The physics of low-frequency earthquakes with doubling recurrence intervals near Parkfield

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I. Project Overview

A. Abstract
In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

A particular tremor family deep below the San Andreas Fault (SAF) exhibited doubling recurrence intervals alternating between about three and six days. Our physics-based model with single homogenous asperity can explain the doubling recurrence intervals of the tremor source. The observed source characteristics show that tremor bursts containing more low-frequency earthquakes (LFEs) are associated long duration. Here, we investigate the physics of the micro-asperities under rapid loading to model the number of LFEs in a burst and the tremor duration. We find that the observed number of LFEs per burst is controlled by peak velocity of the modeled slip event. However, the duration of the observed tremor burst is not directly controlled by the duration of the modeled slip event. The results reveal that the LFEs are triggered shortly after the slip events, and the mechanism is similar to mainshock/aftershocks interactions. Our numerical study may enable us to decipher the fundamental difference between tremors and earthquakes in terms of their moment and duration.

B. SCEC Annual Science Highlights
Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

1. Fault and Rupture Mechanics (FARM)
2. Seismology
3. Earthquake Simulators.

C. Exemplary Figure
Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.
Figure 1. Recurrence pattern of the period-doubling Parkfield tremors and numerical simulations. A) Observed tremor recurrence pattern and number of LFEs per burst, modified from Shelly (2010). Each tremor burst consists of 1 to 5 LFEs in most cases. Burst preceded by a shorter recurrence interval are associated with more LFEs throughout the sequence (consecutive bursts are connected with a gray line). The regular oscillation of recurrence intervals between about three and six days is from mid-2003 to the onset of the 2004 Parkfield earthquake. The sudden disappearance of the 6-day recurrence intervals coincides with the 2004 Parkfield earthquake. The gradual recovery of recurrence intervals is from the onset of the Parkfield earthquake to the end of 2007, around two years. B) Numerical simulation of the Parkfield tremor activity incorporating a change in effective confining pressure (red profile) after the Parkfield earthquake. The colored circles denote the maximum velocity of the slip events. Fast ruptures are preceded by shorter recurrence intervals. The 2004 Parkfield earthquake results in a rapid occurrence of slip events, followed by a sequence of multiplets with varying period-multiplying factors.

D. SCEC Science Priorities
In the box below, please list (in rank order) the SCEC priorities this project has achieved. See https://www.scec.org/research/priorities for list of SCEC research priorities. For example: 6a, 6b, 6c

5d. Development of physics-based models of slow slip and tectonic tremor.

E. Intellectual Merit
How does the project contribute to the overall intellectual merit of SCEC? For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?

We developed a physics-based model to understand the tremor recurrence intervals, which may provide insight into understanding the effect of pore pressure change on recurrence interval variability of the earthquakes. Our model explains the period-doubling phenomenon of the tremor family, which was not previously explained. We are creative in applying the occurrence of slow-slip and fast-slip events to explain the doubling intervals of the tremor family.

F. Broader Impacts
How does the project contribute to the broader impacts of SCEC as a whole? For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities,
instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?

A significant contribution was made by a female graduate student (underrepresented).

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at http://www.scec.org/user/login and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email web@scec.org for assistance.

N.A
II. Technical Report

The technical report should describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the report. (Maximum 5 pages, 1-3 figures with captions, references and publications do not count against limit.)

A. Objective

The main objective of this project is to understand the physics of a particular tremor family deep below the San Andreas Fault (SAF). Our current model with single homogenous asperity can explain the doubling intervals and the postseismic transient of the tremor family. Our present aim is to advance the model by incorporating micro-asperities to explain the source properties, mainly the number of low-frequency earthquakes in each tremor event for years of slip cycles. We also aim to investigate triggering of tremors by distant earthquakes as well as tides.

B. Methodology

We use BICyclE (Boundary Integral Cycle of Earthquakes) program (Lapusta and Rice, 2003, Lapusta and Liu, 2009) to simulate fault slip evolution during all stages of the earthquake cycle. Our three-dimensional fully dynamic model is based on the laboratory-derived rate-and-state-dependent friction law (Dieterich, 1978,1979).

