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b-values as a Proxy for Stress: Inferences from Dynamic Modeling of the 2004 Parkfield Earthquake

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Abstract

Previous studies of the frequency-magnitude distribution of earthquakes in different tectonic settings have shown that the b-value in the frequency-magnitude distribution can vary significantly in the range 0.4-2.0 (Wiemer and Wyss, 2002). In particular, active faults are characterized by a high spatial variability of the b-value (e.g., Parkfield). Furthermore, the regions of the active faults that exhibit anomalously low *b*-values seem to correlate very well with asperities (regions that are strongly coupled, i.e., locked, and which generate large amplitudes of slip co-seismically). Thus, it has been hypothesized that fault asperities may be mapped by maxima in local earthquake probability, which in turn can be computed from the *a*- and *b*-values of the frequency-magnitude distribution. One possible explanation for the strong correlation between *b*-values and asperities is that patches of the faults that are weakly coupled (low level of friction) cannot build up stress and thus slip in frequent small earthquakes (high *b*-value), whereas regions that are strongly coupled (high level of friction) can remain locked under larger stresses, and slip only in more infrequent large earthquakes (low *b*-value). Further support to the hypothesis that *b*-values contain information on the state of stress of the crust comes from the recent observation that normal faulting earthquakes (which are expected to occur under the lowest stress levels) present the highest *b*-values, whereas strike-slip earthquakes have intermediate *b*-values, and thrust earthquakes (expected to occur under the highest stresses) present the lowest *b*-values. In view of the strong correlations between *b*-values and state of stress across different stress regimes, one question arises: "Can *b*-values actually be used to predict the state of stress of the crust in a quantitative way?" In order to answer this question, we studied the 2004 Parkfield, California, earthquake (Figure 1). The Parkfield region has been extensively studied in terms of *b*-values (Figure 2), and source model (Figure 3) – it is thus an ideal setting to study a possible quantitative relation between *b*-values and stress.

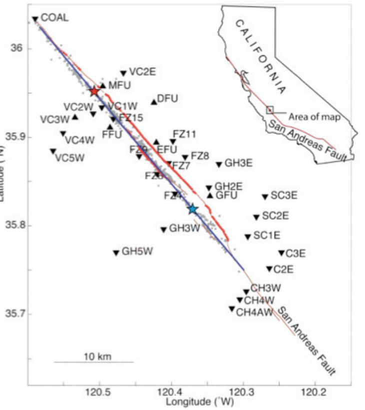


Figure 1. Map of Parkfield, California. The blue star marks the 2004 M6 epicenter and the red star marks the 1966 M6 epicenter. The aftershocks are shown by gray dots (Thurber et al., 2006). The strong-motion accelerographs are marked by triangles, and the modeled fault plane is shown by a blue line overlaying the fault trace.

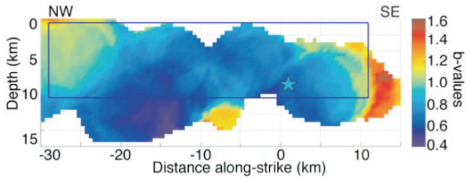


Figure 2. Map of b-values on the Parkfield section of the San Andreas Fault (Schorlemmer and Wiemer, 2005). The blue star marks the M6 2004 hypocenter and the blue rectangle shows the fault plane we model.

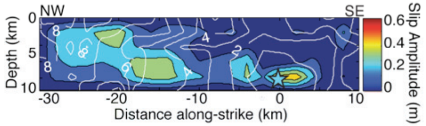


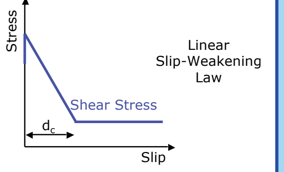
Figure 3. Slip distribution of the M6 2004 Parkfield earthquake, obtained by inversion of strong ground-motion (Liu et al., 2006). Slip amplitude is shown by the color scale, and rupture time is indicated in white lines (1-sec contours).

