fold zone is one of the most significant folds in the Cul-de-Sac
334 plain. It is ~15-km long, 1-2 km wide and ~200 m high. It extends between Carrefour Beaugé
335 and Fonds-Parisien (Fig. 3 and 7). Figure 7a is a mosaic of aerial photographs (pixel: 30 cm
336 resized into 15 m) showing the Ganthier fold zone incised by rivers and gullies. The eastern
337 part of the fold zone exposes Pliocene marine marly sediments and the western part exposes
338 tilted Quaternary fluvial sediments (Fig. 7b, 7c and 7d). In the eastern part, the Pliocene marl
339 is exposed and eroded at the top of the fold. The Quaternary sediments are exposed along the
340 flanks of the fold and are less eroded. The fold zone is crosscut by a series of north-flowing
341 rivers, including the Bois Galette river (18.528840°/-72.078400°). In the field, we observed
342 that this river, where it crosses the fold, is incised into unconsolidated, interbedded
343 conglomerates and fine sediments oriented N138°E and dipping 33°N (Fig. 7c, d). In an
344 unnamed drainage about 2 km west of Ganthier (and ~1 km west of Bois Galette), charcoal
345 from a 10 m-thick section of interbedded fluvial and ponded lacustrine sediments yielded a
346 calibrated radiocarbon age of 4978 ± 158 cal. yr B.P. [Briggs *et al.*, 2012].

347

348 North of the Ganthier fold zone, we observe that the plain adjacent to the fold is
349 “wrinkly” over a ~10 km-long, ~2 km-wide band (Fig. 7a, b). This subtle topography is
350 characterized by numerous dry incisions along the western shore of the Azuëi Lake. The
351 incisions may be due to intermittent streams and thus have water when it rains. Following the
352 slopes, some of the channels flow northeastward into the Azuëi Lake, others flow
353 southwestward into the plain. We remark that each northeast-flowing drainage faces a
354 southwest-flowing one. These drainages might have used to flow one side (northeastward).
355 And by tectonic uplift, the upstream might be cut from its downstream and now flow to the

356 opposite sense (southwestward). This drainage reversal leaves wind gaps between the two
357 branches. Thus, the whole topographic “band” undergoes active folding (the Balan Fold). The
358 described mechanism corresponds to a classical effect of anticlinal folding as studied
359 elsewhere [e.g., *Hubert-Ferrari et al.*, 2007].

360

361

362 **4.3.- Jacquet Fold and Thrust**

363

364 On the LIDAR data we see that the topography of the Cul-de-Sac plain is disturbed by
365 the Jacquet arc-shaped fold (Fig. 8a). The fold is oriented $N105\pm 20^\circ E$. It is ~7 km long, 0.1-
366 1.5 km wide and up to 260 m high. The width and the altitude of the Jacquet Fold decrease
367 westward. This fold has a morphology similar to the other young folds in the Cul-de-Sac
368 alluvial plain, and dipping Upper Miocene limestone beds are exposed in the eastern part of
369 the fold (Fig. 8b). In the central part of the fold we mapped ponded sediments and several
370 active, entrenched channels associated with alluvial terraces, suggesting Late Quaternary
371 folding.

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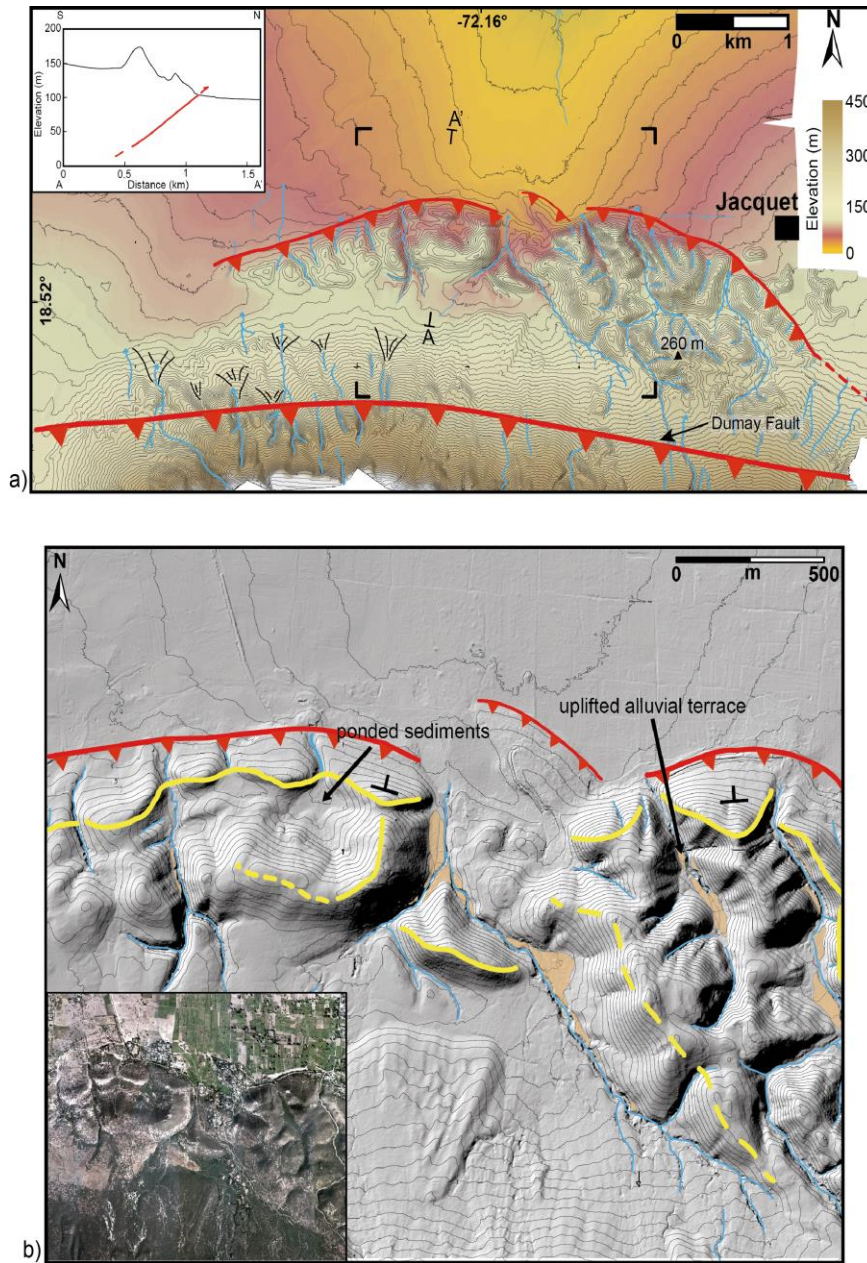


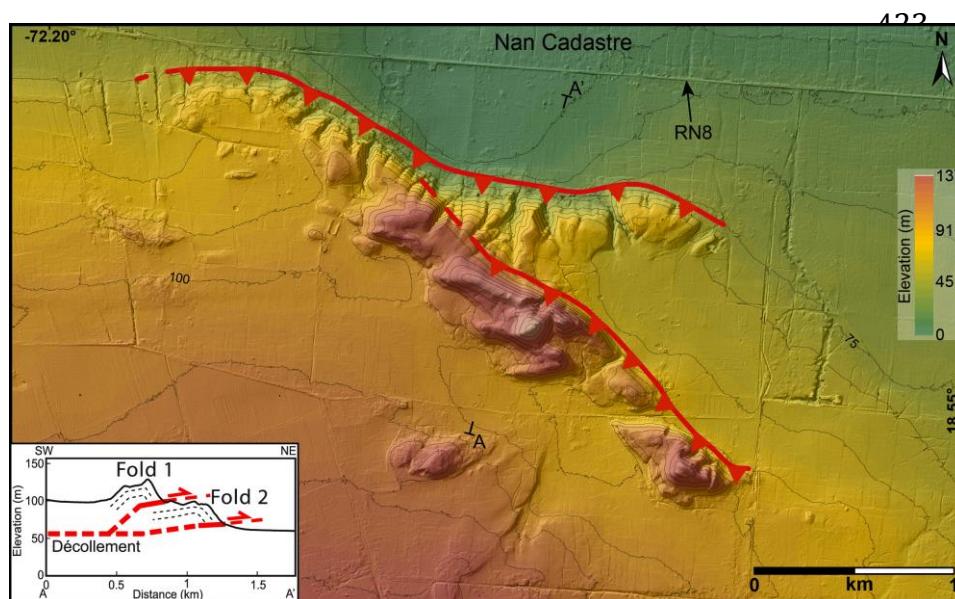
Figure 8: a) LIDAR (pixel: 1 m) topographic map of the Jacquet fold. Black box is the location of b). Inset shows a topographic profile (AA') across the fold zone. The value of the fault dip is arbitrary. b) Zoom showing numerous entrenched streams in the fold. Orange shaded areas are alluvial terraces. Contours are 5 m interval. Yellow lines are Upper Miocene beds. Inset: the same area on aerial photograph (pixel: 30 cm) offering a better resolution for the observation of the Upper Miocene outcrops.

