Testing Earthquake Recurrence Models: Space-Time Patterns of Slip-Deficit at Parkfield

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ABSTRACT

In our fiscal year 2002 proposal we presented two research projects which we have pursued. The first was a test of the time-predictable earthquake recurrence model and the second was inversion of geodetic data for time-varying deformation at Parkfield, CA. The first of these two projects has been completed. We summarize the results here, with emphasis on how we tackled the tasks stated in the original proposal. The second project is ongoing. We applied for and were awarded a continuation grant for fiscal year 2003 for the study of transient deformation. Here we briefly summarize the progress made to date.

PROJECT 1: TESTING THE TIME-PREDICTABLE RECURRENCE MODEL USING GEODETIC DATA

The time-predictable recurrence model

A key ingredient of seismic hazard assessment is an accurate model for the temporal distribution of earthquakes. The time-predictable recurrence model [*Shimazaki and Nakata*, 1980] is based on the idea of elastic rebound [*Reid*, 1910] and states that, assuming a constant loading rate and a fixed threshold stress for fault failure, the time required for an earthquake to occur is that needed to recover the stress released in the most recent event. This leads to the expectation that earthquake probability increases with time since the last event. Since this model is thought to incorporate some of the physics behind the earthquake cycle it is often preferred over purely statistical models for earthquake recurrence when sufficient data are available. While the model does not account for many factors affecting earthquake occurrence, it is incorporated in hazard predictions world-wide, including those for northern California [*WG99*, 1999], southern California [*WG95*, 1995], New Zealand [*Stirling*, 2000], and Japan [*Annaka and Yashiro*, 1998].

The model was formally stated in terms of fault stress. Stress, however, is difficult to measure directly, so strain is often used as a proxy for stress. This is, in fact, what *Shimazaki and Nakata* [1980] did in practice. For the time-predictable model, this is equivalent to expressing the interevent time as the ratio of the coseismic moment release to the interseismic moment deficit rate. *Segall and Harris*, [1987] discuss the representation of fault stress by moment in terms of the accumulation and release of elastic strain energy.

The coseismic moment, M_o, is given by:

$$M_o = \mu \iint_A s dA \tag{1}$$

where μ is the shear modulus, A is the area that slipped, and s is the (spatially variable) fault slip. This fault slip can be estimated from geodetic data. For the interseismic period, we consider a fault that is continuously loaded by steady aseismic slip below the seismogenic zone. If the seismogenic zone were creeping everywhere at the long-term deep slip-rate, then no strain would accumulate. If the slip-rate of the seismogenic zone lags the deep slip-rate, however, strain will build up. The slip-deficit leads to a moment deficit, the rate of which can be used to estimate interevent time, t_i:

$$\dot{M}_d = \mu \iint_A (\dot{s}_\infty - \dot{s}) dA \tag{2}$$

$$t_i = M_o / \dot{M}_d \tag{3}$$

where $\dot{M}_d$ is the moment deficit rate, and $\dot{s}_\infty$ - $\dot{s}$ is the (spatially variable) slip deficit rate (given the deep slip-rate, $\dot{s}_\infty$, and the forward slip-rate on the seismogenic fault, $\dot{s}$). As with the coseismic slip, the interseismic slip deficit rate distribution may be inferred by inversion of geodetic data.

Rationale for testing the time-predictable model and methodological considerations

We used Parkfield, CA (fig. 1a) as the test locale for our study. Based on Parkfield's history of moderate earthquakes, a prediction was made that a M~6 would occur in 1988 ± 4.3 years [*Bakun and McEvilly*, 1984], but to date the most recent event of this size was in 1966. *Harris and Segall* [1987] and *Murray et al.* [2001] both inferred an area of low slip-rate on the southeastern portion of the Parkfield fault segment (fig. 1b), suggesting that strain has been accumulating here throughout the interseismic period since 1966 even though no earthquake has occurred. Although the famous Parkfield prediction was not based on the time-predictable model, another study [*Segall and Harris*, 1987] used this model to estimate a range of expected recurrence times for the anticipated earthquake. The maximum interevent time (29 years) predicted by *Segall and Harris's* study has since passed. This could reflect modeling assumptions they made; alternatively it may be an indication that the time-predictable model's forecasting capability is unreliable. Therefore, we set out to conduct a rigorous test of the time-predictable model, avoiding the previously made assumptions.

