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Tidal triggering of earthquakes suggests poroelastic behavior on the San Andreas Fault

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ABSTRACT

Tidal triggering of earthquakes is hypothesized to provide quantitative information regarding the fault's stress state, poroelastic properties, and may be significant for our understanding of seismic hazard. To date, studies of regional or global earthquake catalogs have had only modest successes in identifying tidal triggering. We posit that the smallest events that may provide additional evidence of triggering go unidentified and thus we developed a technique to improve the identification of very small magnitude events. We identify events applying a method known as inter-station seismic coherence where we prioritize detection and discrimination over characterization. Here we show tidal triggering of earthquakes on the San Andreas Fault. We find the complex interaction of semi-diurnal and fortnightly tidal periods exposes both stress threshold and critical state behavior. Our findings reveal earthquake nucleation processes and pore pressure conditions – properties of faults that are difficult to measure, yet extremely important for characterizing earthquake physics and seismic hazards.

1. Background

Earthquake triggering can occur in response to both quasi-static stress changes and dynamic forcing. Aftershocks are a well-known example of triggering by quasi-static and dynamic stress transfer, while triggering of distant earthquakes by seismic waves is an example of strictly dynamic triggering (Delorey et al., 2015; Gomberg et al., 2004; Gonzalez-Huizar et al., 2012; Hill et al., 1993). Earthquake triggering has the potential to be extremely valuable in probing stress state characteristics such as critical state (near failure) conditions (Brinkman et al., 2015; Brodsky and van der Elst, 2014; Johnson et al., 2013; van der Elst et al., 2013). Triggering by Earth tides can be particularly informative since tides are always present and observations can be stacked in time, in contrast to dynamic earthquake triggering which can occur only during or after the passage of large amplitude seismic waves.

Earth tides are caused by the gravitational pull of the sun and moon, which induce periodic stresses related to the rotation of the Earth relative to the sun and moon (semi-diurnal, ~12 h and diurnal, ~24 h). A longer-period modulation of these cycles arises due to the orbit of the moon around the Earth (fortnightly, ~14.7 days). Earth tides impart both normal and shear stresses on fault surfaces in the upper crust. During tidal-induced periods of increasing Coulomb stress on a fault, the stressing rate is much higher than the long-term tectonic stressing rate determined from the average stressing rate between M_w6 earthquakes near Parkfield, California (Agnew, 1997; Kim and Dreger, 2008). Tidal triggering of earthquakes has been observed locally preceding large earthquakes (Tanaka, 2010, 2012; Tanaka et al., 2002b), and also in global or regional datasets that span longer periods of time (Cochran et al., 2004; Metivier et al., 2009; Tanaka et al., 2002a; Tsuruoka et al., 1995). Tides also trigger earthquakes at volcanoes (Emter, 1997; Mcnutt and Beavan, 1981; Rydelek et al., 1988) and ocean tides (Stroup et al., 2007; Tolstoy et al., 2002; Wilcock, 2001, 2009) may trigger earthquakes in ocean basins.

Continental crust is thought to be critically stressed (Townend and Zoback, 2000) meaning that faults near failure are ubiquitous. If this is true, then we might expect earthquake triggering to be widespread in response to transient stresses associated with tides and large amplitude seismic waves; however this is not observed (Vidale et al., 1998). We propose that observations of the tidal triggering of earthquakes are scarce because most earthquakes and therefore most triggered earthquakes are small and below detection limits. The barrier to observing tidally triggered earthquakes may simply be a lack of completeness in the catalog. Thus our intent here is to improve detections of small earthquakes to determine if tidal triggering of earthquakes is occurring in regions where it is currently not detected using existing earthquake cat-

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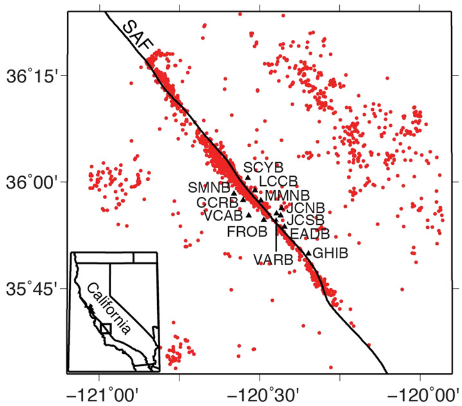

Fig. 1. Map. Red circles represent earthquakes from the NCSN catalog in calendar years 2012–2014 that are within 50 km of Parkfield, California and 50 km of the SAF. The black curve labeled "SAF" represents the San Andreas Fault. The labeled black triangles represent the stations of the HRSN used in this study. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

alogs. Our test case is a segment of the SAF near Parkfield, California (Fig. 1) because it is well instrumented, has a relatively high ambient seismicity rate, and is known to exhibit tidal triggering of low frequency earthquakes (LFEs) (Thomas et al., 2012; van der Elst et al., 2016) and non-volcanic tremors (NVTs) (Thomas et al., 2009) in the middle crust.