408 **4.4.- Nan Cadastre Fold and Thrust**

409

410 We used the high-resolution LiDAR DEM to map another young fold that we refer to
411 as the Nan Cadastre Fold [*Saint Fleur et al., 2015*] (Fig. 9 and S4). It is located in the center
412 of the Cul-de-Sac plain, between Grise river (west) and Blanche river (east) and bounded to
413 the north by the Nan Cadastre Village (Fig. 9). The area is characterized by low hills ~80 m
414 high. The Nan Cadastre Fold is among the smallest fold zones in the Cul-de-Sac plain. It is ~4
415 km long and 0.5-1 km wide. It is also located ~5 km from the Ganthier Fold and may
416 prolongate it west-northwestward. The fold zone is divided into 2 main branches: a northern
417 one and a southern one underlain by folds oriented N110-115°E and N130°E, respectively. We
418 interpret that the folds are related to an emergent thrust ramp rooted on a south-dipping, low-
419 angle, shallow décollement which splays from the master high-angle ramp located under the
420 higher relief of the Massif de la Selle – Sierra de Bahoruco anticline (Fig. 9, inset) [*Saint*
421 *Fleur et al., 2015*].

422



433 Figure 9: The area of the Nan Cadastre Fold. LIDAR (pixel: 1 m) of the area showing that the fold deforms the
434 northern front of the fan of Grise river. RN8: National Road # 8. Contours are 5 m interval. Inset is a SW-NE

435 topographic profile (AA') showing the morphology of the two branches of the fold and our interpretation of the
436 geometry of the associated thrusts (see text for details).

437

438 **4.5.- Thrusting of the paleofan of Port-au-Prince**

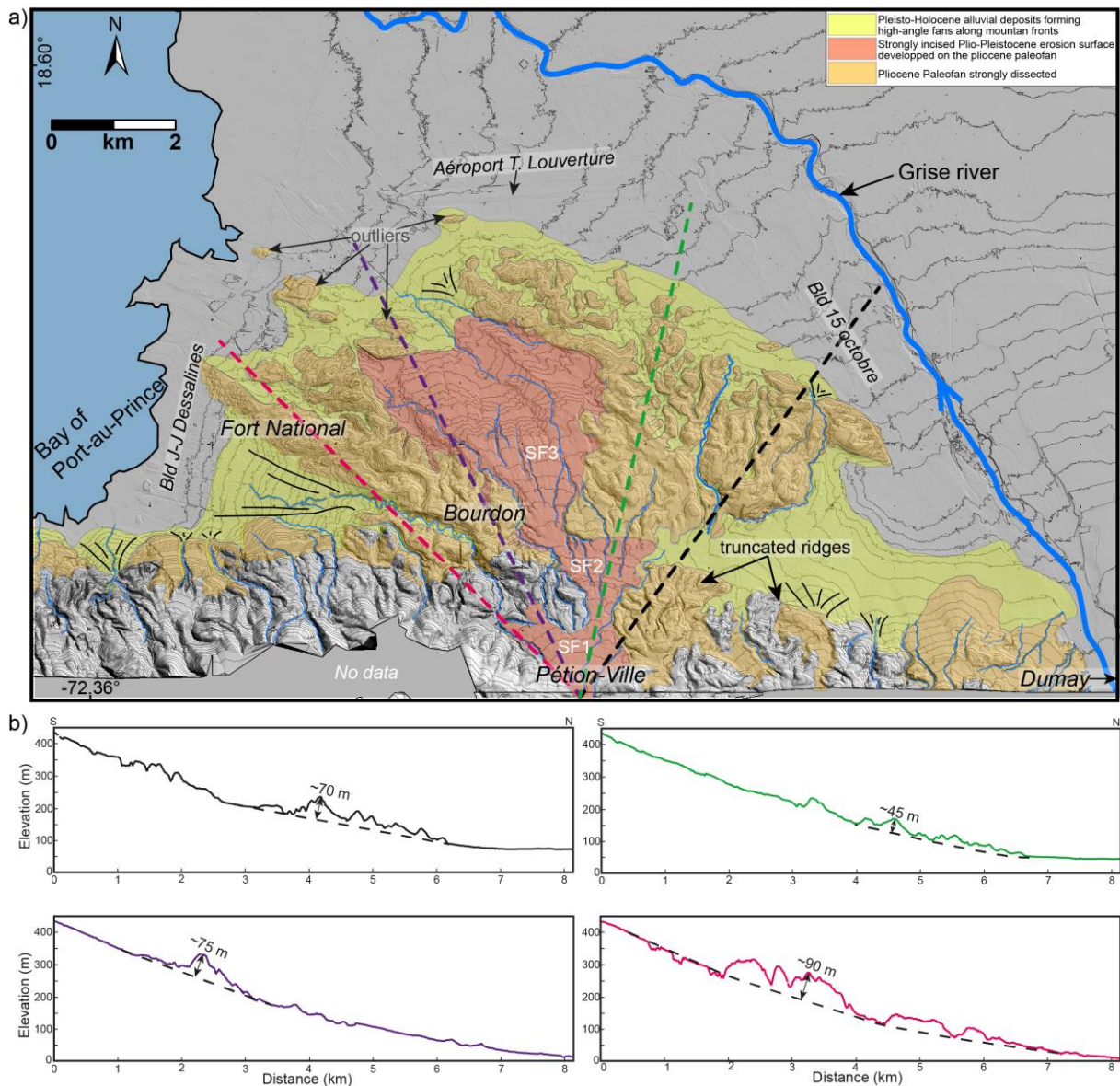
439

440 The PaP paleofan spans from Pétion-Ville (south) to the Aéroport Toussaint
441 Louverture (north), and from Boulevard Jean-Jacques Dessalines (west) to Boulevard 15
442 octobre (east) (Fig. 10a). Within the fan are two parallel, 5-6 km long, 1-3 km wide, N125°E
443 elongate hill ranges underlain by Pliocene fanglomerates. The hills are deeply eroded and
444 incised by numerous streams and rills and reach elevation of ~300 m. The hills are about 50-
445 100 m higher than the adjacent areas of the paleofan, which are Quaternary in age [[Cox et al.,](#)
446 [2011](#)] (Fig. 10b).

