Final Technical Report
Inferring Rate and State Dependent Frictional Parameters at Parkfield, CA using numerical models and Geodetic data

External Award Number 07HQGR0110
June 2007 - May 2008

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Technical Abstract

Numerical earthquake instability models provide insight into the processes controlling the nucleation of earthquake rupture and silent transient slip events. Numerical models based on rate- and state-dependent friction laws require the input of several laboratory derived frictional parameters. Numerous laboratory experiments have been conducted to explore the dependence of the frictional parameters on various conditions such as temperature and gouge thickness in order to determine the appropriate parameters for real faults, but relatively few studies have attempted to directly compare field measurements with the proposed frictional laws. The abundance of GPS and seismic data that records postseismic deformation following the 2004 Parkfield earthquake provides an unprecedented opportunity to try to resolve the frictional properties on this section of the San Andreas fault.

In this proposed study we develop 3D rate- and state-dependent friction models of afterslip following the 2004 Parkfield earthquake and deep transient creep following the 2003 San Simeon earthquake in order to investigate the frictional properties of the San Andreas fault. In particular, we focus on deep afterslip on the San Andreas fault as revealed by transients in rate of tremor production.

Our simulations demonstrate that a frictional model for deep transient fault creep is consistent with observed tremor transients and with shallow afterslip recorded by GPS data. The hypothesis of deep fault creep as the driving mechanism for deep tremor on the San Andreas fault is plausible. The conditions required to produce the creep

transients are similar to conditions shown by [*Liu and Rice*(2009)] required to produce episodic transient creep events at Cascadia with low effective normal stress of order 0.1-10 MPa and small $a - b$ of order $10^{-2.5}$ or less. As suggested by [*Liu and Rice*(2009)], the small $a - b$ values are consistent with laboratory results for gabbro, a composition that is expected for lower crustal rocks.

Background and approach

Field an laboratory studies indicate that deformation in the lower crust tends to localize into narrow shear zones. Yet, until recently direct evidence for the extension of large active strike slip faults like the San Andreas extend as discrete faults below the seismogenic zone into the lower crust has remained elusive. Recent observations of tremor in the lower crust near Parkfield, CA ([*Nadeau and Dolenc*(2005)],[*Shelly*(2010)]) provide the first direct evidence of active faulting in the lower crust below nominally seismogenic depths. [*Shelly*(2010)] cites these observations as evidence that the San Andreas fault exists as a localized structure extending at least to the bottom of the crust. Studies from other plate tectonic settings suggest a link between fault creep and tremor activity rates. Tremor appears to be the manifestation of low frequency earthquakes generated by shear slip on the subducting plate interface ([*Shelly* et al.(2007)], [*Wech and Creager*(2007)], [*Ide* et al.(2007)]) and is often highly correlated spatially and temporally with slow slip events imaged with GPS data (Wech 2009, [*Aguiar* et al.(2009)], cite Noel's work). Numerical studies of deep creep at subduction zones show that these spontaneous creep events associated with tremor generation can be produced under conditions of very low effective normal stress (i.e., nearly lithostatic pore pressure) and near the transition from velocity weakening to velocity strengthening ([*Liu and Rice*(2007)] and [*Liu and Rice*(2009)]). This inference of low effective normal stress is corroborated by observations of triggered tremor activity attributed to small stress changes from the passage of seismic waves (e.g., Peng and others). [*Thomas* et al.(2009)] showed that tremor deep on the San Andreas fault near Parkfield, CA correlates with small tidally-induced shear stress changes on the fault indicating shear failure at near-lithostatic pore pressure and very low coefficient of friction ($\mu < 0.1$).

