

Comment on: “Historical perspective on seismic hazard to Hispaniola and the northeast Caribbean region” by U. ten Brink et al.

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1. Introduction

The analysis of historical earthquakes in the northeastern Caribbean by *ten Brink et al.* [2011] (hereafter, TB11) addresses the occurrence of large and destructive historical earthquakes associated with the North American-Caribbean plate boundary. One conclusion presented in TB11 is that the recurrence interval for large earthquakes on the left-lateral, strike-slip Septentrional Fault (SF) (Figure 1a) is approximately 300 years. Their Figure 7 shows rupture of the SF across the entire island of Hispaniola in CE 1200, 1542, and 1842. Our comment challenges this model for SF earthquake recurrence because it is inconsistent with our published paleoseismic data that show no large historical earthquake is associated with surface rupture along the SF east of Santiago (Figure 1a) [*Prentice et al.*, 1993; *Mann et al.*, 1998; *Prentice et al.*, 2003].

Historical records of earthquakes prior to the 20th century rarely provide direct observations linking a specific fault with a particular earthquake. Researchers of historical earthquakes typically formulate hypotheses such as those presented in TB11 associating earthquakes with particular faults, based on their modeled isoseismals. In contrast, paleoseismic studies based on direct observations of the fault zone and reliable age analyses provide fault-specific data to constrain when, within the uncertainty of the data, a particular section of a fault did or did not produce large surface-rupturing earthquakes. A model based solely on historical accounts of ground shaking and damage is useful in the absence of paleoseismic data, but interpretations based on historical accounts alone do not have the same resolution as geologic data that constrain the timing and location of fault surface rupture. The ambiguity inherent in using intensity centers alone to assign an historical earthquake to a particular fault is well illustrated by Figure 3 in *Bakun et al.*, [2012], which shows the intensity center for the 1946 earthquake immediately adjacent to the SF (Figure 1a, green triangle). Yet this earthquake is well known to have occurred on the North Hispaniola

thrust belt, not on the SF [Dolan and Wald, 1998]. (We note an error in TB11's Figure 4 showing the intensity center for the 1946 earthquake: the intensity center and all intensity locations are systematically mislocated about 50 km to the north compared to Figure 3 in Bakun *et al.*, [2012].) TB11 dismiss existing paleoseismic data as a constraint when they attribute the 1842 and 1562 Hispaniola earthquakes to the SF. Our published paleoseismic data contradict their interpretation; therefore we believe their model for SF recurrence is incorrect.

2. Paleoseismic Data from sites near Rio Cenoví and Rio Licey

Paleoseismic data from detailed studies along the SF show there has been no historical (i.e. post-1492) surface rupture on the SF in the central Cibao Valley east of Santiago, and therefore, neither the 1562 nor 1842 earthquakes ruptured the SF in this region. [Prentice *et al.*, 2003; Mann *et al.*, 1998; Prentice *et al.*, 1993]. In previous studies, we excavated eight fault-crossing trenches, all of which show evidence for the most recent surface rupture; three of these trenches exposed stratigraphic and structural relations and yielded multiple radiocarbon samples that allow us to constrain the age of the most recent surface-rupturing earthquake (MRE), while the remaining five trenches do not provide data that allow age constraint of the MRE. In two trenches the evidence is clear that the MRE is prehistoric in age. We collected a suite of radiocarbon samples in both the Rio Cenoví West and the Rio Cenoví East trenches throughout the unfaulted stratigraphic section that overlies the fault zone. [Prentice *et al.*, 1993 and 2003]. Radiocarbon analyses show that the sedimentary horizons overlying the faulted strata are prehistoric (Figure 1b). Because these samples are from unfaulted, post-earthquake deposits, they provide very strong evidence that the MRE is prehistoric. It is well established that in general fault rupture repeats within a narrow zone [e.g. Rockwell and Ben-Zion, 2007; Rymer *et al.*, 2011] and therefore unfaulted sediments overlying an active fault zone provide strong evidence that no fault surface rupture has occurred

since the deposition of the unfaulted horizons. The Rio Licey trench 3 exposure yielded samples that are consistent with a prehistoric age for the MRE, but do not on their own rule out surface rupture in 1562 at this site (these data do, however, rule out 1842 surface rupture at this site) (Figure 1b) [Prentice *et al.*, 2003]. TB11 infer, according to their Figure 7, that both the 1562 and 1842 earthquakes ruptured the SF across the entire island of Hispaniola. However, TB11 provide no explanation for the observation that unfaulted strata overlying the active fault zone date to more than 500 YBP in our trenches at the Rio Cenoví sites east of Santiago.