447

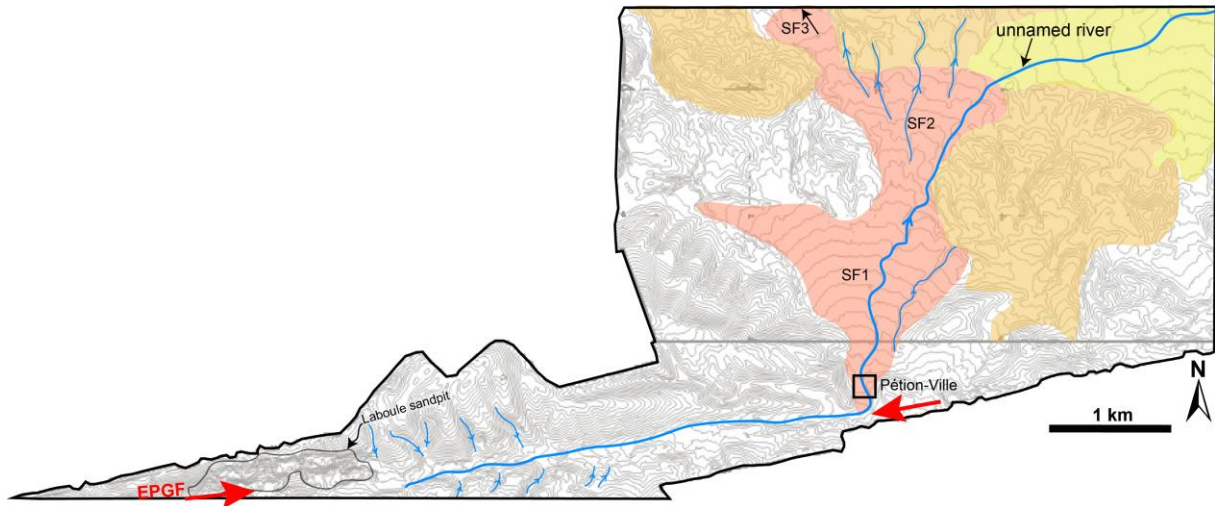
448 In the middle of the paleofan, between the two Pliocene hill ranges, Cox *et al.*, (2011)
449 mapped a Plio-Pleistocene erosion surface that we interpret as an inset alluvial fan (Fig. 10a).
450 This Plio-Pleistocene alluvial fan continues to the south until the apex of the overall paleofan.
451 This inset fan is less eroded and less deeply incised than are the Pliocene hill ranges,
452 supporting the interpretation that it is younger. Furthermore, the fact that the Plio-Pleistocene
453 fan does not continue until the northern front of the Pliocene deposits may suggest that they
454 were not emplaced simultaneously. Also, the Plio-Pleistocene fan is developed on the
455 Pliocene paleofan, thus it is not the result of progradation of the whole paleofan. We divide
456 the Plio-Pleistocene surface into three sub-fans: a southernmost one (SF1) in the town of
457 Pétion-Ville, a central one (SF2), and a northern one (SF3) (Fig. 10a and 11). The
458 southernmost sub-fan, SF1 is about 1-km long and up to ~2 km wide. It abuts against Mio-
459 Pliocene rocks and only extends to the north within a relatively narrow space of ~0.4 km wide

460 between the Mio-Pliocene rocks to the west and a vestige of the Pliocene paleofan to the east.
461 At this place, SF1 is deeply incised, suggesting that the stream was forced to flow through this
462 narrow gap. At the same time, the middle of the pre-mentioned narrow space corresponds to
463 the apex of the central sub-fan, SF2. SF2 is ~1.6 km long and up to ~1.3 km wide and is more
464 incised than SF1. SF2 abuts against the southwestern edge of the eastern Pliocene hill range
465 and continues to the west along a narrow space of ~0.7 km wide. Similarly to SF2, the middle
466 of the latter narrow space acts as the apex of SF3. SF3 has about the same degree of incision
467 as SF2, and is ~2.2 km long and up to ~3 km wide.
468



469 Figure 10: a) Geologic map of the paleofan of Port-au-Prince. The paleofan is mainly made of an eroded
 470 Pliocene alluvial sediment layer on which are deposited younger alluvial fans (e.g., Plio-Pleistocene). The
 471 geologic contacts are modified from Cox *et al.* (2011). Topographic contour interval is 10 m. Topographic data:
 472 LIDAR (pixel: 1 m). b) Radial topographic profiles on the paleofan showing that the latter may have been
 473 uplifted by several tens of meters. Vertical exaggeration: 5. The colors of topographic profiles are the same as the
 474 lines locating them in a).

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480 Figure 11: Geomorphic relationship between the unnamed river mapped on Fig. 3 and the EPGF. The river is
 481 controlled by the EPGF and flows eastward along the fault trace and bends northward from the apex of PaP
 482 paleofan (near Pétion-Ville). The geologic information is the same as in Fig. 10. Topographic contour interval is
 483 10 m. Topographic data: LIDAR (pixel: 1 m).
 484

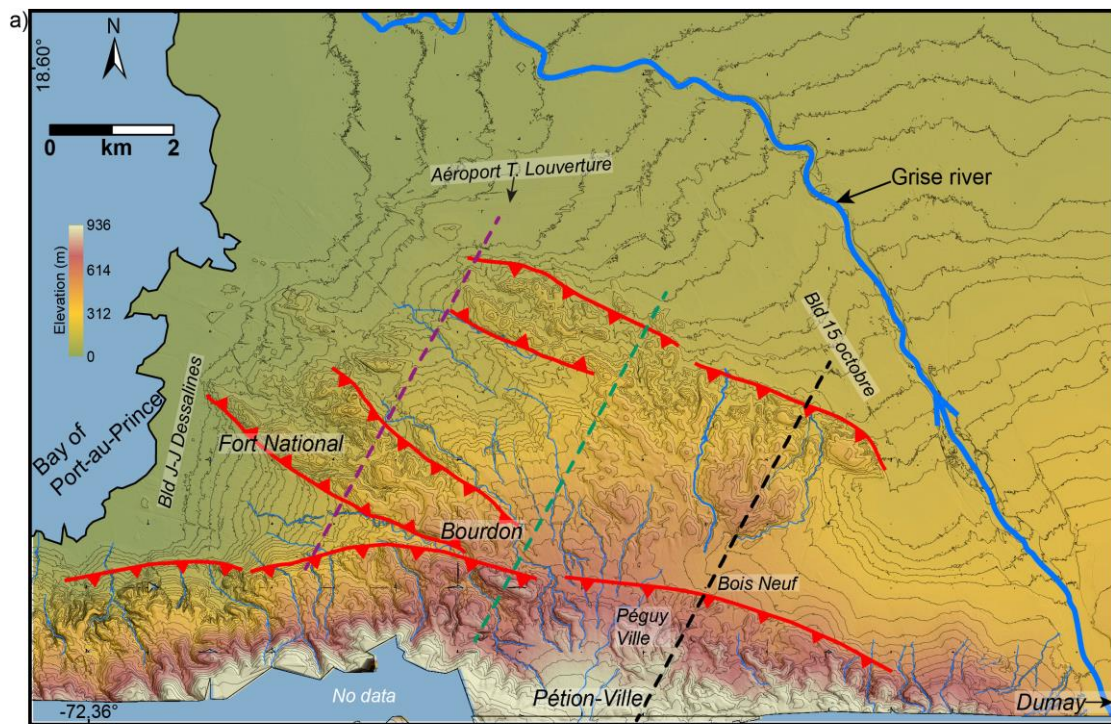
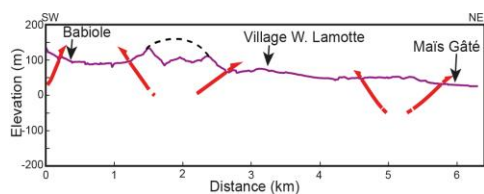
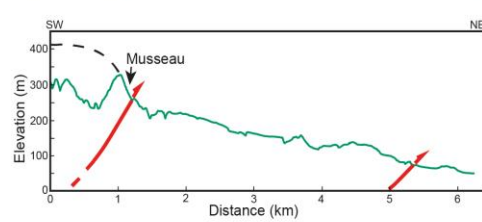
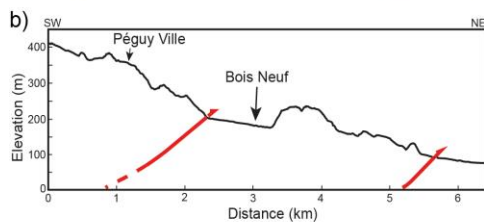


Figure 12:
 a) Fault map in



Port-au-Prince sho

502 wing multiple faults across the paleofan of Port-au-Prince. Topographic contours are 10 m interval. Topographic
503 data: LIDAR (pixel: 1 m). b) Topographic profiles on the paleofan showing the morphology of the structures.
504 Vertical exaggeration: 5. Note that the faults crosscut several significant neighborhoods of Port-au-Prince. The
505 colors of topographic profiles are the same as the lines locating them in a).