Our approach is to use inversion of geodetic data to estimate an upper bound on the time required to recover the strain released in the 1966 earthquake as given by (3). According to the time-predictable model, another earthquake will happen when this strain is reaccumulated. If we can show at high confidence that the time since 1966 has exceeded the predicted upper bound interevent time, then the time-predictable model has failed at Parkfield. The existing questions surrounding earthquake recurrence at Parkfield make it an interesting place to test the model. More importantly, this area, unlike most, possesses an extensive history of geodetic measurements spanning both the 1966 earthquake and the interseismic period since then [*King et al.*, 1987; *Segall and Harris*, 1987; *Murray et al.*, 2001]. Furthermore, the fault geometry at Parkfield is simple, consisting of only the San Andreas, unlike the San Francisco Bay Area or southern California which are characterized by several parallel active fault strands.

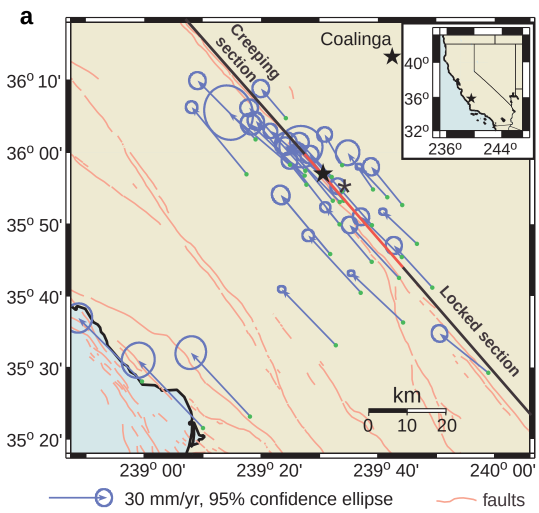
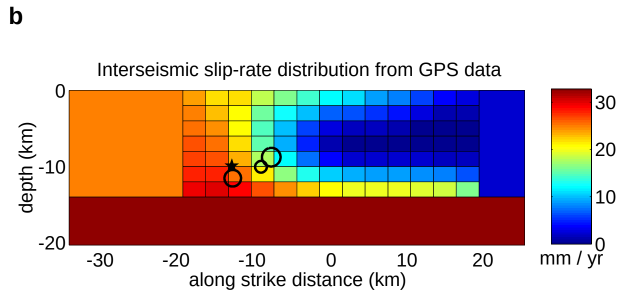


Figure 1: a) The Parkfield area. Vectors are GPS velocities (1991-1998) relative to North America. The model fault (black and red line) was based on the mapped fault trace and seismicity [e.g., *Murray et al.*, 2001]. Star on San Andreas is the 1966 epicenter, asterisk is the town of Parkfield. The M 6.5 1983 Coalinga earthquake is also shown.



b) Interseismic slip-rate estimated from the GPS data in part (a) [*Murray et al.*, 2001]. The gridded portion of the fault represents the seismogenic part and corresponds to the red segment of the model fault in fig. 1a. The transition depth is at the base of the gridded area. The contribution to GPS velocity from slip on the creeping section of the San Andreas and from slip below the transition depth were incorporated with uniformly slipping dislocations (these dislocations are larger than shown in fig 1b). The locations of the 1992 M 4.3, 1993 M 4.6, and 1994 M 4.7 earthquakes are shown as circles with equivalent rupture area of a 3 MPa stress drop crack. The star is the 1966 hypocenter.

There were three complications to the estimation of bounds on interevent time which we had to address. First, inversion of geodetic data for slip or slip-rate distribution is nonunique. Often the inverse problem is regularized by application of spatial smoothing, however in this case the moment or moment deficit rate of the resulting distribution is contingent on the amount of smoothing applied. Moreover, geodetic data can not well resolve the depth of the transition between the seismogenic and the deeper aseismically slipping crust or the long term slip-rate on the aseismically slipping portion. Finally, when calculating an upper bound on the interevent time as in (3) it is necessary to properly account for the joint probability distribution of moment and moment deficit rates, rather than using the maximum moment estimate and minimum moment deficit rate estimate to find an "upper bound". At the time of our proposal, we still needed to develop a method that addressed these issues, particularly the last two. We have done so, as discussed in the following section.

Method and Results

The major steps in our analysis are as follows: 1) Estimate the 1966 coseismic moment and the interseismic moment deficit rate using constrained inversion of geodetic data. 2) Use a probability distribution of transition depth and deep slip-rate for the interseismic period to account for uncertainties in these parameters. 3) Employ the bootstrap statistical procedure to account for the joint probability distribution of moment and moment deficit rate in order to find a distribution of predicted interevent times from which 95% confidence limits can be obtained.

