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Imbricated slip rate processes during slow slip transients imaged by low-frequency earthquakes

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A B S T R A C T

Low Frequency Earthquakes (LFEs) often occur in conjunction with transient strain episodes, or Slow Slip Events (SSEs), in subduction zones. Their focal mechanism and location consistent with shear failure on the plate interface argue for a model where LFEs are discrete dynamic ruptures in an otherwise slowly slipping interface. SSEs are mostly observed by surface geodetic instruments with limited resolution and it is likely that only the largest ones are detected. The time synchronization of LFEs and SSEs suggests that we could use the recorded LFEs to constrain the evolution of SSEs, and notably of the geodetically-undetected small ones. However, inferring slow slip rate from the temporal evolution of LFE activity is complicated by the strong temporal clustering of LFEs. Here we apply dedicated statistical tools to retrieve the temporal evolution of SSE slip rates from the time history of LFE occurrences in two subduction zones, Mexico and Cascadia, and in the deep portion of the San Andreas fault at Parkfield. We find temporal characteristics of LFEs that are similar across these three different regions. The longer term episodic slip transients present in these datasets show a slip rate decay with time after the passage of the SSE front possibly as $t^{-1/4}$. They are composed of multiple short term transients with steeper slip rate decay as $t^{-\alpha}$ with α between 1.4 and 2. We also find that the maximum slip rate of SSEs has a continuous distribution. Our results indicate that creeping faults host intermittent deformation at various scales resulting from the imbricated occurrence of numerous slow slip events of various amplitudes.

1. Introduction

Faults are complex interfaces with heterogeneous properties. This is notably reflected by the large fluctuations of fault surface topography found over a broad range of scales on fault outcrops (Candela et al., 2009). Deciphering the physics of fault systems is challenging due to the wide range of time and spatial scales associated with fault slip (Ben-Zion, 2008). Our ability to probe the dynamics of fault systems at depth is limited by the coarse spatial resolution provided by surface data (e.g. Radiguet et al., 2011). A common conceptual framework to rationalize the diversity of fault slip behavior is a model of fault interface consisting of locked, unstable patches capable of nucleating earthquakes and embedded in a stable fault matrix capable of steady or transient aseismic slip. The interactions between these two rheological components lead to a rich variety of phenomena such as slow slip events (SSEs) (e.g. Radiguet et al., 2011), earthquake swarms (e.g. Lohman and McGuire, 2007; Villegas-Lanza et al., 2015), creep episodes recorded along strike slip faults (Wesson, 1988; Jolivet et al., 2015; Rousset et al., 2016) or in laboratory experiments (Måløy et al., 2006; Lengliné et al., 2012), afterslip (e.g. Miyazaki et al., 2004) and earthquake triggering mediated by elastic stress transfers (e.g. Dieterich, 1994) or by intervening aseismic slip transients (e.g. Ariyoshi et al., 2009, 2012; Lui and Lapusta, 2016). The main ingredients describing the dynamics of such interfaces are i) slow loading, ii) the heterogeneous nature of the medium and iii) long range elastic interactions. We can gain insight into the overall loading and stressing cycles of faults by analyzing the temporal behavior of slip in different geological contexts. Because direct imaging of small-amplitude slow slip at depth is often not possible, here we exploit the seismic signals that accompany slow slip, which we consider markers of the local slip rate on the fault interface (Frank, 2016). By analyzing such signals and their statistical properties we obtain information about the physics of the deforming heterogeneous medium and find that the transient deformation on different faults share common features, suggesting a common mechanical process.

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Low frequency earthquakes (LFEs) are a particular type of seismic event recorded in several subduction zones and strike slip faults. They are characterized by a depletion in radiated energy at high frequencies compared to regular tectonic earthquakes. LFEs occur in environments where mostly aseismic slip is expected, generally in swarms forming tectonic tremors and often in conjunction with geodetically-detected slow slip transients. Numerous observations indicate that LFEs result from the dynamic shear failure on an otherwise aseismic interface (Shelly et al., 2006; Ide et al., 2007; Frank et al., 2013; Royer and Bostock, 2014). If LFEs can be considered a passive monitor of slow slip at depth (Shelly et al., 2011; Frank and Shapiro, 2014; Frank et al., 2015a,b), they provide high-resolution information about the spatio-temporal evolution of aseismic transients (Frank, 2016).

Indeed the concomitant increase of tremor/LFE activity and transient strain recorded by surface sensors suggests that both signals share the same mechanical origin. The propagation of a slow slip pulse along the fault interface is generally considered as both the driver of LFEs and the source of surface displacements associated with SSEs (Bartlow et al., 2011). Such slow slip fronts are also predicted by numerical and theoretical models of velocity-dependent frictional interfaces (Ariyoshi et al., 2009, 2012; Hawthorne and Rubin, 2013a). However the limited sensitivity and resolution of geodetic instruments severely challenges the detection of transient deformation episodes such that only the largest SSEs are captured. LFEs are detected all the time, yet SSEs are not. Most likely, weak transient deformation episodes have gone undetected. Notably, in the Parkfield segment of the San Andreas fault, numerous LFEs are recorded but no geodetic signals have been reported from deep slow slip events (Johnston et al., 2006). Here we propose to use LFEs to characterize the small amplitude transients invisible to GPS. Yet, the analysis of LFE activity is not straightforward and requires a detailed processing in order to relate the analyzed signal to the slip on the interface. This difficulty is especially related to the strong time-clustering of the LFE activity at short time-scale, which can dominate the signal (Trugman et al., 2015). We thus develop here a new method to extract the signature of slow slip events from the discrete occurrence of LFEs.