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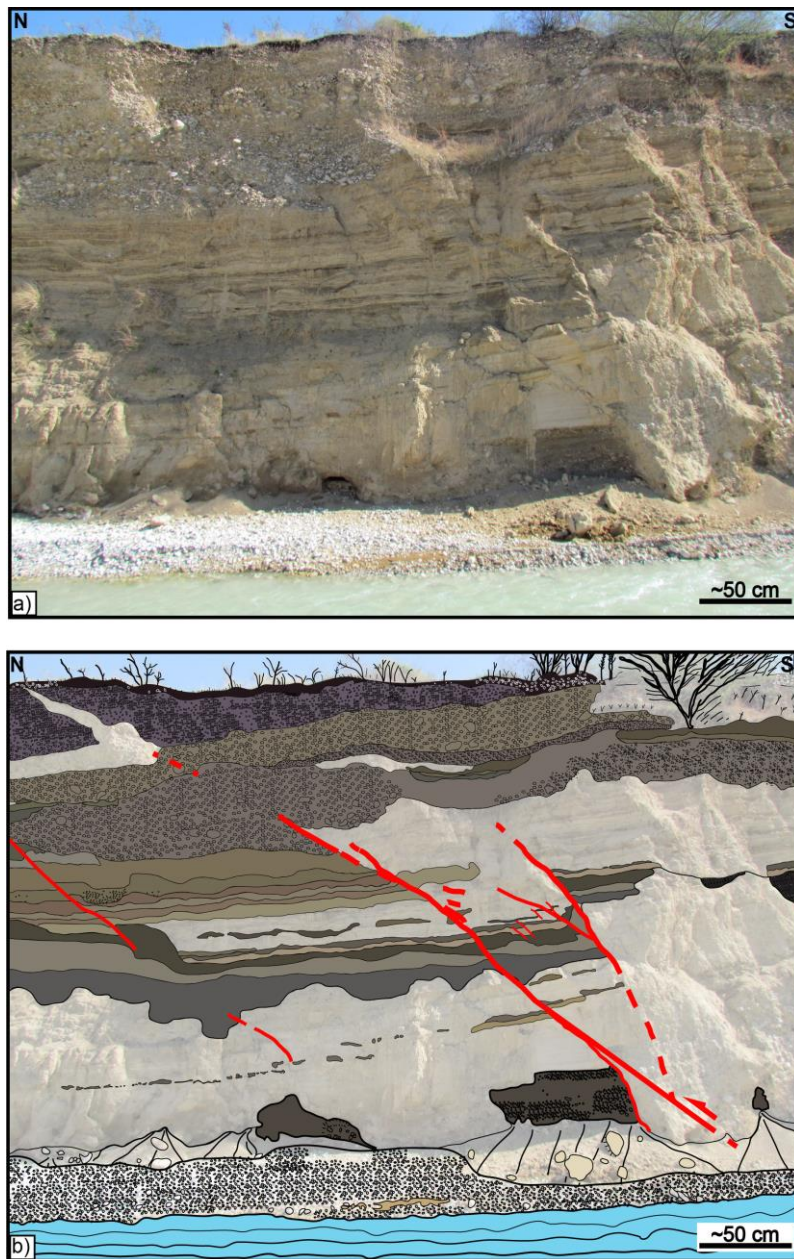
508 Pleisto-Holocene alluvial deposits are shown in bright yellow on Fig. 10a including
509 high-angle fans at mountain fronts [[Cox et al., 2011](#)]. The high-angle fans may be explained
510 by high topographic discrepancy between the mountain fronts and the plain in this area (see
511 topographic profile of Fig. 2b). This Pleisto-Holocene unit is also widely deposited around the
512 paleofan, including within the deep incisions.

513

514 The extensive incision of the paleofan, and the hills in particular, may be explained by
515 a scenario of successive variations of the level of the bay of Port-au-Prince. In this case, after
516 the deposition of the paleofan, its related river and channel complex (rills) flowed to the bay.
517 A drop of the level of the bay might force the streams to adjust their incision profiles in order
518 to reach the low sea level. This scenario is consistent with the overall orientation of the
519 incisions on the hill ranges. However, the successive low levels of the bay should have
520 actually been balanced by highstands since its emplacement. In fact, the incisions are so deep
521 that we propose that they have been exacerbated by tectonic uplift. The Pliocene hill ranges
522 described above bear some resemblance to the other young folds identified in the Cul-de-Sac
523 plain, and they may be the result of active folding. Since the borders of the proposed folds are
524 relatively sharp, they may be controlled by bivergent thrusts (Fig. 12a). This suggests that the
525 paleofan is faulted and that active faults cut through several significant neighborhoods of
526 Port-au-Prince (e.g., Bourdon, Fort National, Péguy Ville) (Fig. 12a and b). As the faulting
527 affects the Plio-Pleistocene deposit, the deformation is active after the deposition of this unit.

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544

545 Figure 13: a) and b) Field photograph and interpretation of the exposure of the Dumay Fault on the eastern wall
546 of Grise river (see figure 3 for location). The fault vertically offsets the sedimentary layers by several
547 centimeters. The fault dips at $50 \pm 15^\circ\text{S}$.

548

549 **4.6.- Dumay Fault**

550

551 The surface of the Grise river fan is smooth with little incision except where it is
552 disturbed by the Nan Cadastre Fold (Supplementary S4). Near the eastern edge of the fan,
553 Holocene sediments seem to be also affected by the Jacquet Fold along which Upper Miocene
554 chalky limestone crops out. To the south of the fan, the EPGF is not well expressed
555 geomorphically and we only recognize the Dumay Fault in the area. In the field, the Dumay
556 Fault is exposed in the eastern cutbank of Grise river (Fig. 13) [*Gold et al.*, 2012; *Saint Fleur*
557 *et al.*, 2015; This study] where a 10-m-high exposure of fluvial sedimentary deposits reveals
558 several reverse faults. The layers are coarse and thick at the lower and upper part, whereas
559 they are relatively fine and thin in the middle of the wall. The sedimentary layers are offset by
560 several centimeters by several branches of the fault, which dips $50 \pm 15^\circ$ to the south (Fig.
561 13). The offset is most visible in the middle of the exposure where the layers are the finest and
562 thinnest. However, the main fracture associated with the fault is well seen at the base of the
563 wall. We do not have any evidence that indicates the fault displaces the sediments near the top
564 of the exposure, and there is no scarp on the surface. However, the surface has been used for
565 farming, so it is possible that the fault has displaced the surface and the scarp has been
566 masked by agricultural activities. In addition to the reverse faulting, strike-slip deformation
567 has been observed ~3.2 km west of Dumay (18.50870° / -72.22909°), along a northwest-
568 flowing tributary of the Grise river. Indeed, a fluvial terrace riser was identified and recorded
569 lateral offset of ~6.5 m [*Prentice et al.*, 2010; *Cowgill et al.*, 2012].

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573 5.- Discussion

574 5.1.- Age constraints for the paleofan of Port-au-Prince

575 Most of the alluvial fans described here are presumed to be of Quaternary age
576 [*Momplaisir*, 1986]. The only fan that was the subject of a detailed study was the paleofan of
577 Port-au-Prince. Using LIDAR topographic data (pixel: 1 m) and field observations, Cox *et al.*
578 (2011) presented a detailed geological map of the PaP paleofan. Although they did not carry
579 out any absolute dating, they used age estimates for correlative regional map units and
580 landscape analysis from field observations. They also combined their dataset with the
581 response of different soil and bedrock layers to the seismic waves recorded during the 2010
582 earthquake [*Cox et al.*, 2011]. They estimated the bulk of the sediments of the paleofan to be
583 of Pliocene age (Fig. 10a). Van Den Berghe (1983) observed that the paleofan was deposited
584 on an 80-m-thick marl layer that is rich in planktonic foraminifera such as *Globorotalia*
585 *margaritae*, characteristic of the Early Pliocene period [*Bolli and Bermúdez*, 1965]. Because
586 they overlie this marl, one can infer that the older fanglomerates of the paleofan are of Early-
587 Middle Pliocene age at most.

588 The variation in hurricane strength could be a cause for variable river behaviour with
589 time. Using especially alkenone and Mg/Ca ratio proxies, it is well documented that the Early
590 Pliocene was 4°C warmer than today [*Brierley and Fedorov*, 2010; *Fedorov et al.*, 2013], and
591 Middle Pliocene was 2-3°C warmer than today [*Brierley et al.*, 2009; *Dowsett and Robinson*,
592 2009; *Dowsett et al.*, 1999; *Haywood and Valdes*, 2004; *Thompson and Fleming*, 1996].
593 Such temperatures might have corresponded to greenhouse conditions [*Brierley et al.*, 2009],
594 and thus led to more tropical storms or cyclones in the Early-Middle Pliocene than today.
595 These hurricanes might have been more frequent and stronger in the Caribbean [*Fedorov et*
596 *al.*, 2010]. Thus, the climatic conditions in the Early-Middle Pliocene time might have been

597 favorable for high rates of erosion and deposition during the formation of the paleofan of
598 Port-au-Prince, the biggest fan of the Cul-de-Sac plain. The other fans in the plain, as they are
599 assumed to be younger, their corresponding catchments might have not experienced the same
600 favorable conditions as the corresponding catchment of the paleofan for sedimentary
601 deposition.

