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Scaling and spatial complementarity of tectonic earthquake swarms

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ABSTRACT

Tectonic earthquake swarms (TES) often coincide with aseismic slip and sometimes precede damaging earthquakes. In spite of recent progress in understanding the significance and properties of TES at plate boundaries, their mechanics and scaling are still largely uncertain. Here we evaluate several TES that occurred during the past 20 years on a transform plate boundary in North Iceland. We show that the swarms complement each other spatially with later swarms discouraged from fault segments activated by earlier swarms, which suggests efficient strain release and aseismic slip. The fault area illuminated by earthquakes during swarms may be more representative of the total moment release than the cumulative moment of the swarm earthquakes. We use these findings and other published results from a variety of tectonic settings to discuss general scaling properties for TES. The results indicate that the importance of TES in releasing tectonic strain at plate boundaries may have been underestimated.

1. Introduction

Sequences of earthquakes without a clear triggering mainshock, referred to as earthquake swarms, have been observed in volcanic and hydrothermal areas for decades. Tectonic Earthquake Swarms (TES) is another category of swarms linked to active tectonic regions. Recent work has helped identifying some common characteristics of TES regarding their release of seismic moment in time and space (Peng and Gomberg, 2010; Vidale and Shearer, 2006). TES have typical durations of days, weeks or months and the majority of their moment release is usually delayed from the onset of the sequences (Chen and Shearer, 2011; Roland and McGuire, 2009; Passarelli et al., 2015). In addition, TES often migrate at velocities of 1 km/day to 1 km/h, affecting larger volumes of rock than might be suggested by the largest earthquake of the sequence (Vidale and Shearer, 2006; Lohman and McGuire, 2007; Roland and McGuire, 2009). Furthermore, established earthquake scaling laws, such as the Gutenberg–Richter, Omori–Utsu or Båth laws, often do not work well for swarms. TES usually do not involve high magnitude events and are thought to release only an insignificant fraction of the accumulated tectonic strain at plate boundaries. However, the role TES play in releasing tectonic strain has rarely been quantified and remains poorly understood.

Based on deformation measurements, some TES have been linked to Slow Slip Events (SSEs) (Cheloni et al., 2017; Lohman and McGuire, 2007; Vallèe et al., 2013; Villegas-Lanza et al., 2016). In addition, several destructive earthquakes, including the 2009 L'Aquila, the 2011 Tohoku and the 2014 Iquique earthquakes, followed TES linked to or driven by SSEs (Borghi et al., 2016; Kato et al., 2012; Schurr et al., 2014).

TES are puzzling for their apparent lack of "order": no significant correlation has been found between their moment release and their duration or migration properties (Peng and Gomberg, 2010; Vidale and Shearer, 2006). Peng and Gomberg (2010) noticed that the moment/duration scaling of TES appears to branch off that for SSEs. However, they postulated that TES might commonly hide aseismic moment, and if this moment were to be detected, e.g. by deformation measurements, then the swarms would scale analogously to SSEs. This hypothesis is difficult to test, due to a lack

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of data on TES spanning different moment scales and tectonic settings. Another issue is that seismicity catalogs are generally not long enough to consider recurrence times of TES, which makes it difficult to assess their role in the long-term tectonic strain budget (Passarelli et al., 2015; Cheloni et al., 2017). Usually, historical information on earthquake swarms is not even included in the historical earthquake catalogs (Passarelli et al., 2015).

To study further the properties of TES and define their interaction behavior over longer time scales we have analyzed ∼20 yr of seismic data containing several well-recorded and energetic TES that occurred on the Húsavík–Flatey Fault (HFF) in North Iceland. We have selected the largest TES sequences and investigated their spatial and temporal organization, before comparing their scaling to that of previously evaluated TES. Finally, we have discussed the possible physical mechanisms behind their behavior.

2. Seismicity along the Húsavík–Flatey Fault and Eyjafjarðaráll Rift

The HFF is a ∼100-km-long right-lateral transform fault and a part of the wider Tjörnes Fracture Zone, which links two segments of the Mid-Atlantic Ridge in Iceland, i.e. the Northern Volcanic Zone to the offshore Eyjafjarðaráll Rift (ER) and Kolbeinsey Ridge (Fig. 1a). The HFF has been active since 7–9 Myr and probably has a cumulative displacement of more than 60 km (Rögnvaldsson et al., 1998). At this latitude the divergence rate between the North American and Eurasian plates is ∼18 mm/yr, of which 6–9 mm/yr is focused on the HFF according to interseismic backslip modeling constrained by GPS (Metzger and Jónsson, 2014, Metzger et al., 2011 and 2013). Three or four magnitude 6.5–7 historical earthquakes occurred on the HFF in the past 300 years with the last large earthquakes in 1872 (Fig. 1a), so the accumulated moment on the fault corresponds approximately to a magnitude 6.8–7.0 earthquake (Metzger and Jónsson, 2014).

Earthquake locations in North Iceland are routinely determined with data collected by the Icelandic National Seismic Network (SIL, Icelandic Meteorological Office), which has a detection threshold ranging from magnitude zero on the eastern HFF to magnitude one offshore (Hensch et al., 2013). The statistical magnitude of completeness, M_c, is slightly higher, or 0.5 on the eastern HFF and 1.5 offshore (Maccaferri et al., 2013). Typical location errors of earthquake hypocenters are of the order of a few kms with a decreasing accuracy moving westward along the HFF (Hensch et al., 2013).