We analyze the timing of LFEs in order to constrain the temporal evolution of the process that drives them. We focus our analysis on LFEs identified in two subduction zones, Mexico and Cascadia, and on the deep portion of the San-Andreas fault at Parkfield. The activity of LFEs is often bursty, with a majority of events grouped into numerous short-lived swarms exhibiting high rates of LFEs (Frank et al., 2016). We first analyze the short-term dynamics of LFEs, revealing a strong clustering that decays quickly with time and that is present in all three datasets. These local short term transient episodes combine over longer time scales into bursts that we associate with SSEs. We show that such larger scale transient episodes occur all the time and with a variable amplitude. The decay of the event rate with time during these bursts illuminates the underlying slow slip rate, indicating a decay of both the slip velocity and the propagation speed of the SSE front with time.

2. LFE catalogs

All LFEs analyzed in this study have been detected through matched-filter searches based on their similarity to previously identified template waveforms (Gibbons and Ringdal, 2006). The LFEs associated with a common template will be referred to as a family. The high similarity of waveforms among LFEs of a given family indicates they originate from very closely located sources. Based on the current location methods, we cannot distinguish if a family is generated by a single source or by distinct sources distributed in a compact area. Here we consider each family represents the repetitive failure of the same asperity along the fault plane. We latter support this assumption based on our modeling results.

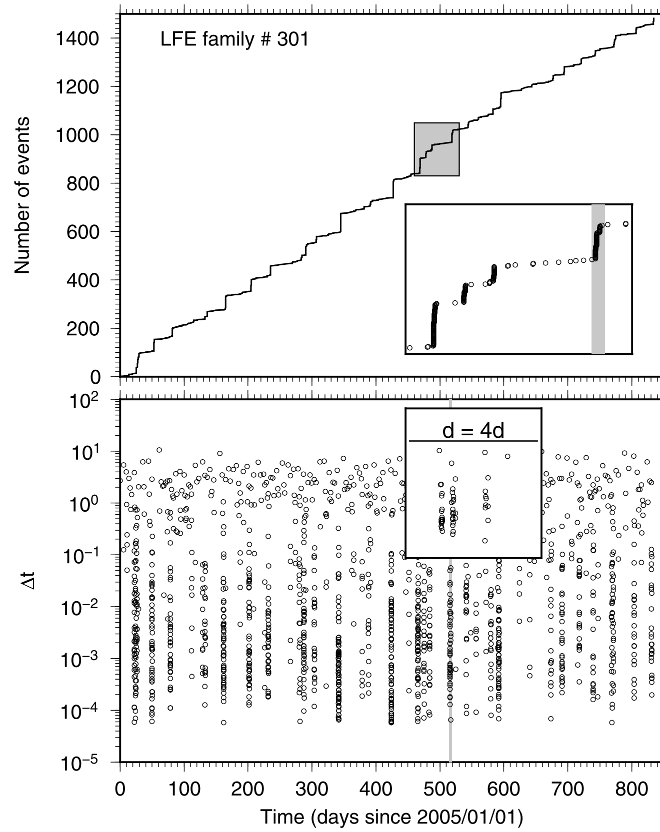

Fig. 1. Example of an LFE family detected on the Mexican interface. Top: The cumulative number of events in the family is displayed as a function of time. We observe an intermittent activity with bursts of LFEs making up the majority of events. The inset shows a zoom of the time period indicated by the gray box. Bottom: LFE recurrence times as a function of time. Bursts appear as vertical streaks of symbols. The inset shows a zoom of the time period indicated by the 4-day long gray interval in the inset of the top figure. We observe that the burst itself is composed of a succession of very short term sequences.

The LFE activity appears time clustered, with a majority of the LFEs in a family occurring during several bursts with only a few events in between (Frank et al., 2016) (Fig. 1).

We use three LFE catalogs in this study (Table 1). We first use a catalog of LFEs that occurred between January 2005 and April 2007 in the Mexican subduction zone (Frank et al., 2014). Some of the LFE families nearest to the trench are perturbed by the occurrence of a large slow slip in 2006 (Radiguet et al., 2011). We also analyze events in the Cascadia subduction zone, underneath Vancouver Island, from the catalog reported in Bostock et al. (2012). The LFEs in this catalog are only reported during the occurrence of large SSEs across almost 11 years, from February 2003 to October 2013. We use as well the Parkfield LFE catalog which comprises 88 LFE families that occurred on the deep portion of the San Andreas fault (Shelly and Hardebeck, 2010; Shelly, 2017). Events in this catalog are distributed over a 10 year long period extending from April 2001 to January 2010, but we only consider LFEs that took place after July 2005, in order to mitigate the impact of the September 2004, M_W6 earthquake on our analysis.

3. Model

We propose a statistical model that aims to reproduce the observed rate of LFEs as a function of time in a given family. No spatial dependence is taken into account in our model and we do not consider any explicit interaction between families. This does