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First direct observation of coseismic slip and seafloor rupture along a submarine normal fault and implications for fault slip history

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ABSTRACT

Properly assessing the extent and magnitude of fault ruptures associated with large earthquakes is critical for understanding fault behavior and associated hazard. Submarine faults can trigger tsunamis, whose characteristics are defined by the geometry of seafloor displacement, studied primarily through indirect observations (e.g., seismic event parameters, seismic profiles, shipboard bathymetry, coring) rather than direct ones. Using deep-sea vehicles, we identify for the first time a marker of coseismic slip on a submarine fault plane along the Roseau Fault (Lesser Antilles), and measure its vertical displacement of ∼0.9 m in situ. We also map recent fissuring and faulting of sediments on the hangingwall, along ∼3 km of rupture in close proximity to the fault's base, and document the reactivation of erosion and sedimentation within and downslope of the scarp. These deformation structures were caused by the 2004 M_w 6.3 Les Saintes earthquake, which triggered a subsequent tsunami. Their characterization informs estimates of earthquake recurrence on this fault and provides new constraints on the geometry of fault rupture, which is both shorter and displays locally larger coseismic displacements than available model predictions that lack field constraints. This methodology of detailed field observations coupled with near-bottom geophysical surveying can be readily applied to numerous submarine fault systems, and should prove useful in evaluating seismic and tsunamigenic hazard in all geodynamic contexts.

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1. Introduction

Seismically active faults routinely experience ruptures that propagate all the way to the Earth's surface. The earthquake surface rupture is characterized by its extent, nature and displacement pattern. It results from a complex combination of parameters, including fault geometry and segmentation, surface geology, fault slip history, or the dynamics and geometry of the seismic rupture at depth. Past and modern coseismic fault ruptures can be readily observed in subaerial environments through field observations, high-resolution microtopography, aerial photography, and satellite imagery, among other methods (e.g., Avouac et al., 2014; DePolo et al., 1991; Klinger, 2005). These detailed studies help constrain the seismogenic history of these faults, and document the accommodation and release of stress and strain (Bhat et al., 2007; King, 2005; Rockwell and Klinger, 2013).

Surface fault rupture studies have been critical to establish scaling laws between earthquake magnitude and observables such as maximum or average faults, displacement and rupture length (e.g., Papazachos et al., 2004; Wesnousky, 2006, 2008). These complement similar scaling laws based solely on subsurface ruptures (Scholz et al., 1986; Wells and Coppersmith, 1994). These seismic scaling laws primarily rely on strike-slip earthquakes, yet may depend strongly on fault type (Stock and Smith, 2000). In this context, normal fault ruptures appear largely under-represented. Owing to the complexity of fault rupture propagation and subsurface geological controls, the surface rupture is typically shorter than the subsurface one, and the data used to constrain these scaling laws suffer from significant scatter (e.g., Wells and Coppersmith, 1994). Predictions of earthquake properties can thus vary by an order of magnitude or more, depending on the fault rupture parameter considered.

While ∼70% of the Earth's seismicity occurs offshore, detailed fault surface rupture observations and associated studies to date are exclusively subaerial. Submarine ruptures can also be associated with tsunami hazard, a threat that has proven to be much more damaging for coastal areas than the earthquakes themselves (Marano et al., 2010). Seafloor observations of coseismic fault ruptures are thus needed to determine whether subaerial observations and associated scaling laws can be extrapolated to the marine environment. Seafloor rupture observations are effectively lacking owing to limitations imposed by the environment, the technological requirements to conduct detailed fieldwork, and the lack of observations prior to seismic events to identify and characterize subsequent coseismic ruptures.

Submarine earthquake geology and history is typically reconstructed from sedimentary records containing turbidities cored offshore and primarily along active margins (e.g., Beck et al., 2012; Goldfinger, 2011, and references therein). High-resolution seismic imaging of co-seismically deposited units can provide information on earthquake activity at greater depths (and therefore on longer timescales) than those probed by coring. However, these techniques do not characterize the rupture induced by individual earthquakes. So far, shipboard geophysical methods (bathymetry, side-scan sonar images) have been used to map recently reactivated faults (Armijo et al., 2005; Cattaneo et al., 2012; Elias et al., 2007), and to evaluate seafloor vertical displacement in the case of extremely large events such as the Tohoku-Oki earthquake (Fujiwara et al., 2011; Kodaira et al., 2012). Seafloor observations have also identified possible submarine coseismic scarps (Armijo et al., 2005; Matsumoto et al., 2009; Tsuji et al., 2012), but extensive seafloor characterizations of fault rupture extent and slip distribution are still lacking.