The data consist of 1) trilateration measurements made by the California Department of Water Resources, the California Division of Mines and Geology, and the USGS from 1959 to 1991, and 2) Global Positioning System (GPS) data collected by the USGS between 1991 and 1998. Following *King et al.* [1987], we estimated interseismic rates of line-length change for all trilateration lines and the coseismic offset for lines with pre-earthquake data. The GPS measurements were processed and analyzed by *Murray et al.* [2001] to estimate velocities of GPS sites. The complete interseismic dataset contains 15 years of additional data beyond that which *Segall and Harris* [1987] used in their original estimation of interevent time using the time-predictable model. Based on previous inversions, we found that the interseismic slip-rate distributions estimated from the trilateration and GPS data differ slightly. Therefore, in the current analysis we treated the two data sets for the interseismic period separately, estimating a moment deficit rate between 1966 and 1991 from trilateration data and from 1991 to 1998 using GPS data.

Following *Johnson et al.* [1994] we employed constrained inversion to determine moments and moment deficit rates consistent with the data without assumptions implicit in regularized inversions. Constrained inversion involves finding the slip distribution on the model fault (fig. 1) that best fits the data, subject to the constraint that the seismic moment equals a specified value. Slip was constrained to be positive (right lateral), but we made no assumption of smoothness (fig. 2a). The upper bound for coseismic slip was 0.8 m, which exceeds the maximum slip estimated in previous studies [*Segall and Harris*, 1987; *Segall and Du*, 1993]. We swept through a range of moments and found a best-fitting slip distribution for each one (fig. 2b). The M_o with the lowest misfit (star in fig. 2b) is optimal in the sense that there are no slip distributions resulting in different moments that fit the data better. The same procedure was used to estimate the moment deficit rate. In this case the maximum allowable slip deficit rate was the deep slip-rate (i.e., the fault was not allowed to slip left laterally).

The range of moments that fit the data acceptably well is more important than the best fitting M_o. To identify this range we used the bootstrap [*Efron and Tibshirani*, 1993]. We resampled the data and repeated the constrained inversions for best-fitting M_o 4,000 times yielding a distribution of M_o estimates, and did the same for the interseismic period to infer the distribution of $\dot{M}_d$. We then used these distributions in the calculation for interevent time. The distributions can also be used to obtain confidence intervals on M_o and $\dot{M}_d$. We found this method for inferring the range of M_o that fit the data to be successful in an empirical test using data predicted from a hypothetical slip distribution (fig. 2c).

Although the resulting estimates of M_o and $\dot{M}_d$ are conditional on an assumed transition depth, and in the case of $\dot{M}_d$, deep slip-rate, it is possible to account for uncertainty in these parameters. Geodetic data provide some constraints on transition depth and deep slip-rate, but they are not uniquely resolved. *Murray et al.* [2001] estimated interseismic slip-rates for a range of transition depth and deep slip-rate pairs with optimal smoothing determined by cross validation [*Wahba*, 1990]. The CVSS, a measure of misfit, is a nearly quadratic function of transition depth and deep slip-rate, and these quantities are highly correlated. The minimum CVSS is at 14 km and 33 mm/yr, in keeping with independent geologic and seismic observations

[*Eaton et al.*, 1970; *Sieh and Jahns*, 1984]. For linear least squares the residual sum of squares (RSS) is quadratic, and the corresponding probability density function (pdf) is proportional to $e^{-\text{RSS}}$. We used the observed distribution of CVSS to generate an approximate pdf proportional to $e^{-\text{CVSS}}$ (fig. 2d). Each time the data were resampled in the bootstrap, a new transition depth / deep slip-rate pair was chosen from this empirical distribution.

