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Exploration of remote triggering: A survey of multiple fault structures in Haiti

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ABSTRACT

Triggering studies provide an important tool for understanding the fundamental physics of how faults slip and interact, and they also provide clues about the stress states of faults. In this study, we explore how seismic waves from the 27 February 2010 *Mw*8.8 Maule, Chile mainshock interact with the left lateral strike-slip Enriquillo–Plantain Garden Fault (EPGF) and surrounding reverse faults in the southern Haiti peninsula. The Chile mainshock occurred 6,000 km away and just 46 days after the 12 January 2010 *Mw*7.0 Haiti earthquake, a tragic event which activated multiple faults in the southern Haiti peninsula. During the surface waves of the Chile mainshock, several tectonic tremor signals were observed, originating from south of the EPGF trace. Cross-correlation of the triggered tremor and transient stresses resolved onto to the EPGF indicates that the Love wave of the Chile mainshock was the primary driving mechanism of the triggered deep shear slip and tremor signals, as opposed to dilatational stress changes generated by the Rayleigh wave. We also searched for any influence of transient stresses on Haiti aftershock activity by applying the matched filter technique to multiple days of seismic data around the time of the Chile mainshock. While we identified a slight increase in Haiti aftershock activity rate, the rate changes were significant only when small magnitude events were included in the significance tests. These observations are generally consistent with recent inferences that deep tectonic tremor is more sensitive than shallow earthquakes to external stress perturbations.

1. Introduction

Seismic activity, such as earthquakes or tectonic tremor, naturally occurs on active fault systems due to tectonic stressing between plate boundaries. While earthquakes mostly occur in the brittle upper crust, deep tectonic tremor (Obara, 2002) is found in the lower crust along major plate-boundary faults, at times accompanying geodetically recorded slow-slip events (*e.g.*, Beroza and Ide, 2011). Sometimes tremor and earthquakes can be triggered by transient stress changes associated with the passing seismic waves of earthquakes (*e.g.*, Peng and Gomberg, 2010; Hill and Prejean, 2015). This process of fault failure induced by seismic waves is commonly known as 'dynamic triggering' and has been observed worldwide in a wide range of tectonic environments (*e.g.*, Brodsky and Prejean, 2005; Velasco et al., 2008; Peng and Gomberg, 2010; Hill and Prejean, 2015). Because seismic waves of distant earthquakes are capable of inducing fault failure, triggering studies can be used as a probe to not only understand a fault's current state of stress but to also better understand how seismic activity occurs on active fault systems and how faults interact with one another (Brodsky and van der Elst, 2014).

Dynamic triggering generally occurs when transient stresses act in the same direction as a fault's natural motion, *i.e.* dynamic Coulomb stress increases (Hill, 2012), but dynamic triggering can

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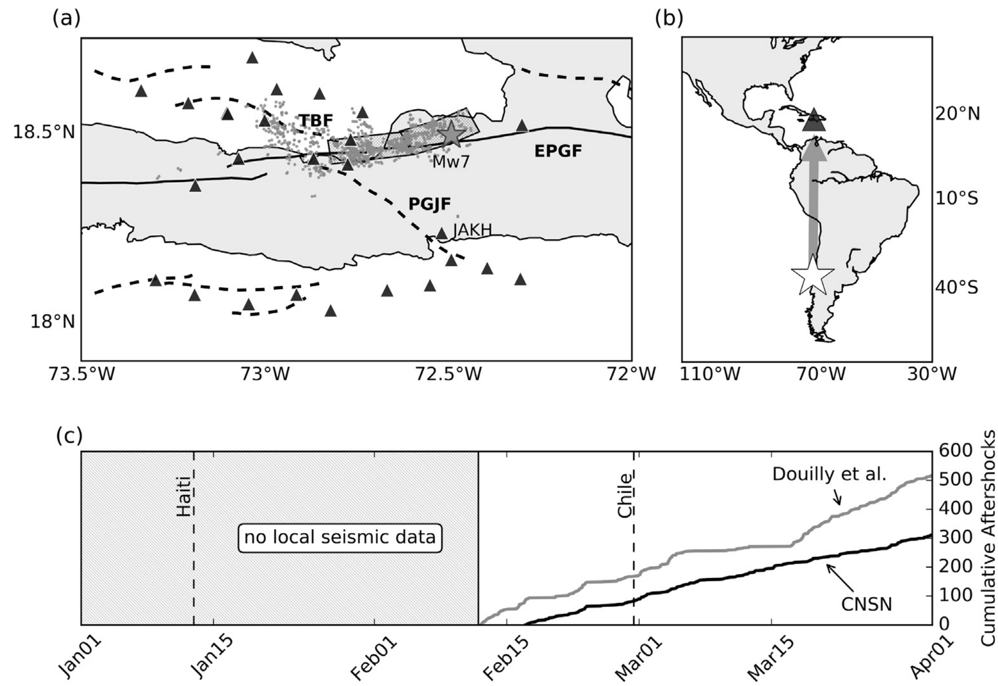