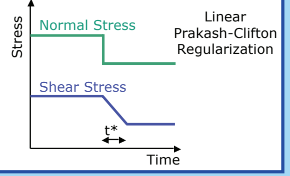
1. Method

In order to model the dynamic rupture and wave propagation throughout the surrounding media we use a Finite Element scheme (Ma and Liu, 2006; Ma et al., in prep.). We use a linear slip-weakening friction law (Ida, 1972), and in order to regularize the Adams instability (which arises in dynamic ruptures when the fault separates two different materials) we use a linear adaptation of the Prakash-Clifton regularization (Prakash and Clifton, 1993).

- Finite Element Method (Ma and Liu, 2006; Ma et al., in prep)
  - FE with one point integration (Ma and Liu, 2006)
  - Stress-velocity formalism
  - Split-node scheme (Andrews, 1999)
  - Absorbing boundaries
  - Viscous and elastic hourglass control
  - 3D Parkfield material structure (Thurber et al., 2006)

- Parameters:
  - Regular grid: 100m x 100m x 100m
  - Vertical fault
  - Strike-slip fault (mode II)
  - Fault: 40km x 15km
  - Half-space: 40km x 60km x 25km
  - d_c: 0.15m
  - Initial Normal Stress: 60MPa
  - Coefficient of Dynamic Friction: 0.3
  - dt: 0.012sec
  - t*: 0.035sec

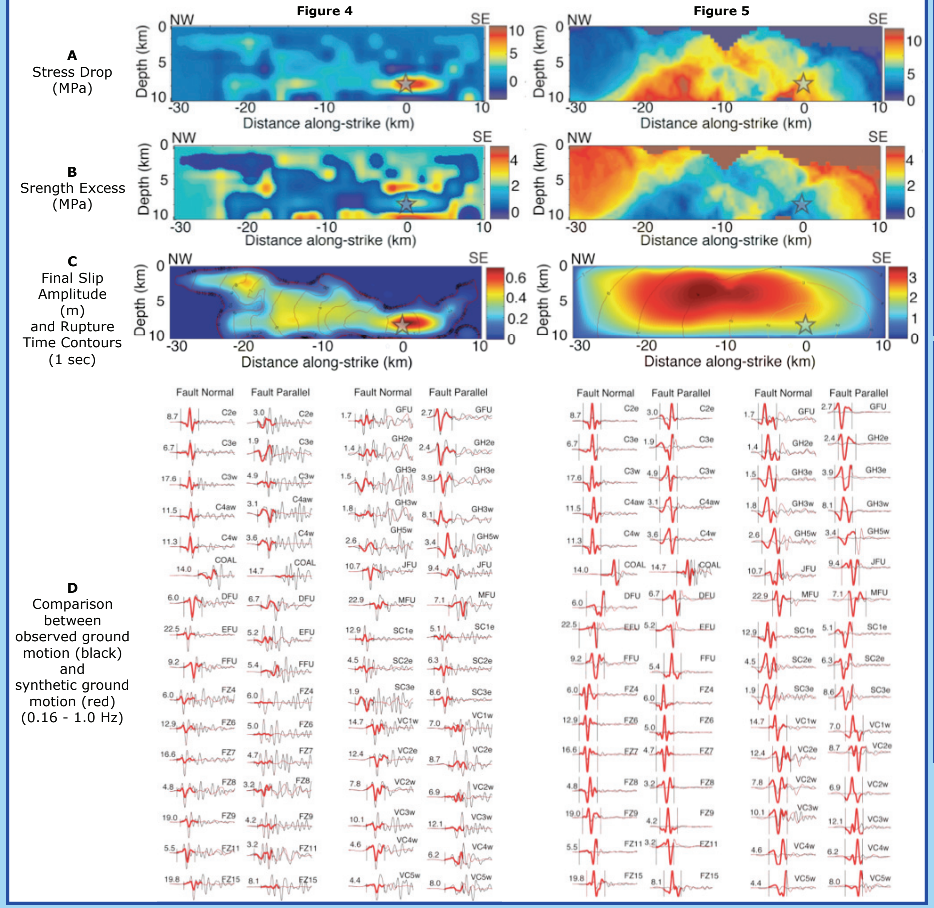




2. Results I - Slip Distribution and Ground Motion

Figure 4. Dynamic model for the 2004 M6 Parkfield earthquake (Ma et al., in prep), based on the kinematic slip distribution (Figure 3). **A)** Stress Drop (= initial stress - final stress); **B)** Strength Excess (= yield stress - initial stress); **C)** Final slip distribution obtained from the dynamic modeling; **D)** Comparison between observed velocity waveforms and synthetic waveforms generated by the dynamic modeling. The observed and synthetic waveforms are aligned in order to minimize the misfit. The names of the stations are indicated to the right of the waveforms, and the maximum velocity in the waveforms is indicated to their left. The hypocenter is a circular patch with a negative strength excess of -0.5MPa.