TB11 misinterpret data from Rio Licey trench 2 [Prentice *et al.*, 2003, Figure 10], and state that the young ages of several samples collected from unit 10/110 indicate that faulting affecting this unit could be as young as 1680-1940, implying an historical surface rupture. However, TB11 apparently misunderstand that unit 10/110 is not a depositional unit, but is the modern soil, which has been actively forming at this location for at least two thousand years, and that young organic material is constantly being bioturbated and mixed into the modern soil as it evolves. Because of the ongoing soil formation processes, the age of the MRE cannot be determined from the radiocarbon ages from unit 10/110 in Rio Licey trench 2, and instead, we rely on the relations and ages in the nearby Rio Licey trench 3, where undeformed depositional strata bury folded and faulted strata that were deformed by the MRE [Prentice *et al.*, 2003]. The same issue with samples from the modern soil also applies to our Tenares trench 2, where dates from the modern soil do not constrain the age of the MRE.

3. Paleoseismic Data from Santiago Viejo (Old Santiago)

TB11 state that a study of a trench at Santiago Viejo (Old Santiago) provides stratigraphic evidence that the 1562 earthquake occurred on the SF, citing an abstract by *Hengesh et al.* [2000]. However, the study of the Santiago Viejo trench provides no conclusive stratigraphic evidence that the 1562 earthquake ruptured the SF, nor does the cited abstract make that claim. The study (which remains unpublished except as an abstract) did not include any radiocarbon ages or ages from any other quantitative age-analysis method. The cited abstract describes an unfaulted horizon containing cultural artifacts from the Spanish settlement of Santiago Viejo, which was founded in 1504 and abandoned after the earthquake in 1562 [*Encyclopedia Britannica Online*, 2012]. The city was not rebuilt at this site after the earthquake, instead the survivors moved to a new location about 5 km away to rebuild. While *Hengesh et al.*, [2000] speculate that the faults terminating below the cultural horizon might represent surface rupture during the 1562 earthquake, the limited data available from that study provide no compelling evidence to support this hypothesis. Instead, the unfaulted cultural horizon suggests to us that the earthquake represented by these faults likely occurred before Spanish occupation at the site, i.e. before 1504. If the base of the cultural horizon represents the establishment of the Spanish settlement, then the faults that terminate below the cultural horizon cannot be related to surface rupture in 1562.

TB11 also do not address why, if the 1842 earthquake ruptured the SF as they propose, the cultural horizon at Santiago Viejo was not faulted during that earthquake. While the age of the base of the cultural horizon is not known, it seems highly unlikely that it is younger than 1842, because this would require that more than 330 years passed after the settlement was established in 1504 until artifacts began to accumulate in the cultural horizon. The Santiago Viejo study, far from contradicting the conclusions in *Prentice et al.*, [2003], can be interpreted to provide additional

support for the conclusion that the SF did not rupture in the central Cibao Valley in either the 1562 or the 1842 earthquake. All three authors listed on the *Hengesh et al.* [2000] abstract agree with this analysis of their study (personal communication, James Hengesh 2/28/12 and 4/6/12; personal communication, Jeffrey Bachhuber, 2/29/12 and 4/5/12; Luis Peña is a coauthor of this comment).

Another key geologic observation related to understanding the earthquake history of the SF is the lack of small left-lateral geomorphic offsets typically associated with an historical surface rupture. Small, single-event offsets of geomorphic features, such as those found along the Enriquillo-Plantain Garden Fault in Haiti [*Prentice et al.*, 2010] and the San Andreas Fault in California [*Sieh*, 1978; *Zielke et al.*, 2010], would be expected along the SF if the fault had ruptured as recently as 1842. We note that the climate in Haiti, where multiple small offsets likely associated with an 18th century earthquake are observed, is no different than the climate in the Dominican Republic.