We relocated all 27969 earthquakes in the SIL catalog (Böðvarsson et al., 1996) from 1997 until 15th of July 2015 that occurred within 10 km from the HFF and ER (Fig. S1). We used the relative location method by Slunga et al. (1995) and a local seismic velocity model from local earthquake tomography (LET), replacing the top 5 km of the layered LET model (Riedel et al., 2005 and 2006) with a velocity gradient (Fig. S2). We then selected 23425 events with horizontal errors <200 m and vertical errors <2 km (Fig. S3, Jakobsdóttir et al., 2013). The relocated events appear more focused and shallower than the automatic locations, consistent with results from previous relocation studies of North Iceland (Rögnvaldsson et al., 1998; Hensch et al., 2008).

We estimated the cumulative seismic moment release per km on the HFF and ER since 1997 and compared it to the slip deficit expected for the same time interval (Metzger et al., 2013; Metzger and Jónsson, 2014). Based on available focal mechanism solutions for the largest earthquakes we calculated the component of the slip vector parallel to the tectonic motion and the component of the fault area parallel to the plate boundary surface (Bird et al., 2002). We used a shear modulus of 30 GPa and an average seismogenic thickness of 10 km (Bird et al., 2002; Metzger and Jónsson, 2014). From this analysis, we find that the fraction of strain released by the earthquakes varies spatially by two orders of magnitude, with 30% of the strain released on the ER segment, but only 3% on the northwestern-most part of the HFF and 0.1% on the remaining part of the fault (Fig. 1b). Full locking of the eastern HFF is consistent with analysis of the stress shadow casted by the 1975–1984 Krafla rifting episode, which involved a sequence of 19 dike intrusions that compressed the easternmost portion of the fault abating the seismic activity (Rögnvaldsson et al., 1998; Maccaferri et al., 2013; Passarelli et al., 2014).

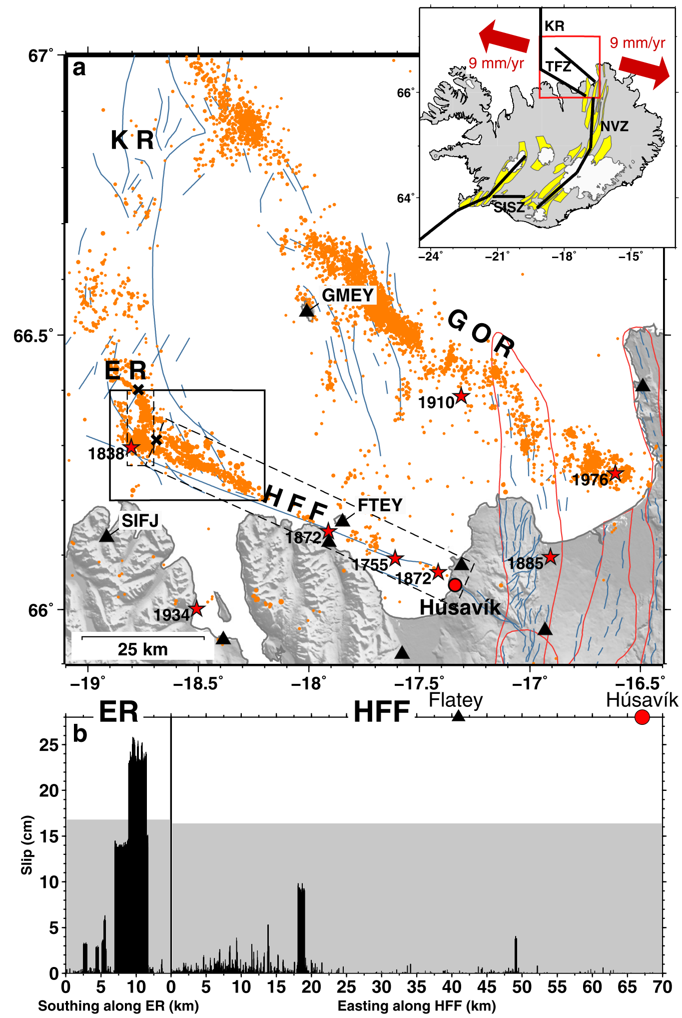

Fig. 1. Earthquake locations in North Iceland and moment release along the Eyjafjarðaráll Rift (ER) and the Húsavík–Flatey Fault (HFF). (a) Earthquakes (orange dots) in the Tjörnes Fracture Zone (TFZ) primarily occur on the HFF and the Grímsey Oblique Rift (GOR). Red stars mark approximate locations of historical $M > 6$ earthquakes, black triangles seismic and GPS (when labeled) stations, blue thin lines mapped faults and fractures, and red thin lines the outlines of fissure swarms and volcanic systems. The black rectangle marks the earthquake swarm study area shown in Fig. 2 while black dashed boxes bound the earthquakes considered in the moment release diagram in (b) with thick black crosses indicating the position of the axes origins. The town of Húsavík is indicated by a red dot. FTEY marks Flatey Island and a GPS station located there and KR stands for Kolbeinsey Ridge. Inset shows the TFZ location in North Iceland and the relative plate velocity. SISZ and NVZ stand for South Iceland Seismic Zone and North Volcanic Zone. (b) Cumulative seismic moment released by earthquakes within the rectangular dashed boxes shown in (a) around the ER and the HFF during 1997–2015 and represented as fault slip. Gray shaded areas are the slip predicted by tectonic loading at plate speed of 9 mm/yr. The slip along ER is projected on the horizontal plane and the dip angles for HFF and ER are 90° and 60° respectively. The rupture areas of earthquakes are calculated using standard scaling (Wells and Coppersmith, 1994) and the fault width is fixed at 10 km for both fault segments. The scalar seismic moment of the earthquakes is derived using the moment-magnitude scaling (Kanamori and Anderson, 1975) and the slip scales with moment assuming a rigidity of 30 GPa. Flatey Island (black triangle) and the town of Húsavík (red circle) are indicated for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)