Fig. 1. Southern Haiti study region and local seismicity. (a) Left-lateral strike-slip Enriquillo–Plantain Garden Fault (EPGF, solid black line) marks the boundary between the Caribbean Plate to the south and Gonâve microplate to the north and is surrounded by several reverse faults (dashed lines), including the Trois Baies Fault (TBF) and Petit Goave–Jacmel Fault (PGJF). Triangles mark seismic stations used in this study. The 12 January 2010 *Mw*7.0 Haiti mainshock (gray star) and its aftershocks (gray dots) occur mostly north of the EPGF. Hatched area marks the east and west fault plane of the Léogâne Fault delineated from aftershock locations (Douilly et al., 2013). (b) Location of the 27 February 2010 *Mw*8.8 Maule, Chile earthquake (white star) and Haiti region (triangle). Arrow marks seismic wave propagation direction (almost perpendicular to EPGF). (c) Haiti aftershocks from the Canadian National Seismograph Network (CNSN) and Douilly et al. (2013). Haiti and Chile mainshocks occurred 46 days apart.

also occur as a result of secondary stress transfer (*e.g.*, Hill and Prejean, 2015). One example of secondary transfer is movement of fluids that exist in Earth's crust by passing seismic waves (*e.g.* Brodsky et al., 2003; Brodsky and Prejean, 2005). Essentially, seismic waves can pressurize fluids in Earth's crust, which may unclamp a fault if great enough and thereby reduces a fault's normal stress and promotes failure, according to the Coulomb failure model (Hill, 2012). Such a secondary triggering process is thought to be responsible for the observation of dynamically triggered earthquakes in extensional and transtensional regions (geothermal and volcanic regions) with ample fluids (*e.g.*, Prejean et al., 2004; Hill and Prejean, 2015). High fluid pressure is also thought to be a contributing factor for the dynamic triggering of tectonic tremor in compressional regions (subduction zones) (Peng and Gomberg, 2010; Beroza and Ide, 2011) and transpressional regions such as the San Andreas Fault in California (Hill et al., 2013; Peng et al., 2015) and the Oriente Fault in Cuba (Peng et al., 2013), as well as the Queen Charlotte Fault and Eastern Denali Fault in western Canada (Aiken et al., 2013, 2015).

In this study, we explore dynamic triggering in the southern Haiti peninsula region (Fig. 1). This region experienced a 240-year quiescence of moderate-size and larger earthquakes until 12 January 2010 when a *Mw*7.0 Haiti earthquake occurred (Bakun et al., 2012). Prior to the 2010 Haiti earthquake, no research quality stations were in operation in the region. The Haiti earthquake prompted many institutions to deploy temporary and permanent seismic stations surrounding the plate-bounding Enriquillo–Plantain Garden Fault (EPGF), both on land and offshore (Fig. 1a) to record aftershock activity (*e.g.*, Mercier de Lépinay et al., 2011). Aftershock activity delineated a previously unmapped north-dipping transpressional fault north of the EPGF as the source of the Haiti earthquake (now known as the Léogâne Fault). Due to static stress transfer, aftershocks also occurred on the reverse Trois Baies Fault (TBF) and transpressional EPGF (Douilly et al., 2013). It is worth noting that aftershock zones are known to be susceptible to triggering (*e.g.*, Hough el al., 2003; Jiang et al., 2010) due to their critically stressed state attributed to stress changes caused by the mainshock.

Forty-six days after the Haiti earthquake, the 27 February 2010 *Mw*8.8 Maule, Chile earthquake occurred about 6,000 km away from Haiti (Fig. 1b). The Chile earthquake is the 6th largest earthquake that has occurred since 1900, and its surface waves have triggered microearthquakes and tremor in many regions of the Western Hemisphere (*e.g.*, Fry et al., 2011; Zigone et al., 2012; Peng et al., 2011, 2013; Gomberg and Prejean, 2013; Aiken et al., 2013, 2015; Aiken and Peng, 2014), as well as icequakes in Antarctica (Peng et al., 2014). Because of its widespread triggering and because the southern Haiti region was in a critically stressed state, we investigate here whether the Chile mainshock triggered earthquakes and/or tectonic tremor on faults activated by the Haiti earthquake in the southern Haiti peninsula region. Such an investigation provides an opportunity to better understand how multiple fault structures that are critically stressed respond to external stress perturbations.

2. Search for dynamic triggering of tremor

2.1. General observations

Amidst the ongoing aftershock activity of the Haiti mainshock, we found tremor signals triggered during the Love and Rayleigh (surface) waves of the Chile earthquake (Fig. 2), though no similar signals were observed in the few days before the Chile earthquake. Three distinct tremor-like signals containing frequencies of ∼1–10 Hz are clearly visible, coincident with the first few cycles of the Love waves. These tremor signals are easily distinguished from the on-going aftershock activity, since the tremor bursts are emergent signals without distinct *P*- or *S*-waves (Fig. 2b) and have a longer duration compared to small, local aftershocks (Fig. 2c). Though the tremor signals are visibly different from the local after-