4. 1842 and 1562 Earthquake Sources

We agree with TB11 (and previous workers) that historical accounts allow the 1842 earthquake to have ruptured the offshore section of the SF north of Haiti. It is possible that the 1842 rupture extended onshore along the SF in western Dominican Republic, west of Santiago Viejo, but the published paleoseismic data show that no surface rupture occurred on the SF in this event from Santiago eastward. The effects of ground shaking and damage to structures are controlled by many local and regional factors, and the 1842 shaking reports in eastern Hispaniola, which strongly influenced TB11 to conclude that the SF ruptured across the entire island, could be related to directivity and local site effects due to a rupture of the SF that terminated west of Santiago Viejo. The 1842 damage reports do not require rupture of the SF across the entire island, and the existing paleoseismic data argue strongly against it. We suspect that the major left-step in

the fault system near Guayabin [Mann *et al.*, 1998] (Figure 1a) may have acted as a segment boundary that halted the 1842 surface rupture, although more paleoseismic research is needed to test this hypothesis.

TB11 admit that their location of the 1562 earthquake is poorly constrained and that it could have been produced by a seismic source other than the SF. Very little is known about the 1562 earthquake, and the analysis of TB11 is based on damage reports from only four localities. Our paleoseismic data show that the 1562 earthquake did not involve surface rupture on the SF east of Santiago. Other possible sources for the 1562 earthquake include the North Hispaniola thrust belt (Figure 1a), or a thrust fault associated with either the Cordillera Central or Cordillera Septentrional. Nothing in the historical record precludes an alternative source for the 1562 earthquake.

5. Worldwide Fault Statistics and Stress Transfer Model

TB11 advocate their 300-year recurrence model for the SF by noting that, at the estimated slip rate they give of 6-12.3 mm/yr, 1.8-3.7 m of slip would accumulate between earthquakes 300 years apart, and stating that this is consistent with average strike-slip fault behavior worldwide. However, [Prentice *et al.*, 2003], documented a minimum of 4.6-5.5 m of slip associated with the most recent surface rupture at the Rio Cenoví East site, which, if representative of the average, is substantially greater than the expected slip using a 300-year recurrence, even if the highest slip rate is used to estimate the offset. Slip associated with strike-slip earthquakes worldwide is highly variable, and there are well-documented strike-slip earthquakes associated with average slip much greater than 3.7 m, including the San Andreas Fault in the Carrizo Plain, California [1857, ~5m, Zielke *et al.*, 2010], the Denali Fault in Alaska [2002, 4.5-5.1m, Haeussler *et al.*, 2004], the Bulnay

Fault in Mongolia [1905, 8 m; *Baljinnyam et al.*, 1993], and the Fuyun Fault in China [1931, 6.3 m; *Klinger et al.*, 2011], for example. There is no reason to assume that the SF must behave in line with any worldwide average, especially given the great variability in strike-slip fault behavior.

TB11 further promote their 300-year recurrence model by noting that a static stress transfer model suggests that the series of large earthquakes on the North Hispaniola thrust from 1943-1953 would have increased the Coulomb stress on the SF, bringing it closer to failure [*Dolan and Bowman*, 2004]. According to TB11, the absence of an earthquake on the SF in response to the increased Coulomb stress associated with the thrust-belt earthquakes is best explained by invoking rupture of the SF across the entire island in 1842, leaving little accumulated stress to be released in the 20th century. However, there are many examples of large earthquakes inducing positive Coulomb stress changes on adjacent faults that are believed to be in the late stages of the earthquake cycle without any subsequent triggered failure of those faults (for example, the 1992 Landers earthquake increased the Coulomb stress on the adjacent southern San Andreas Fault segments [*Stein et al.*, 1992] without triggering a large earthquake in the ensuing two decades). The lack of a large SF earthquake following the 1943-1953 North Hispaniola earthquake sequence does not require that the 1842 earthquake ruptured through eastern Hispaniola, nor does it indicate that the SF is not currently storing significant accumulated stress.

6. Conclusion

Geologic observations are inconsistent with the model proposed by TB11 that the recurrence interval for large earthquakes on the SF is 300 years. The earthquakes in 1842 and 1562 were not associated with surface rupture along the SF east of Santiago; if they had ruptured the SF east of Santiago, evidence for historic surface rupture would be visible in the paleoseismic trenches at Rio Cenoví East and Rio Cenoví West. A recurrence model for Hispaniola earthquakes that is consistent with both paleoseismic data and the historical record would yield a more robust assessment of the island's seismic hazard than the recurrence model proposed by TB11, which relies on analysis of historical intensity data alone to assign sources to the 1562 and 1842 earthquakes.