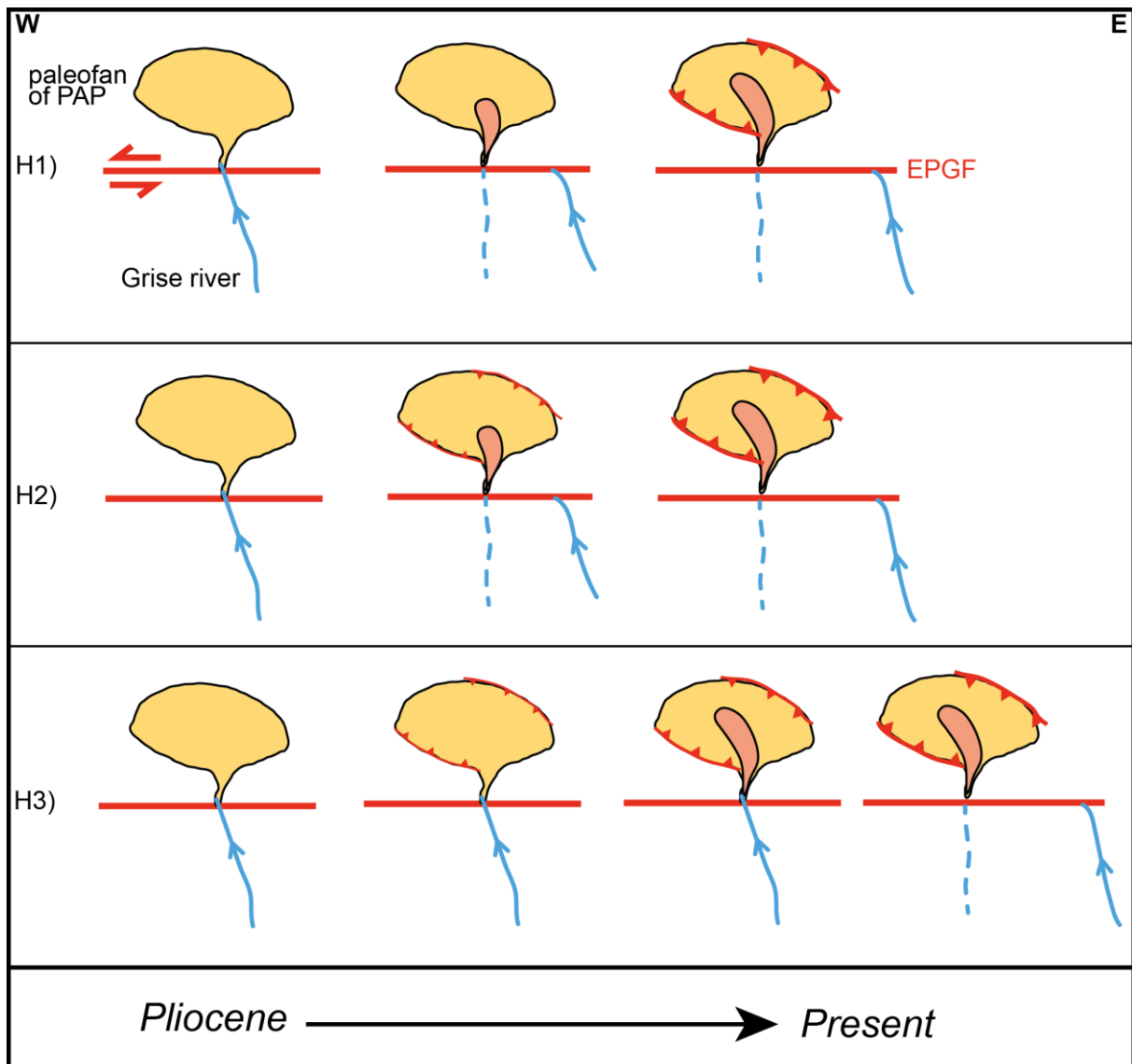
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603 **5.2.- Offset timing and slip rate**

604 By considering that the paleofan of Port-au-Prince is of Pliocene age, its offset of $7.9 \pm$
605 0.3 km is necessarily posterior. We propose three hypotheses (H) for the timing of the offset
606 of the paleofan (Fig. 14):

607 H1) the offset might have begun since the Pliocene shortly after deposition of the
608 Pliocene fanglomerates. This implies that the inset Plio-Pleistocene fan (SF1-SF3, Fig. 10a)
609 was formed while the strike-slip faulting was active. Then, the overall paleofan was folded
610 (after the offset) (Fig. 14).

611



612

613 Figure 14: Sketch showing our three different hypotheses (H1-H3) on the timing of the offset of the paleofan of

614 Port-au-Prince (see text for discussion). Yellow area: Pliocene fanglomerates; pinkish area: Plio-Pleistocene fan.

615 The dotted blue line indicates that it is possible that the Plio-Pleistocene fan was deposited by another river other
 616 than the Grise river.

617

618 H2) the offset began after the deposition of the Pliocene fanglomerates, and the inset

619 Plio-Pleistocene surface was formed during the offset. But, the folding was also active during

620 the offset.

621 H3) the Pliocene fanglomerates were deposited, then folded without being left-
622 laterally offset. The inset Plio-Pleistocene fan was deposited afterward, while the folding
623 continued. Then, the overall paleofan started to be offset.

624

625 (H1) implies that the Pliocene paleofan and the younger inset Plio-Pleistocene fan
626 would have been folded by the same amount. However, the Pliocene fanglomerates are much
627 higher and more incised than the inset Plio-Pleistocene fan, suggesting that they are more
628 deformed. According to (H2), the offset would have initiated at the Pliocene (~5.3-2.6 Myr
629 BP). In this case, the horizontal slip rate would be 1.4-3.2 mm/yr. According to (H3), the
630 paleofan was in front of Grise river after the formation of the inset Plio-Pleistocene fan. In
631 this case the offset of the paleofan of Port-au-Prince would be, at most, of Pleistocene age,
632 younger than ~2.6 Myr (following the International Stratigraphic Chart [*Gradstein et al.*,
633 2004; *Ogg et al.*, 2008]). This implies a minimum slip rate of ~3 mm/yr.

634 Westward, the EPGF offsets by 40 ± 10 km Lower Miocene folds (Massif de la Selle,
635 Massif de la Hotte) implying that the fault is younger than 15 Myr at this place [*Saint Fleur*
636 *and Klinger*, under review; *Saint Fleur*, 2014]. This would imply a minimum slip rate of 2-3
637 mm/yr.

638 These rates are comparable to those estimated using GPS data: 6 ± 2 mm/yr near Port-
639 au-Prince [e.g., *Symithe and Calais*, 2016]. Indeed, because the geologic rate is a minimum,
640 and the offset age of the fan could be as young as 1 Myr and still be Pleistocene, the geologic
641 and geodetic rates are not much different. Also, given the error on the geodetic rate, it could
642 be as low as 4 mm/yr, not much different from a minimum geologic rate of 3 mm/yr.

643 **5.3. Relevance of the observed deformation**

644 The active folds mapped here are characterized by low hills in the Cul-de-Sac –
645 Enriquillo trough and mainly disturb the topography of alluvial fans associated with north- or
646 south-flowing rivers. The topography created by the deposition of the fans is characterized by
647 gentle slopes oriented N-S, while hills that disrupt the fans have abrupt slopes that are
648 oriented \sim N115°E, oblique to the fans. Thus, it is unlikely that the hills were formed by
649 depositional processes associated with the fans. Moreover, we have shown that the hills are
650 linear and higher (up to 260 m above sea level) than the fans. The existence of wind gaps,
651 uplifted alluvial terraces, ponded sediments, tilted Quaternary beds, and the youthful
652 morphology of the hills are the result of active folding in the Cul-de-Sac plain. These
653 Quaternary folds are located near the eastern tip of the Enriquillo-Plantain Garden Fault
654 (EPGF). They strike parallel to the other folds belonging to the Trans-Haitian Belt and belong
655 to the same system.