Shelly and Johnson (2011) show that the rate of tremor deep on the San Andreas fault was modified by static stress changes on the fault induced by the nearby 2003 M6.7 San Simeon Earthquake and the 2004 M6.0 Parkfield earthquake. Figure 1a shows the tremor rate was drastically reduced on the San Andreas fault north of Parkfield in the 30 days following the 2003 San Simeon Earthqauke in regions where the right-lateral shear stress was reduced. Following this 30-day period, the tremor rates generally returned to the pre-earthquake rate (Figure 1c). The tremor rate was drastically increased in the same region following the 2004 Parkfield earthquake when the right-lateral shear stress was increased (Figure 1b). The plot of cumulative number of tremor events with time in Figure 1d,e shows a logarithmic pattern with a high rate of tremor in the first month or so after the earthquake followed by a gradual return to the pre-earthquake rate. Shelly and Johnson (2011) suggested that the tremor rates following the 2004 Parkfield earthquake may be driven by deep afterslip on the San Andreas fault.

However, any deep, triggered fault slip would be too deep and small to detect with geodetic instruments at the ground surface and therefore the link between tremor activity and deep fault creep remains circumstantial. The time series of transient tremor episodes have a similar appearence to creep episodes. The observation of nearly complete terminate of tremor in a stress shadow following the San Simeon Earthquake is remarkably similar to the observed termination of shallow fault creep on the San Andreas and Hayward faults in a stress show induced by the nearby 1989 Loma Prieta and 1983 Coalinga earthquakes, respectively. The logarithmic rate of decay of tremor activity following the 2004 Parkfield earthquake is similar to the typically observed logarithmic decay in surface deformation rates attributed to afterslip following earthquakes (cite Langbein).

In this study we add to the growing evidence that deep tremor on the San Andreas fault is driven by fault creep by showing that numerical simulations of frictional fault creep are entirely consistent with observed tremor transients.

Transient creep model

We consider a model for frictional fault creep governed by the single-state-variable rate- and state-dependent friction law that relates shear stress, τ, to normal effective stress, σ, and sliding velocity, V, as

$$\tau = \sigma \left[\mu + a \ln \left(\frac{V}{V_o} \right) + b \ln \left(\frac{V_o \theta}{d_c} \right) \right] \tag{1}$$

where μ is the nominal coefficient of friction, V_o is a reference sliding velocity, d_c, is the critical sliding distance and is related to the distance over which asperity contacts are renewed during sliding, and a and b are material-dependent parameters that are determined emprically in the laboratory. We use the "ageing" version of the friction law with state parameter, θ evolving as

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{d_c}. \tag{2}$$

To identify friction parameters to use in numerical simulations, we first use a single-degree-of-freedom spring-slider model to invert the stacked tremor count time series shown in Figure 1d for friction parameters (SOM for details). The spring-slider is perturbed by the shear and normal stress changes on the fault imposed by the San Simeon Earthquake (Figure 1f). Figure 2b shows spring-slider model results that reproduce the duration of the observed quiescence. Assuming typical laboratory values of $a = 0.01$, the effective normal stress on the fault is low, of order 0.1-10 MPa, and $\sigma(a - b)$ must be very small, of order 10^{-6} to 10^{-2} MPa, which is at least an order of magnitude lower than values inferred from afterslip studies (references).

We simulate creep on a planar fault subjected to static shear and normal stress changes from the San Simeon and Parkfield earthquakes. For simplicity, we assume that the fault creeps at steady-state sliding conditions before the introducing the stress change. We adopt the interseismic slip model of Murray and Segall (2001) for the steady sliding rate. Using the spring-slider simulations as a guide, we assign values of $\sigma = 1$ MPa,