2. Earthquake catalogs

Traditional earthquake catalogs like that provided by the Northern California Seismic Network (NCSN) require a sufficient number of phase arrivals in order to estimate location and magnitude, which limits their completeness. Tidal correlation is suggested, but not statistically significant in the NCSN catalog (Fig. S1). We hypothesize that its significance could be limited by the stringency of the catalog location requirements. Thus, we develop a catalog in which we emphasize only detection and discrimination of phase arrivals so that the occurrence of smaller events may be cataloged, even when a precise location cannot be obtained (see examples in Figs. 2 and S2). Discrimination in this context means discriminating local, regular earthquakes from distant earthquakes, non-earthquake sources on Earth's surface, and deeper LFEs and NVTs. We search for earthquakes by looking for seismic energy arriving across the NCSN that is consistent with emissions from local earthquakes.

NVTs are detected by identifying similar, emergent, long-duration waveforms across a seismic array cannot be explained by surface sources or noise (Obara, 2002). Correlation techniques are often used to identify and locate NVTs because they do not have impulsive or easily identifiable phase arrivals (Wech and Creager, 2008). Small earthquakes are similar in the sense that it is difficult to pick phase arrivals when the signal to noise ratio is low even when a signal has obvious earthquake characteristics. These earthquakes are missing from traditional catalogs because though they are often easily identified, they are difficult to characterize. Even with minimal characterization, these earthquakes contain valuable information and are worth cataloging.

We apply a similar approach to finding small earthquakes as others have used to find NVTs (Obara, 2002; Wech and Creager, 2008). We use unique array characteristics of local earthquakes to identify them in continuous data. Cross-correlating the waveform envelope, we look for energy within the 5–10 Hz band that has apparent velocities consistent with body waves emanating from sources within the local crust. Waves from regional and distant sources are highly attenuated in this band. The highest amplitude waves from non-earthquake, surface sources have apparent velocities of surface waves and in the 5–10 Hz band have very small displacements at the depths of the borehole instruments of the NCSN. Also, since we do not use station pairs closer together than 5 km, only very energetic non-earthquake sources will be recorded on two or more instruments. (See methods for a full description of the earthquake detection method and the supplementary data for our complete catalog.)

Our coherence-derived earthquake catalog covers the calendar years 2012–2014 and contains 6735 earthquakes. In addition to the earthquakes we detect, we add 206 earthquakes from the NCSN catalog that are within 50 km of Parkfield and 5 km of the SAF that do not correspond to an earthquake in our base catalog, resulting in a total catalog of 6941 earthquakes. During the same period of time there are 1654 earthquakes in the NCSN earthquake catalog within 50 km of Parkfield and 5 km of the SAF. We do not determine a location for our detections other than to note the closest station. However by comparing our detections to matching detections in the NCSN earthquake catalog, we estimate that most ($>90\%$) are also within about 50 km of Parkfield. 75% of the events in the NCSN catalog within 50 km of Parkfield are within 5 km of the SAF (Fig. S3), and thus we assume the same for our catalog. Our detections with matching entries in the NCSN earthquake catalog are not biased with regard to the distribution of depths found in the full NCSN catalog for the study period and region, which have a mean depth of 6.4 km and a median depth of 5.2 km.

For each earthquake in our catalog, we assign a phase for both the semi-diurnal cycle and the fortnightly cycle (Fig. S4). An important point is that the total tidal stress time series is not a simple sinusoid. When we refer to the semi-diurnal phase, what we mean is the phase associated with the total tidal stress time series, whose period is dominated by the semi-diurnal period of $\sim$12.4 h. In any given cycle, the apparent period and phase is perturbed somewhat by the influence of other tidal components whose periods are close to 12 or 24 h. However, over long periods of time the average period is the semi-diurnal period. We determine the phase from the entire tidal stress time series because faults do not feel each tidal component independently. In the case of the fortnightly cycle, we use the timing of lunar phases to determine the phase.

We here consider temporal processes that could mimic tidally modulated clustering but be only coincidently correlated with tidal stresses. The lunar semi-diurnal component (M_2) has the largest amplitude with more than twice that of the solar semi-diurnal component (S_2). The phase of the M_2 component dominates the phase of the total stress signal. With a period of $\sim$12.4 h, the phase of the M_2 component progressively shifts relative to daytime and nighttime hours, so over the three year study period there is no net correlation with any diurnal signal anthropogenic or otherwise (see supplemental material). Potential biases introduced by seasonal processes do not affect the total catalog because the duration of our study is three full calendar years.

The other manner in which there may be apparent correlation of seismicity with tides is if aftershocks or other clustered events are correlated with tidal stresses but not caused by tidal stresses. Since our detection catalog contains only the timing of earthquakes, we do not have enough information to apply standard algorithms to remove aftershocks. Instead, we test the possibility that aftershock clustering could invalidate our measurements by creating 10000 synthetic catalogs that contain aftershocks using an ETAS model consistent with California seismicity (Field et al., 2014) but no explicit periodic forcing. We performed a maximum likelihood estimation (MLE) testing the periodicity of the synthetic catalogs against the periodicity of our catalog. Only 24 of the 10000 synthetic catalogs were more periodic than ours on the semi-diurnal cycle. All of these 24 synthetic catalogs contained