656 To the west of Port-au-Prince, Saint Fleur *et al.* (2015) have recently shown the
657 existence of the Lamentin fold and thrust, and the latter are connected to the EPGF.
658 Momplaisir (1986) also showed the existence of the Trois-Baies Fault that might be connected
659 to the EPGF. We thus suggest that the folds along the northern margin of the Massif de la
660 Selle correspond to blind thrusts connected to the EPGF. But, the EPGF is not geomorphically
661 well expressed in this area where the deformation is distributed between strike-slip and thrust
662 faults. The \sim 50° south-dipping Dumay Fault, for example, which does not show significant
663 vertical offset in the field (Fig. 13) may have a significant component of strike-slip near the
664 eastern end of the EPGF [Prentice *et al.*, 2010; Cowgill *et al.*, 2012]. We propose that the
665 transpressive N95-100°E Dumay Fault marks a transition between the Léogâne – Pétion-Ville
666 shear zone and the Bahoruco Fault (Fig. 15). Indeed, the fault system undergoes another
667 significant azimuth change along the Bahoruco Fault, which is \sim N130°E-striking and

668 accommodates reverse motion. The Dumay and Bahoruco faults, along with the young thrusts
669 in the Cul-de-Sac – Enriquillo plain and the Southern Hispaniola Fault, contribute to maintain
670 the present-day uplift of the Massif de la Selle – Bahoruco Mountain Range (Fig. 15); this is
671 consistent with the highest elevations (e.g., Pic La Selle) bordered by these faults.

672

673 **5.4. Implications for Seismic Hazard**

674

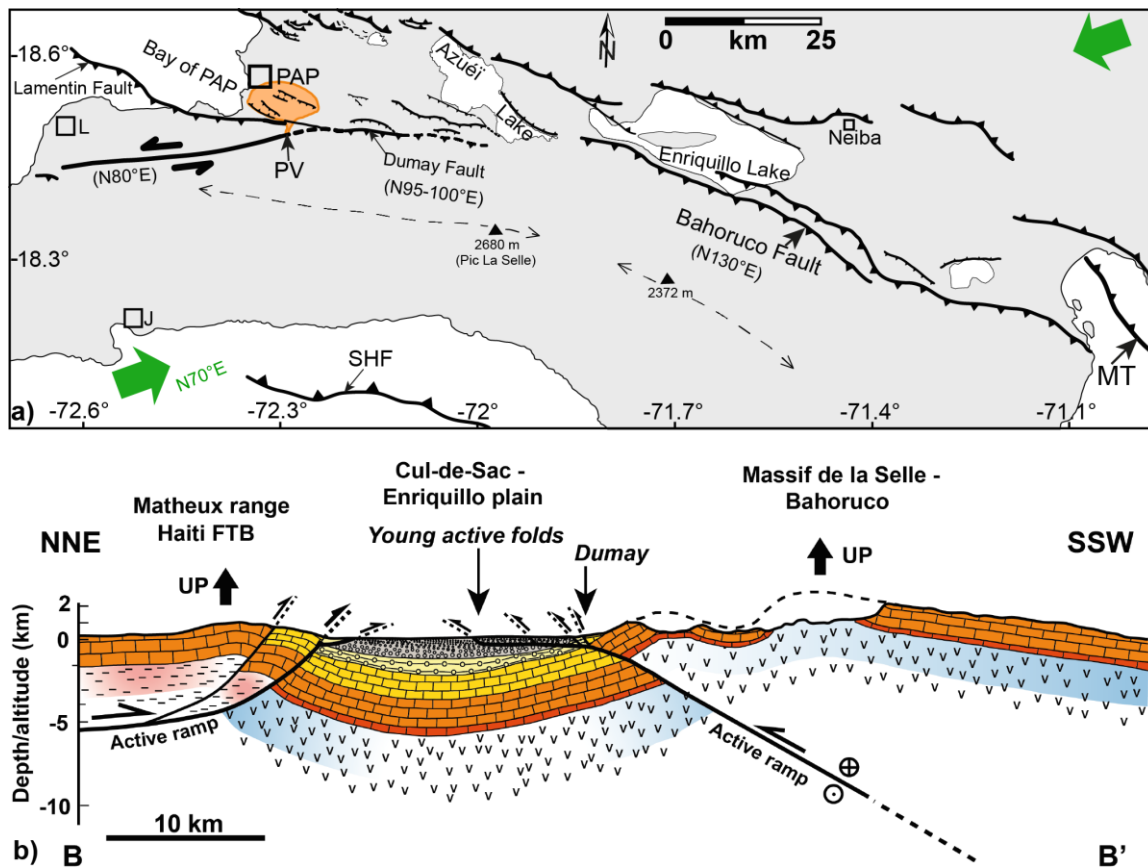
675 The 2010 Haiti earthquake revealed the complexity of fault systems in southern Hispaniola.
676 Wang *et al.*, (2018) found both evidence for strike-slip and reverse faulting in southern Azu ei
677 Lake. The strike-slip fault is deeply buried and less active than the thrust cutting the lake bed
678 [Wang *et al.*, 2018]. This is consistent with the lack of geomorphic expression of the EPGF in
679 the area and may indicate that Holocene activities are provided by the transpressive Dumay
680 Fault, the Bahoruco Fault and the young thrusts along the Cul-de-Sac – Enriquillo plain. From
681 a kinematic point of view, the EPGF system changes from a significant shear zone at P etion-
682 Ville, at the apex of PaP paleofan, to accommodate transpression and mainly compression to
683 the east of Port-au-Prince, representing a high seismic hazard. The young folds and thrusts in
684 the Cul-de-Sac – Enriquillo trough show two families. A north-dipping one connected to the
685 Matheux-Neiba Fault zone and a south-dipping one aligning to the south and connected to the
686 Enriquillo-Dumay-Bahoruco fault zone (Fig. 15). We propose that the two families form two
687 distinct deformation fronts in the Cul-de-Sac – Enriquillo trough, consistent with the suturing
688 of the northern island-arc structures and the oceanic plateau terrane of the southern peninsula
689 [Mann *et al.*, 1991]. Thus, the Cul-de-Sac – Enriquillo trough represents a significant seismic
690 hazard for the two capital cities, Port-au-Prince and Santo Domingo.

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697 Figure 15: Fault kinematics in southern Hispaniola. Near Port-au-Prince, the deformation is partitioned between
698 strike-slip and reverse faults. The Dumay Fault is transpressive and the Bahoruco Fault is compressive. The
699 green arrows represent the boundary conditions, that is, the oblique convergence between North American and
700 Caribbean plates. Orange shaded is the paleofan of Port-au-Prince. L: L og ane; J: Jacmel; PAP: Port-au-Prince;
701 PV: P tion-Ville; EPGF: Enriquillo-Plantain Garden Fault; SHF: Southern Hispaniola Fault; MT: Muertos
702 Trench. b) Overall structural section showing the style of deformation (see Fig. 2 for location). FTB: Fault and
703 Trust Belt.

704

705 6. Conclusions

706

707 In this study we have, in a first part, acquired morphometric data for six fans and their
708 associated drainage basins along the northern piedmont of the Massif de la Selle. These data
709 revealed that the paleofan of Port-au-Prince is not facing its initial source. Our dataset has

710 shown that the drainage basins have areas up to ~9 times larger than their related fan areas,
711 compatible with the empirical law linking drainage basin and fan areas [Bull, 1962; 1977].
712 The only exception is Port-au-Prince, which present-day drainage basin is ~5.5 times smaller
713 than its paleofan. We inferred that the paleofan was displaced by 7.9 km by the Enriquillo
714 fault from its original drainage basin. This offset implies a minimum slip rate of ~3 mm/yr.

715 In a second part, we have shown evidence for active folding characterized by low hills
716 in the Cul-de-Sac – Enriquillo trough. In particular, many of those folds have been mapped
717 using high-resolution geospatial data and field observations. The folds mainly disturb the
718 topography of alluvial fans. Those folds and thrusts are connected to the Enriquillo-Dumay-
719 Bahoruco fault zone.