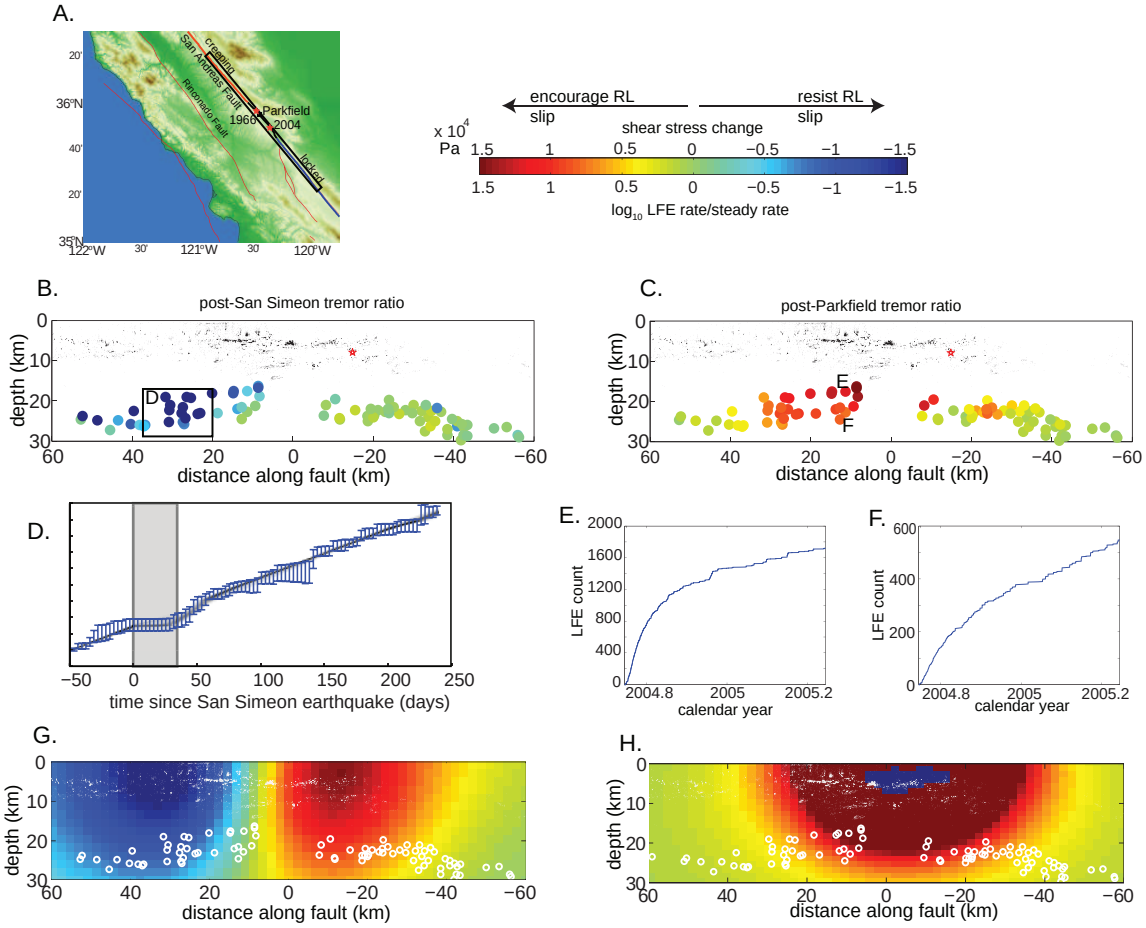

Figure 1: A. Location of study area. B. Average tremor rate for 30 days after the San Simeon earthquake normalized by average rate 180 days before. C. Average tremor rate for 30 days after the Parkfield earthquake normalized by average rate 180 days before. D. Stack of tremor time series in the box in part B. E., F. Tremor time series at locations in part C. G. Shear stress change due to San Simeon Earthquake. H. Shear stress change due to Parkfield Earthquake.