Figure 5. Same as Figure 4, but the initial conditions (Stress Drop and Strength Excess) are now proportional to the b-values observed in Parkfield (Figure 5). We scaled both stress drop and strength excess so that their maximum and minimum values matched those in Figure 4.



3. Results II - Analysis and Summary

In order to quantify the goodness of the dynamic models computed – both based on the kinematic slip distribution (Figure 4 and on b-values (Figure 5) – we calculated the misfit between observed and synthetic ground-motion (Figures 4D and 5D). The misfit was calculated in two different ways: 1) using a correlation misfit function (M1), which measures the similarity in the shape of the waveforms; and 2) using the squared difference between the two waveforms (M2), which further takes in account the amplitude of the waveforms. M3 and M4 were computed in the same way as M1 and M2, respectively, but using only the fault-normal component of motion. The misfit was computed in a window of 5 sec (thick red line in the synthetics), after aligning observed and synthetic ground-motion.

In addition to the two models shown in Figures 4 and 5, we also computed a suite of dynamic ruptures between the two end-member cases (stress conditions inferred from kinematic slip model (kin) and b-values distribution (bval)). We also computed dynamic ruptures where stress drop and strength excess were proportional to the squared on the b-values distribution (bval2). The results are summarized in the table below. NP identifies models that did not propagate. The smallest misfit values and highest correlation of the final slip distribution with the kinematic slip distribution (best models) are shown in red.

Stress Drop	Stregth Excess	Misfit (observations-synthetics)				Correlation w/ kinematic slip distribution
		M1 (correlation)	M2 (squared differences)	M3 - normal (correlation)	M4 - normal (square diff.)	
kin	kin	63.9337	3.76E+04	31.9587	2.77E+04	0.4775
bval	bval	63.6432	4.51E+04	31.9029	2.84E+04	0.1225
bval	kin	62.9758	4.16E+04	31.38	2.81E+04	0.1226
kin	bval	NP	NP	NP	NP	NP
bval2	bval2	NP	NP	NP	NP	NP
bval2	kin	64.1338	4.27E+04	31.8615	2.81E+04	0.1443
(bval+kin)/2	(bval+kin)/2	63.5023	4.00E+04	31.872	2.79E+04	0.2126
bval2	.2 MPa	63.8644	3.99E+04	32.0557	2.80E+04	0.1233
7 MPa	bval	NP	NP	NP	NP	NP
bval2	.2 MPa	64.5812	3.90E+04	32.3137	2.80E+04	0.1452

Discussion and Conclusions

- ✓ It is possible to find a stress distribution on the fault based on b-values that generates waveforms which resemble the ground motion observed during the 2004 M6 Parkfield earthquake reasonably well. The stress distribution is found from b-values using the following relationship:

$$\text{Stress Drop} = -6.6 + 10.0 / \text{b-value} \quad \text{(MPa)}$$

$$\text{Strength Excess} = 8.5 - 4.6 / \text{b-value} \quad \text{(MPa)}$$

- ✓ Using squared differences (which take in account waveform amplitudes) to measure the fit between observed and synthetic ground-motion, the best model is the one with both stress drop and strength excess based on the kinematic slip distribution.
- ✓ Using a correlation function (which assesses the similarity of the waveforms shape) to measure the fit between observed and synthetic ground-motion, the best model is the one with the stress drop based on b-values and strength excess based on the kinematic slip distribution.
- ✓ The model based solely on b-values generates a large amount of slip on the fault, which in turn generates too large ground-motion.
- ✓ The b-values distribution is too smooth to reproduce the rupture detail inferred from kinematic modeling of the observed ground-motion.

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