720 In addition to the strike-slip deformation, the young thrusts documented in Port-au-
721 Prince and in the Cul-de-Sac plain are similar to the Lamentin fault. Port-au-Prince is thus
722 threatened by the 2010-earthquake type, involving both strike-slip and reverse faulting [*Saint*
723 *Fleur et al., 2015; Rodriguez et al., 2018*]. These two structure families result from the
724 oblique tectonic context of compression between the rigid Bahamas bank on the North
725 American plate and the Caribbean plate. The deformation related to the oblique compression
726 is actually partitioned between structures accommodating preferably the compressional
727 component of the motion, that is, the numerous folds and thrusts that we have identified, and
728 structures that accommodate the lateral motion, such as the Septentrional Fault and the EPGF.
729 In particular, the young active thrusts in the Cul-de-Sac plain deserve further tectonic
730 investigations in terms of fieldwork, balanced cross-section, together with dating in order to
731 constrain their shortening rate in the direct vicinity of Port-au-Prince.

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735 **Acknowledgments**

736

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746 **References**

747

748 Ali, S. T., A. M. Freed, E. Calais, D. M. Manaker, and W. R. McCann (2008), Coulomb stress
749 evolution in Northeastern Caribbean over the past 250 years due to coseismic, postseismic
750 and interseismic deformation, *Geophysical Journal International*, 174(3), 904-918.

751

752 Bakun, W. H., C. H. Flores, and U. S. ten Brink (2012), Significant Earthquakes on the
753 Enriquillo Fault System, Hispaniola, 1500-2010: Implications for Seismic Hazard, *Bulletin of*
754 *the Seismological Society of America*, 102(1), 18-30.

755

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

759

760 Bilham, R. (2010), Structural geology: Invisible faults under shaky ground, *Nature*
761 *Geoscience*, 3(11), 743-745.

762

763 Bolli, H. M., and P. J. Bermúdez (1965), *Zonation based on planktonic foraminifera of Middle*
764 *Miocene to Pliocene warm-water sediments*, 29 pp., Boletín Informativo / Asociación
765 Venezolana de Geología Minería y Petróleo.

766

767 Brierley, and A. V. Fedorov (2010), Relative importance of meridional and zonal sea surface
768 temperature gradients for the onset of the ice ages and Pliocene- Pleistocene climate
769 evolution, *Paleoceanography*, 25(2).

770

771 Brierley, A. V. Fedorov, Z. Liu, T. D. Herbert, K. T. Lawrence, and J. P. LaRiviere (2009),
772 Greatly expanded tropical warm pool and weakened Hadley circulation in the early Pliocene,
773 *Science*, 323(5922), 1714-1718.

774

775 Briggs, R. W., C. S. Prentice, A. J. Crone, R. D. Gold, K. W. Hudnut, and R. Narcisse (2012),
776 Late Quaternary Blind Thrust Faults along the Southern Margin of the Cul-de-Sac Plain,
777 Haiti: A Newly Recognized Seismic Source?, *AGU Fall Meeting*.

778

779 Bull, W. B. (1962), Relation of textural (CM) patterns to depositional environment of alluvial-
780 fan deposits, *Journal of Sedimentary Research*, 32(2).

781

782 Bull, W. B. (1977), The alluvial-fan environment, *Progress in Physical Geography*, 1(2), 222-
783 270.

784

785 Calais, E., and B. Mercier de Lépinay (1995), Strike-slip tectonic processes in the northern
786 Caribbean between Cuba and Hispaniola (Windward Passage), *Marine Geophysical*
787 *Researches*, 17(1), 63-95.

788

789 Calais, E., A. Freed, G. Mattioli, F. Amelung, S. Jónsson, P. Jansma, S.-H. Hong, T. Dixon, C.
790 Prépetit, and R. Momplaisir (2010), Transpressional rupture of an unmapped fault during the
791 2010 Haiti earthquake, *Nature Geoscience*, 3(11), 794-799.

792

793 Calmus, T. (1983). Contribution à l'étude géologique du massif de Macaya(sud-ouest d'Haïti,
794 Grandes ACalmusntilles): sa place dans l'évolution de l'orogène Nord-Caraïbe (Doctoral
795 dissertation).

796

797 Calmus, and J. M. Vila (1988), The Massif of Macaya (Haiti): the evolution of a Laramide
798 structure in the left-handed-strike-slip boundary between North-America and Caribbean
799 Plates, *Bol. Depto. Geol. Uni-Son.,* 5, 63-69.

800

801 Cooper, J. C. (1983), Geology of the Fondo Negro region, Dominican Republic, State
802 University of New York at Albany. Department of Geological Sciences.

803

804 Cowgill, E., Bernardin, T. S., Oskin, M. E., Bowles, C., Yıkılmaz, M. B., Kreylos, O., ... &
805 Bawden, G. W. (2012). Interactive terrain visualization enables virtual field work during rapid
806 scientific response to the 2010 Haiti earthquake. *Geosphere*, 8(4), 787-804.

807

808 Cox, B. R., J. Bachhuber, E. Rathje, C. M. Wood, R. Dulberg, A. Kottke, R. A. Green, and S.
809 M. Olson (2011), Shear wave velocity-and geology-based seismic microzonation of Port-au-
810 Prince, Haiti, *Earthquake Spectra*, 27(S1), S67-S92.
811

812 DeMets, C., R. G. Gordon, and D. F. Argus (2010), Geologically current plate motions,
813 *Geophysical Journal International*, 181(1), 1-80.
814

815 de St-Méry, M. (1803). Description topographique, physique, civile, politique et historique de
816 Saint-Domingue. Philadelphie, 1797. *La danse. Parme*
817

818 Dixon, T. H., F. Farina, C. Demets, P. Jansma, P. Mann, and E. Calais (1998), Relative motion
819 between the Caribbean and North American plates and related boundary zone deformation,
820 *JOURNAL OF GEOPHYSIC RESEARCH*, 103, 15,157-115,182.
821

822 Dolan, J. F., Mullins, H. T., Wald, D. J., & Mann, P. (1998). Active tectonics of the north-
823 central Caribbean: Oblique collision, strain partitioning, and opposing subducted slabs.
824 *Special Papers-Geological Society of America*, 1-62.
825

826 Douilly, R., Haase, J. S., Ellsworth, W. L., Bouin, M. P., Calais, E., Symithe, S. J., ... &
827 Meremonte, M. E. (2013). Crustal structure and fault geometry of the 2010 Haiti earthquake
828 from temporary seismometer deployments. *Bulletin of the Seismological Society of America*,
829 103(4), 2305-2325.
830

831 Dowsett, and M. M. Robinson (2009), Mid-Pliocene equatorial Pacific sea surface
832 temperature reconstruction: a multi-proxy perspective, *Philosophical Transactions of the*
833 *Royal Society A: Mathematical, Physical and Engineering Sciences*, 367(1886), 109-125.
834

835 Dowsett, J. A. Barron, R. Z. Poore, R. S. Thompson, T. M. Cronin, S. E. Ishman, D. A.
836 Willard, and J. A. Barren (1999), Middle Pliocene paleoenvironmental reconstruction:
837 PRISM2. USGS Open File Report.
838

839 Fedorov, C. M. Brierley, and K. Emanuel (2010), Tropical cyclones and permanent El Niño in
840 the early Pliocene epoch, *Nature*, 463(7284), 1066-1070.
841

842 Fedorov, C. Brierley, K. Lawrence, Z. Liu, P. Dekens, and A. Ravelo (2013), Patterns and
843 mechanisms of early Pliocene warmth, *Nature*, 496(7443), 43-49.
844

845 Feuillet, N. (2000). *Sismotectonique des Petites Antilles: Liaison entre activité sismique et*
846 *volcanique* (Doctoral dissertation, Paris 7).
847

848 Fraser, G. S., and P. G. DeCelles (1992), Geomorphic controls on sediment accumulation at
849 margins of foreland basins, *Basin Research*, 4(3-4), 233-252.
850

851 Giles, P. T. (2010), Investigating the use of alluvial fan volume to represent fan size in
852 morphometric studies, *Geomorphology*, 121(3), 317-328.
853

854 Gold, R. D., C. S. Prentice, A. J. Crone, R. W. Briggs, and R. Narcisse (2012), Evidence of
855 multiple, prehistoric, ground-rupturing earthquakes along the Enriquillo-Plantain Garden

856 Fault system near Port-au-Prince, Haiti, paper presented at AGU Fall Meeting Abstracts.
857

858 Gradstein, F. M., J. G. Ogg, and A. G. Smith (2004), *A geologic time scale 2004*, Cambridge
859 University Press.
860

