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Present-day shortening in Southern Haiti from GPS measurements and implications for seismic hazard

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ABSTRACT

The ~3 M inhabitant capital region of Haiti, severely affected by the devastating January 12, 2010, M7.0 earthquake, continues to expand at a fast rate. Accurate characterization of regional earthquake sources is key to inform urban development and construction practices through improved regional seismic hazard estimates. Here we use a recently updated Global Positioning System (GPS) data set to show that seismogenic strain accumulation in southern Haiti involves an overlooked component of shortening on a south-dipping reverse fault along the southern edge of the Cul-de-Sac basin, in addition to the well-known component of left-lateral strike-slip motion. This tectonic model implies that ground shaking may be twice that expected if the major fault was purely strike-slip, as assumed in the current seismic hazard map for the region.

1. Introduction

On January 12, 2010, Haiti was struck by a devastating – though not unexpected – earthquake (Bilham, 2010) (Fig. 1). Because its epicenter was located in the near vicinity of the Enriquillo Plaintain Garden Fault (EPGF), a major active fault part of the left-lateral strike-slip boundary between the Caribbean and North American plates (Fig. 1), it was first thought that the event had ruptured a portion of the strike-slip EPGF. Independent studies based on geodetic (Calais et al., 2010; Hayes et al., 2010; Hashimoto et al., 2011; Mercier de Lépinay et al., 2011; Symithe et al., 2013), geological (Prentice et al., 2010), and seismological data (Douilly et al., 2013) showed that the earthquake had actually ruptured a previously unmapped fault with a source mechanism combining strike-slip and reverse faulting, in a setting resembling the 1989 Loma Prieta earthquake in California (e.g., Dietz and Ellsworth, 1990; Beroza, 1991). This composite source mechanism was a first indication that the conventional interpretation of the EPGF in southern Haiti as a purely strike-slip fault system may need revisiting.

GPS measurements in the northeastern Caribbean have established that the 19 mm/yr relative motion between the Caribbean and North American plates, slightly oblique to the plate boundary direction in Hispaniola, is accommodated by shortening on the North Hispaniola fault to the north and strike-slip motion on the ~E–W striking Septentrional and Enriquillo faults throughout the island (Calais et al. (2002), Manaker et al. (2008), Fig. 1). Further geodetic studies making use a larger number of geodetic sites identified an additional component of boundary–normal shortening in southern Haiti (Calais et al., 2010; Benford et al., 2012; Symithe et al., 2015), consistent with the composite source mechanism of the 2010 earthquake but, again, questioning the purely strike-slip nature of the EPGF system in the region (Mann et al., 1995).

Here, we revisit the present-day tectonic setting of southern Haiti by testing published tectonic models in light of geodetic data acquired since the 2010 earthquake. We show that the well-known strike-slip motion affecting the area is accompanied by an even larger component of shortening on a south-dipping reverse fault along the southern edge of the Cul-de-Sac basin, which holds the ~3 M people capital city of Port-au-Prince. This tectonic scenario implies that ground shaking may be twice that expected if the major fault was purely strike-slip, as assumed in the current seismic hazard map for the region.

2. Tectonic setting

The EPGF has long been recognized as a major tectonic feature of southern Haiti, where it was first named "*Linéament Tiburon-Pétionville*" from the eponymous end-points of its surface trace mapped using airphoto interpretation (Duplan, 1975), then "*Décrochement Sénestre Sud Haïtien*" (Calmus, 1983). Subsequent studies however tended to minimize its importance as an active plate boundary fault. The EPGF does not appear as a major feature on the 250,000th Haiti geological maps (Momplaisir and Boisson, 1988). Pubellier et al. (1991) proposed that slip on the EPGF stopped in the Late Miocene when deformation in southern Hispaniola became compressional as the Haiti fold-and-thrust belt (Fig. 1) was propagating southward to its present position with its

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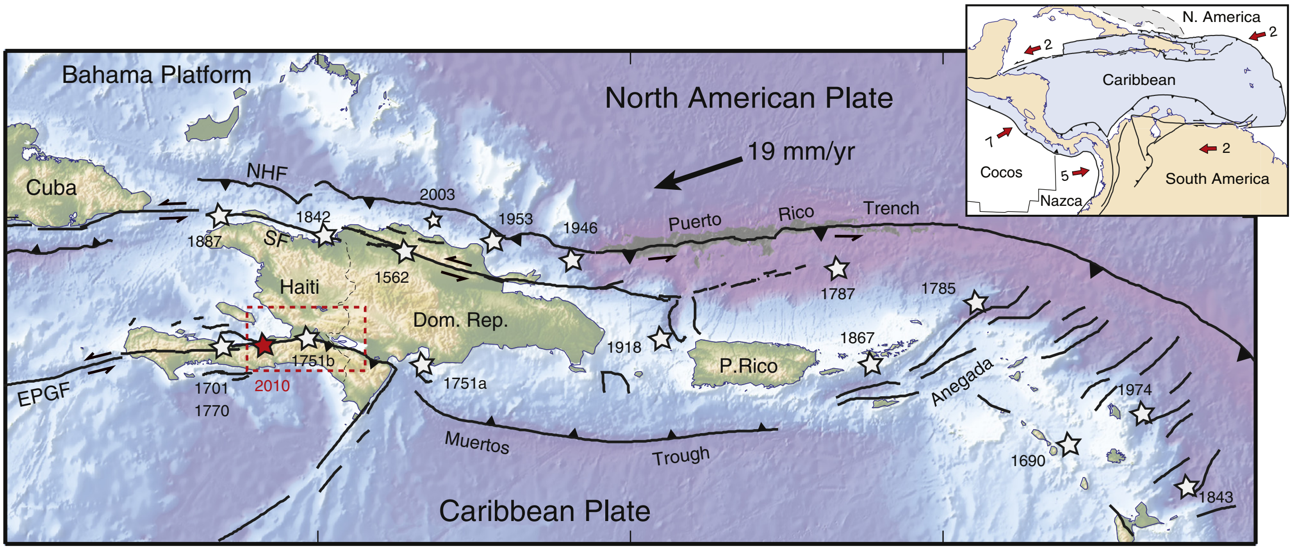