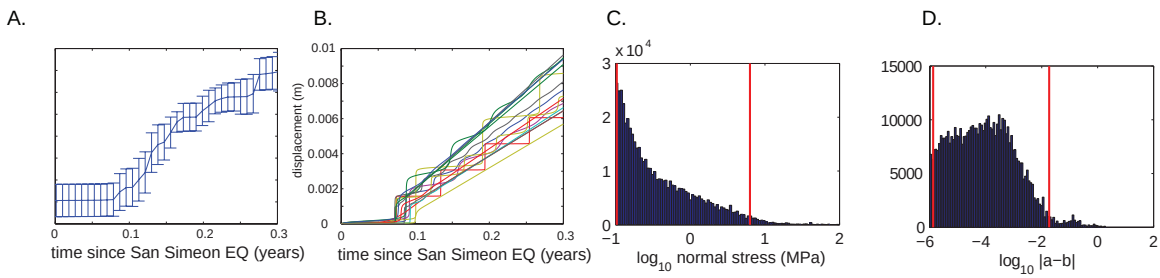

Figure 2: A. Stack time series as in Figure 1D. B. Examples of spring-slider simulations of transient creep due to San Simeon stress changes. C. Posterior probability distribution of effective fault normal stress. Red bars show 95% bounds. C. Posterior probability distribution of rate-state parameter $a - b$. Red bars show 95% bounds.

$a - b = 10^{-4}$, and $d_c = 10^{-4}$ m below 15 km depth on the fault. Above 15 km depth we assign values of $\sigma = 50$ MPa, $a - b = \times 10^{-3}$, and $d_c = 10^{-3}$ m, consistent with studies of afterslip following the 2004 Parkfield earthquake (references).

Results

Figure 3 compares five time-snapshots of observed tremor rates and modeled creep rates following the San Simeon earthquake. The tremor rates are computed by fitting a smooth curve through the individiual tremor time series in the catalog (cite Shelly) and smoothing in space. The 30-40 day cessation of tremor north of Parkfield (zero x-axis) is clear in the left side of Figure 3. The region of decreased tremor rate is initally at least 60 km long and gradually closes down over the 30-40 days with the accelerated tremor rates surrounding the shrinking region of decreased tremor rate. This same temporal-spatial evolution is observed in the model result on the right side of Figure 3. South of Parkfield, the tremor behaves differently. Smaller patches of tremor approximately 20 km in length appear to oscillate from high to low rates over periods of many days. This type of behavior is reproduced in the model by assigning different friction parameters to patches of the fault to force shorter-wavelength creep transients. We assigned smaller values of $\sigma(a - b) = -10^{-4}$ between distances of -15 and -25 km to force this oscillatory behavior. The lower $\sigma(a-b)$ value assigned to this region is perhaps consistent with higher triggerability of the tremor as shown by Shelly et al. (2011, NGS). These simulations confirm the spring-slider results and show a remarkable similiarity between modeled creep behavior and observed tremor rate variations following the San Simeon Earhquake.

Figure 4 shows that a fault model with the same frictional parameters as the previous model can produce transient creep following the 2004 Parkfield earthquake that is generally consistent with the spatial-temporal evoution of tremor. During first day following the earthquake there is widespread triggering of tremor extending 40 km north and south of Parkfield. This pulse dies out by the end of day 1. Beginning near the end of day 1, the tremor rates are reduced over much of the deep fault except for a zone of high tremor activity centered near the 0 coordinate that expands with time, reaches maximum size after about 7-10 days, and then shrinks down until tremor rates are generally near the steady background rate after about 50 days. This pattern is observed in the model creep rates. Instantaneous static stress changes from the mainshock induce a widespread pulse of accelerated creep below 15 km depth that lasts for about 1 day. As this first pulse of dies out, afterslip on the shallower parts of the fault has propagated into the deep creeping region and a second, slower pulse of accelerated afterslip is observed for about 50 days. The duration and spatial extent of this afterslip pulse is similar to duration and spatial extent of transient tremor.

Reports Published

Shelly, D., and K. M. Johnson (2011), Tremor reveals stress shadowing, deep postseismic creep, and depth-dependent slip recurrence on the lower-crustal San Andreas fault near Parkfield, Geophys. Res. Lett., doi:10.1029/2011GL047863.