861 Guérit, L. (2014), Caractéristiques morpho-sédimentaires des cônes alluviaux et reconstitution
862 de leurs paléo-flux d'eau et de sédiments. Exemples naturels du piedmont nord du Tian Shan
863 (Xinjiang, Chine) et modélisation expérimentale, 266 pp, Université Paris Diderot (Paris 7).
864

865 Harvey (1997), The role of alluvial fans in arid zone fluvial systems, *Arid zone*
866 *geomorphology (2nd edition)*. John Wiley & Sons, 231-260.
867

868 Hayes, G., R. Briggs, A. Sladen, E. Fielding, C. Prentice, K. Hudnut, P. Mann, F. Taylor, A.
869 Crone, and R. Gold (2010), Complex rupture during the 12 January 2010 Haiti earthquake,
870 *Nature Geoscience*, 3(11), 800-805.
871

872 Haywood, A. M., and P. J. Valdes (2004), Modelling Pliocene warmth: contribution of
873 atmosphere, oceans and cryosphere, *Earth and Planetary Science Letters*, 218(3), 363-377.
874

875 Hubert-Ferrari, A., J. Suppe, R. Gonzalez-Mieres, and X. Wang (2007), Mechanisms of active
876 folding of the landscape (southern Tian Shan, China), *J. Geophys. Res.*, 112, B03S09,
877 doi:10.1029/2006JB004362.
878

879 Lacassin, R., Klinger, Y., & Feuillet, N. (2013). Sismotectonique du tremblement de terre du
880 12 janvier 2010 en Haïti. *Outre-terre*, (1), 163-183.

881

882 Manaker, D. M., E. Calais, A. M. Freed, S. T. Ali, P. Przybylski, G. Mattioli, P. Jansma, C.
883 Prépetit, and J. B. de Chabalier (2008), Interseismic Plate coupling and strain partitioning in
884 the Northeastern Caribbean, *Geophysical Journal International*, 174(3), 889-903.

885

886 Mann, P., K. Burke, and T. Matumoto (1984), Neotectonics of Hispaniola: plate motion,
887 sedimentation, and seismicity at a restraining bend, *Earth and Planetary Science Letters*, 70,
888 311-324.

889

890 Mann, P., P. McLaughlin, and C. Cooper (1991), Geology of the Azua and Enriquillo basins,
891 Dominican Republic; 2, Structure and tectonics, *Geological Society of America Special
892 Papers*, 262, 367-390.

893

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

897

898 Mann, P., E. Calais, J.-C. Ruegg, C. DeMets, P. E. Jansma, and G. S. Mattioli (2002), Oblique
899 collision in the northeastern Caribbean from GPS measurements and geological observations,
900 *Tectonics*, 21(6), 7-1-7-26.

901

902 Mather, A., A. Harvey, and M. Stokes (2000), Quantifying long-term catchment changes of
903 alluvial fan systems, *Geological Society of America Bulletin*, 112(12), 1825-1833.

904

905 McCann, W. R. (2006), *Estimating the threat of tsunamogenic earthquakes and earthquake*
906 *induced-landslide tsunami in the Caribbean*, World Scientific Publishing, Singapore.

907

908 Mercier de Lépinay, et al. (2011), The 2010 Haiti earthquake: A complex fault pattern
909 constrained by seismologic and tectonic observations, *Geophysical Research Letters*, 38(22).

910

911 Momplaisir, R., & Boisson, D. (1988). Carte Géologique de la République d'Haiti, South-East
912 sheet (Port-au-Prince). *BME*.

913

914 Momplaisir, R. B. A. (1986). Contribution a l'Etude Geologique de la partie orientale du
915 massif de la hotte (presqu'île de sud d'Haiti): synthese structurale des marges de la presqu'île a
916 partir de donnees sismiques (Doctoral dissertation, Ph. D. thesis).

917

918 Nettles, M., and V. Hjörleifsdóttir (2010), Earthquake source parameters for the 2010 January
919 Haiti main shock and aftershock sequence, *Geophysical Journal International*, 183(1), 375-
920 380.

921

922 Ogg, J. G., G. Ogg, and F. M. Gradstein (2008), *The concise geologic time scale*.

923

924 Pindell, J. L., S. C. Cande, W. C. Pitman III, D. B. Rowley, J. F. Dewey, J. Labrecque, and W.
925 Haxby (1988), A plate-kinematic framework for models of Caribbean evolution,
926 *Tectonophysics*, 155, 121-138.

927

928 Prentice, C., P. Mann, L. R. Peña, and G. Burr (2003), Slip rate and earthquake recurrence
929 along the central Septentrional fault, North American–Caribbean plate boundary, Dominican
930 Republic, *Journal of Geophysical Research*, 108(B3).

931

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

935

936 Pubellier, M., J. M. Vila, and D. Boisson (1991), North Caribbean neotectonic events: The
937 Trans-Haitian fault system. Tertiary record of an oblique transcurrent shear zone uplifted in
938 Hispaniola, *Tectonophysics*, 194, 217-236.

939

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

943

944 Rodriguez, J., Havskov, J., Sørensen, M. B., & Santos, L. F. (2018). Seismotectonics of south-
945 west Dominican Republic using recent data. *Journal of Seismology*, 1-14.

946

947 Saint Fleur, N., & Klinger, Y. (under review). Detailed map, displacement, paleoseismology,
948 and segmentation of the Enriquillo-Plantain Garden Fault in Haiti.

949

950 Saint Fleur, N., Feuillet, N., Grandin, R., Jacques, E., Weil- Accardo, J., & Klinger, Y. (2015).
951 Seismotectonics of southern Haiti: A new faulting model for the 12 January 2010 M7. 0
952 earthquake. *Geophysical Research Letters*, 42(23), 10-273.

953

954 Saint Fleur, N. (2014). Sismotectonique du système de failles d'Enriquillo et du séisme du 12
955 janvier 2010 (M7.0) en Haïti (Doctoral dissertation, Ph. D. thesis).

956

957 Sykes, L. R., W. R. McCann, and A. L. Kafka (1982), Motion of Caribbean Plate during last 7
958 million years and implications for earlier Cenozoic movements, *Journal of Geophysical*
959 *Research*, 87(B13), 10656.

960

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

964

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

967

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

971

972 Thompson, R. S., and R. F. Fleming (1996), Middle Pliocene vegetation: reconstructions,
973 paleoclimatic inferences, and boundary conditions for climate modeling, *Marine*
974 *Micropaleontology*, 27(1), 27-49.

975

976 Toloczyki, M., & Ramirez, I. (1991). Geologic map of the Dominican Republic 1: 250,000.
977 *Ministry of Industry and Commerce, Department of Mining, Geographic Institute of the*
978 *Univerisity of Santo Domingo.*
979
980 Van Den Berghe, B. (1983), Evolution sédimentaire et structurale depuis le Paléocène du
981 secteur massif de la Selle(Haiti) «Baoruco»(République dominicaine)-«nord de la ride de
982 Beata» dans l'orogène nord Caraïbe(Hispaniola-Grandes Antilles).
983
984 van den Bold, W. A. (1975), Neogene biostratigraphy (Ostracoda) of southern Hispaniola,
985 *Bull. Am. Paleontol.*, 66(286), 599-639.
986
987 Wang, J., Mann, P., & Stewart, R. R. (2018). Late Holocene structural style and seismicity of
988 highly transpressional faults in southern Haiti. *Tectonics*, 37(10), 3834-3852.
989
990 Weissmann, G. S., and G. E. Fogg (1999), Multi-scale alluvial fan heterogeneity modeled with
991 transition probability geostatistics in a sequence stratigraphic framework, *Journal of*
992 *Hydrology*, 226(1), 48-65.
993
994 Wessels, R. J., Ellouz-Zimmermann, N., Bellahsen, N., Hamon, Y., Rosenberg, C.,
995 Deschamps, R., ... & Leroy, S. (2019). Polyphase tectonic history of the Southern Peninsula,
996 Haiti: from folding-and-thrusting to transpressive strike-slip. *Tectonophysics*, 751, 125-149.
997
998 Whipple, K. X., and C. R. Trayler (1996), Tectonic control of fan size: the importance of
999 spatially variable subsidence rates, *Basin Research*, 8(3), 351-366.