The friction properties and the effective confining pressure controls the stability of slip in a simple model with velocity-weakening asperity surrounded by a velocity-strengthening (unconditionally stable) region (Rice and Ben-Zion, 1996; Ruina, 1983; Scholz, 1998; Tse and Rice, 1986). Linear stability analysis (Ruina, 1983) and experiments of finite-size ruptures (Ampuero et al., 2002) indicate critical values of the non-dimensional parameter R=h* above which asperities are seismogenic (conditionally unstable) and below which perturbations are transient and short lived (conditionally stable), where R is the linear dimension of the asperity and h* is a combination of the frictional parameters and the effective confining pressure. These studies provide invaluable insight about evolution of slip on faults.

C. Results

We find that a single asperity with homogenous frictional properties can produce two distinct slip events in the same area, which in turn produce doubling intervals. Pore-pressure changes and related diffusion can cause the change in the tremor activity suddenly after the 2004 Parkfield earthquake. We find that the observed number of LFEs per burst is controlled by peak velocity of the modeled slip event (Figure 1). However, the duration of the observed tremor burst is not directly controlled by the duration of the modeled slip event (Figure 2). The results reveal that the LFEs are triggered shortly after the slip events, and the mechanism is similar to mainshock/aftershocks interactions.
D. Significance

Apart from understanding the peculiar characteristic of doubling intervals of tremors, we may be able to understand the tremor source characteristics in general. It is possible that, similar to this particular tremor source, the succession of slow- and fast-slip events are promoted by a particular combination of geometric and frictional properties of the seismo-genic zone and its surroundings. Hence, the results of our study have important implications in understanding the great earthquakes, which are thought to be preceded by slow-slip events (2011 Mw9.1 Tohoku-Oki and the 2014 Mw8.1 Iquique earthquakes).

E. References


Figure 1. Recurrence pattern of the period-doubling Parkfield tremors and numerical simulations. A) Observed tremor recurrence pattern and number of LFEs per burst, modified from Shelly (2010). Each tremor burst consists of 1 to 5 LFEs in most cases. Burst preceded by a shorter recurrence interval are associated with more LFEs throughout the sequence (consecutive bursts are connected with a gray line). The regular oscillation of recurrence intervals between about three and six days is from mid-2003 to the onset of the 2004 Parkfield earthquake. The sudden disappearance of the 6-day recurrence intervals coincides with the 2004 Parkfield earthquake. The gradual recovery of recurrence intervals is from the onset of the Parkfield earthquake to the end of 2007, around two years. B) Numerical simulation of the Parkfield tremor activity incorporating a change in effective confining pressure (red profile) after the Parkfield earthquake. The colored circles denote the maximum velocity of the slip events. Fast ruptures are preceded by shorter recurrence intervals. The 2004 Parkfield earthquake results in a rapid occurrence of slip events, followed by a sequence of multiplets with varying period-multiplying factors.
Figure 2. Recurrence pattern of the period-doubling Parkfield tremors and numerical simulations. A) Observed tremor recurrence pattern and duration of the tremors, modified from Shelly (2010). Each tremor burst endures in a range between 0 and 50 seconds. Burst preceded by a shorter recurrence interval are associated with long duration throughout the sequence (consecutive bursts are connected with a gray line). The regular oscillation of recurrence intervals between about three and six days is from mid-2003 to the onset of the 2004 Parkfield earthquake. The sudden disappearance of the 6-day recurrence intervals coincides with the 2004 Parkfield earthquake. The gradual recovery of recurrence intervals is from the onset of the Parkfield earthquake to the end of 2007, around two years. B) Numerical simulation of the Parkfield tremor activity incorporating a change in effective confining pressure (red profile) after the Parkfield earthquake. The colored circles denote the event duration of the slip events. Events with short duration are preceded by shorter recurrence intervals. The 2004 Parkfield earthquake results in a rapid occurrence of slip events, followed by a sequence of multiplets with varying period-multiplying factors.