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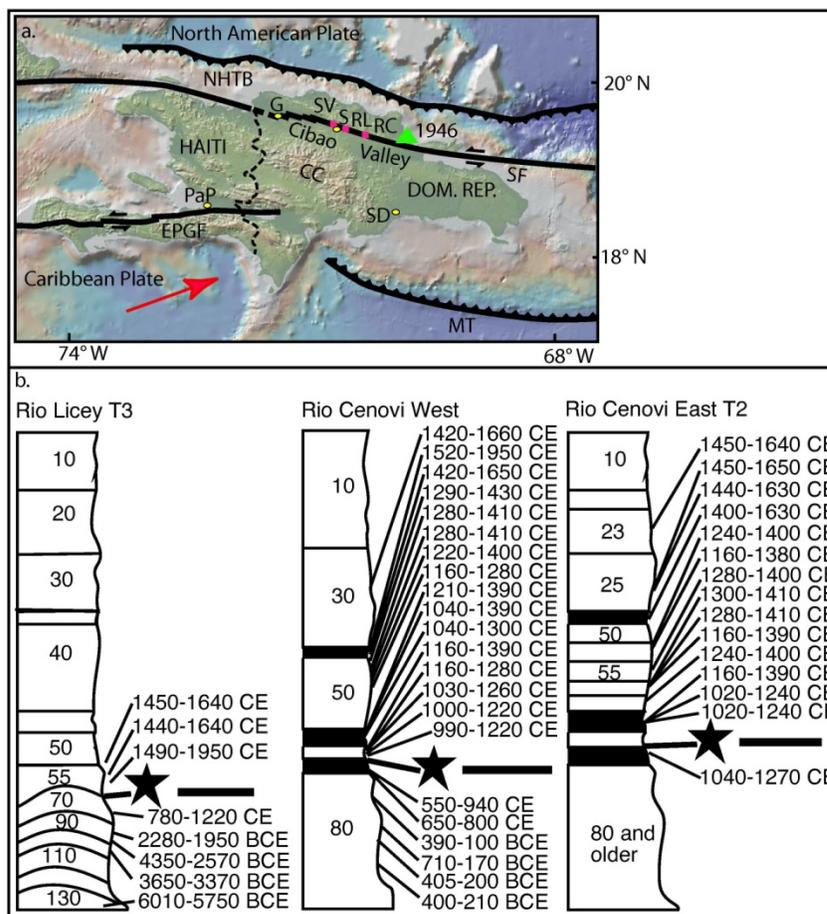


Figure 1. a. Map of Hispaniola from digital elevation model, showing major plate-boundary faults (bold black lines). Red arrow indicates motion of Caribbean Plate relative to North American Plate at about 19.5 mm/yr. EPGF=Enriquillo-Plantain Garden Fault; MT=Muerdos trench; NHTB=North Hispaniola thrust belt; SF=Septentrional Fault. Yellow circles indicate towns and cities: G=Guayabin, PaP=Port-au-Prince, S=Santiago, SD=Santo Domingo. Red squares show locations of trench sites discussed in text: RC=Rio Cenoví, RL=Rio Licey, SV=Santigo Viejo. CC=Cordillera Central. Green triangle is intensity center for 1946 NHTB earthquake from *Bakun et al.*, 2012. b. Schematic diagram showing stratigraphic sections from Rio Licey trench 3, Rio Cenoví West trench, and Rio Cenoví East trench 2. Stars indicate stratigraphic position of most recent earthquake within the sections. Strata above stars are unfaulted. Strata below the stars are faulted and/or folded. Heavy horizontal bars separate post-earthquake radiocarbon ages above from pre-earthquake radiocarbon ages below. Radiocarbon ages are dendrochronologically-calibrated two-sigma age ranges for individual samples collected from horizons as indicated. Radiocarbon ages are the youngest within each horizon, only those in stratigraphic order are shown. See *Prentice et al.* [1993, 2003] for full datasets and discussions.