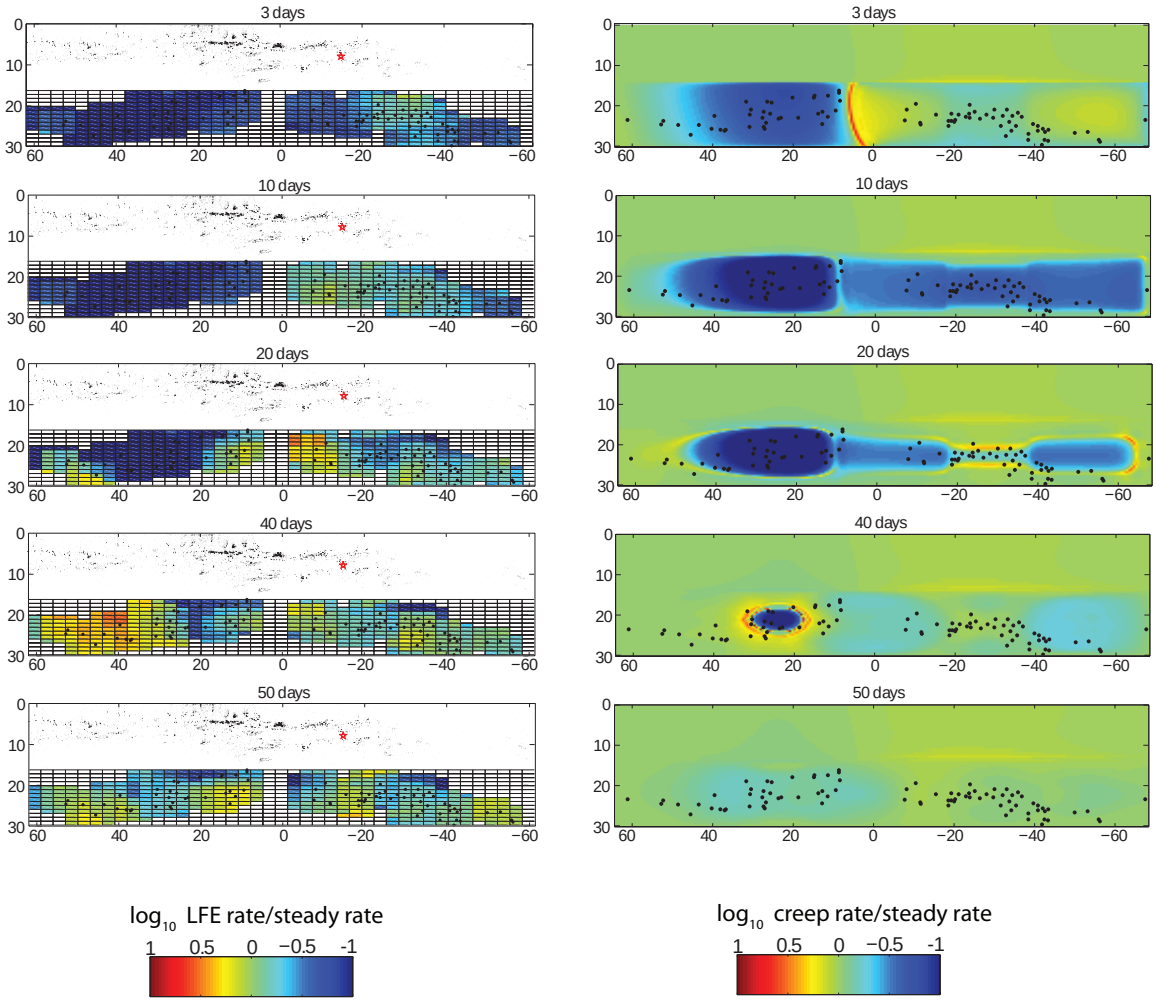

Figure 3: Left side shows observed tremor rates at various days following the San Simeon earthquake. Right side shows modeled creep rates following San Simeon earthquake.