This study presents high-resolution geophysical data acquired in December 2013 along the Roseau fault, an active normal fault that produced a M_W 6.3 earthquake in 2004 in the Guadeloupe archipelago (French West Indies, Fig. 1). Our data analysis demonstrates an unequivocal link between observed deformation structures and this seismic event allowing us to characterize the distribution and nature of the coseismic fault rupture at the seafloor, and to identify possible links between coseismic fault reactivation and erosional or depositional processes along the submarine fault scarp. We also measure the magnitude of coseismic displacement at a specific outcrop along the fault. Our results validate model predictions of fault rupture and tsunami generation in the area, and are compared with subaerial observations of normal fault rupture and associated scaling laws. We also demonstrate the feasibility of high-resolution seafloor mapping, and its importance for expanding our understanding of fault rupture and dynamics to the marine environment.

2. Intra-arc active faulting and seismicity: Les Saintes Graben (French Antilles)

The Les Saintes graben extends between Guadeloupe and Dominica Islands (Fig. 1) accommodating internal deformation of the Lesser Antilles arc due to oblique plate convergence (Feuillet et al., 2002, 2011a). This graben shows a long history of interacting volcanic emplacement and faulting, and is bound to the southwest by the ∼40 km long, NE dipping Roseau Fault (RF), which is segmented into several ∼5–15-km long portions (Fig. 1B). In its northern part, these are arranged as right-stepping echelons, trending N140°E, and crosscutting the seafloor in the vicinity of the Les Saintes archipelago, which is highly populated and a major tourist destination. The southern Roseau Fault section instead shows left-stepping echelons, with an overall trend of N120°E (Leclerc et al., in press).

The cumulative fault scarp height varies along the Roseau Fault trace and peaks at >150 m at its center, coinciding with the most prominent echelon, hereafter termed the Roseau echelon. The cumulative scarp dissects the flank of the volcanic arc, which slopes towards the southwest, and captures sediments from the Les Saintes Islands and adjacent reef platform, which are then channeled along the base of the Roseau scarp. These sediments, together with debris from the fault scarp, make up a >300-m thick layer within the hangingwall basin (Leclerc et al., in press).

On November 21st, 2004, the M_W 6.3 Les Saintes earthquake struck the Guadeloupe archipelago, one of the strongest earthquakes to have occurred on French territory in the last decades. Ground shaking up to intensity-VIII was felt on Terre-de-Bas (Cara et al., 2005), triggering landslides and ground fissuring that seriously damaged ∼50% of the buildings (Feuillet et al., 2011a). The ∼10 km deep epicenter was located offshore, ∼15 km SE of the Les Saintes plateau (Fig. 1B). Relocation of the aftershock sequence indicates that this mainly extensional M_W 6.3 earthquake ruptured the Roseau fault, which dips at ∼55° to the NE at depth (Bazin et al., 2010; Feuillet et al., 2011a). This triggered a tsunami with a maximum run-up of 3.5 m on the nearby coasts of Les Saintes archipelago (Le Friant et al., 2008). Lacking direct observations, ad-hoc models of fault slip and tsunami sources were used to estimate a seafloor rupture with an along-strike extent ranging between <10 km and ∼15 km, and normal displacements of up to 1 m, with an average of 0.3–0.6 m (Feuillet et al., 2011a; Le Friant et al., 2008). The focal mechanisms of both the main shock and the largest aftershocks indicate extension in the NE quadrant. The modeled rupture rake shows that the main event also accommodated a minor left-lateral slip component (Feuillet et al., 2011a). Aftershocks occurred mainly north of the original hypocenter, beneath Les Saintes plateau and along the northern echelons of the Roseau fault, in response to a static stress increase at the tip of the rupture (Feuillet et al., 2011a). In particular, the strongest aftershocks, 8–12 km deep and reaching M_W up to 5.8, did not trigger