Fig. 1. Current tectonic setting of the northeastern Caribbean. SF = Septentrional fault, EPGF = Enriquillo Plantain Garden Fault. Stars show large (M<7) instrumental and historical earthquakes. Red rectangle shows the area displayed on Fig. 2.

active front currently thrusting onto the Cul-de-Sac basin along the Neiba–Matheux range. In their view, the EPGZ was reactivated as a normal fault in the Quaternary as a result of crustal loading imparted by the fold-and-thrust belt to the north (Pubellier et al., 2000).

Mann et al. (1995) proposed a drastically different interpretation where the EPGF is a quasi-vertical, left-lateral, active strike-slip fault running across southern Hispaniola from the westernmost tip of Haiti to the Enriquillo basin in the Dominican Republic. The fault is indeed well-marked in the morphology throughout the southern Peninsula of Haiti as a quasi-linear feature with push-ups and pull-aparts (Calmus, 1983; Momplaisir, 1986). This holds until about 72.27 W near the city of Pétionville where the EPGF intersects the Cul-de-Sac plain (Fig. 2). East of that point, its imprint on the morphology becomes more subtle. Mann et al. (1995) describe a series of gentle folds affecting plio-quaternary sediments along the southern edge of the Cul-de-Sac basin and into the Enriquillo basin in the Dominican Republic that they interpret as *en échelon* drag folds marking the trace of EPGF (Fig. 2A). The Cabritos island in the Enriquillo lake is the easternmost of these folds and, in that interpretation, is the surface expression of a vertical EPGF at depth. Hence, most of the recent maps show the EPGF as a single – though segmented – left-lateral strike-slip fault extending from Jamaica to the west all the way through southern Haiti and into the Enriquillo basin in the Dominican Republic to the east.

This interpretation contrasts with early geologic work in southern Haiti where the EPGF, well expressed along the Southern Peninsula, is mapped as abutting against a north-verging reverse fault system that mark the southern edge of the Cul-de-Sac basin (Fig. 2B, Bourgueil et al., 1988). Recent geological surveys of the Port-au-Prince area support this interpretation and show that these N110 E reverse-sinistral faults affect Quaternary alluvial sediments throughout the city and to the east (Terrier et al., 2014). At a broader regional scale, Saint Fleur et al. (2015) used high-resolution air photos and lidar topography to revisit the plio-quaternary folds identified by Mann et al. (1995) along the southern edge of the Cul-de-Sac basin. They propose that they are fault-propagation folds on top of shallow-dipping decollements emerging well into the Cul-de-Sac basin and rooted on a south-dipping low-angle reverse fault underneath the high relief Massif de la Selle (Fig. 2B). In their interpretation, the Cul-de-Sac basin is actively overthrusted on both sides by the Matheux–Neiba range in the north and the Massif de la Selle in the south while the EPGF is a young (<2 Ma) fault propagating eastward throughout southern Haiti.

3. GPS data

We use GPS data acquired in Haiti and the Dominican Republic since 2003 to test the tectonic models described above, determine the geometry of the major active faults in southern Haiti, and quantify the related elastic strain accumulation to inform regional hazard assessment. GPS data acquisition and processing procedures are provided in Symithe et al. (2013). The solution used here is an improved sub-sample of their data set that includes additional GPS measurements collected in Haiti and the Dominican Republic from June 2014 to April 2015. As a result, we now have a dense distribution of GPS sites covering the whole island, in particular the southern part of Haiti.

The regional velocity field (Fig. 3) shows left-lateral motion between the Caribbean and North American plates at 17–19 mm/yr, slightly oblique to the plate boundary direction. Velocities in Hispaniola show a north–south gradient with up to 15 mm/yr of integrated left-lateral shear strain across the island, consistent with previous findings (Symithe et al., 2015). A new observation, however, is a component of boundary–normal shortening readily visible on Fig. 3. This shortening affects the central and western parts of Hispaniola, except the Southern Peninsula of Haiti west of 72.5 W where velocities in a Caribbean frame are parallel to the E–W-trending EPGF (Calais et al., 2016).

This shortening component, that adds to the well-known regional left-lateral shear, is readily visible on the profile displayed on Fig. 3 where we project the GPS velocities onto directions parallel and normal to the EPGF strike. We observe a well-defined velocity gradient, both in the shortening and strike-slip components, coincident with the contact between the Cul-de-Sac basin and the Massif de la Selle. Although strike-slip motion at about 6–7 mm/yr was expected (Manaker et al., 2008; Benford et al., 2012; Symithe et al., 2015), the significant component of shortening visible on the profiles had not been documented before. In the following, our objective is to determine the geometry of the fault system that accommodates the observed strike-slip and shortening localized along the southern edge of the Cul-de-Sac basin.

4. Elastic model

We implement a simple model where faults are simulated as rectangular dislocations in an elastic half-space. We follow the classically-used backslip approach of Savage (1983) and calculate surface deformation due to faults locked in the upper, seismogenic, crust as the difference