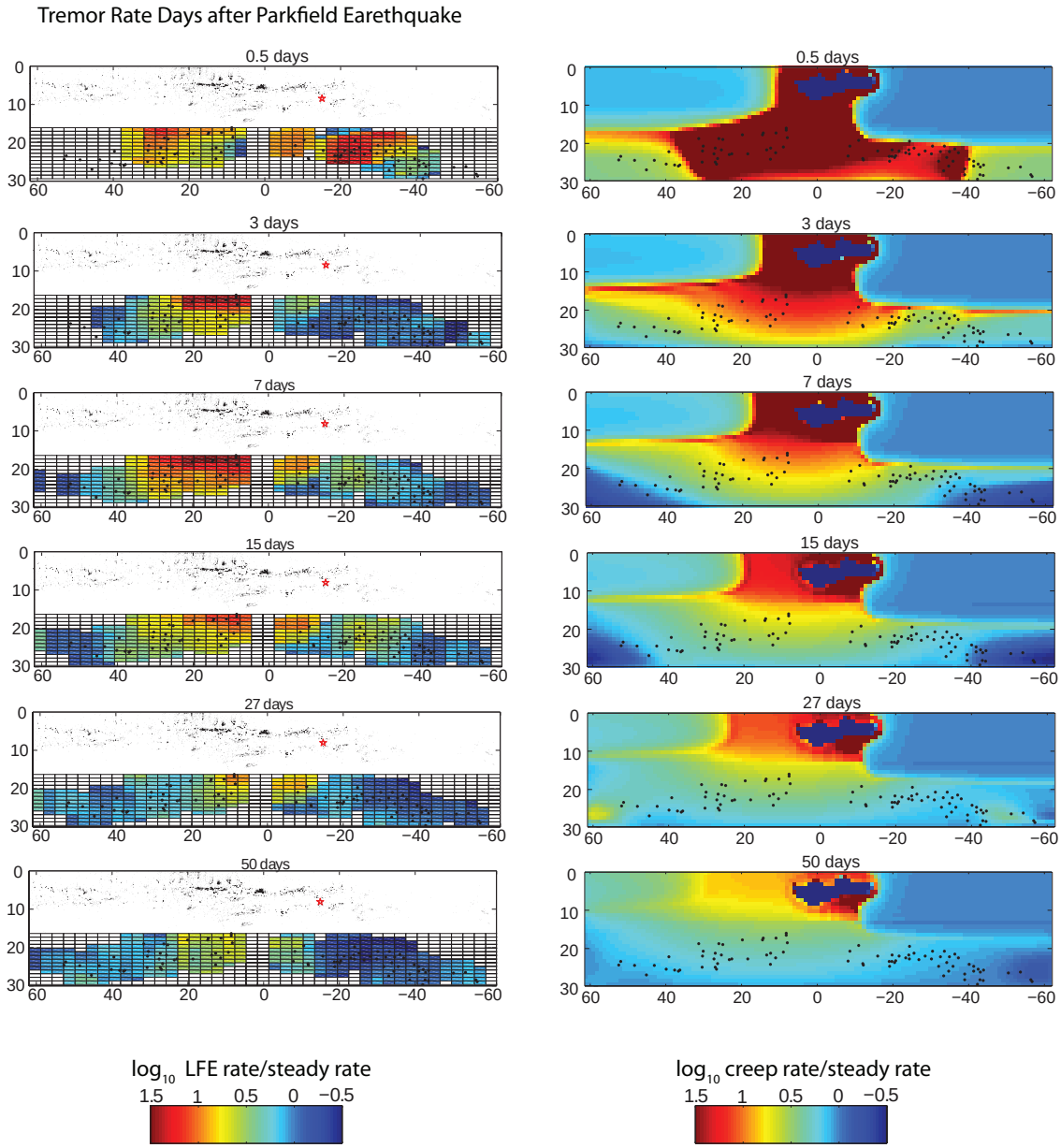

Figure 4: Left side shows observed tremor rates at various days following the Parkfield earthquake. Right side shows modeled creep rates following the Parkfield earthquake.

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