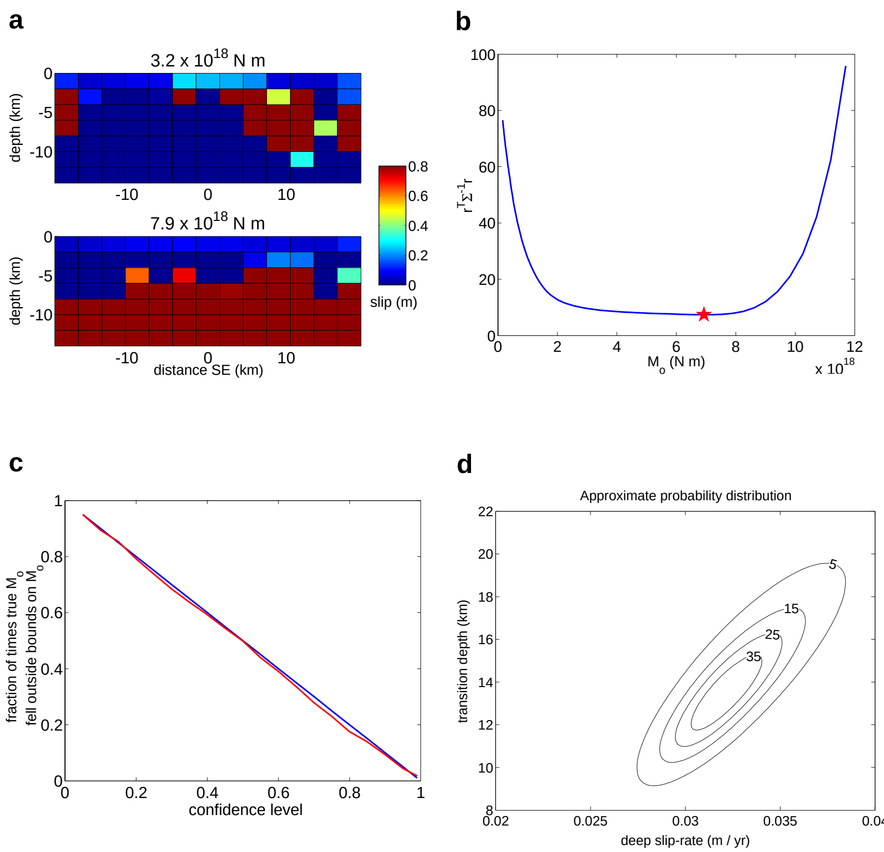


Figure 2: Constrained inversion and bootstrap procedure. a) Slip distributions from constrained inversion corresponding to 95% confidence limits on coseismic M_o for transition depth of 14 km. b) Misfit as a function of coseismic M_o. c) Test of the constrained inversion / bootstrap method for bounding M_o using synthetic data. We repeated the constrained inversion and bootstrap process 700 times with different random errors added to the synthetic data. The fraction of times the "true" M_o fell outside the inferred range is shown as a function of confidence interval (fig. 3c, red line). For comparison, the blue line shows the predicted behavior; e.g., at the 95% confidence level the "true" M_o should fall outside the range 5% of the time. d) approximate probability distribution for transition depth and deep slip-rate based on $e^{-\text{CVSS}}$.

To determine bounds on the interevent time that properly account for the joint probability distribution of the moment and moment deficit rates, we first calculated a distribution of interevent times (fig. 3) by forming the ratio of M_o to $\dot{M}_d$ using values drawn from the distributions for each of these quantities. We took care that for each pair of M_o and $\dot{M}_d$ both were found using the same transition depth. Noting that we had 25 years of trilateration measurements without a Parkfield earthquake, we estimate the interevent time as:

$$\Delta t = \frac{M_{o_{1966}}}{\dot{M}_d^t} \qquad (4)$$

if $M_{o_{1966}} - (\dot{M}_d^t \times 25\text{yrs}) \le 0$, and

$$\Delta t = 25\text{yrs} + \frac{M_{o_{1966}} - (\dot{M}_d^t \times 25\text{yrs})}{\dot{M}_d^G} \qquad (5)$$

if $M_{o_{1966}} - (\dot{M}_d^t \times 25\text{yrs}) > 0$ where the next earthquake is predicted to occur in 1966+Δt. $M_{o_{1966}}$ is the coseismic moment, $\dot{M}_d^t$ is the moment deficit rate inferred from trilateration data, and $\dot{M}_d^G$ is that inferred from GPS data.

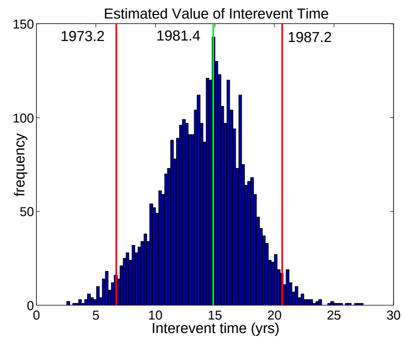


Figure 3: Distribution of interevent time estimated from the constrained inversion and bootstrap procedure. The 95% confidence interval is indicated by the red lines; the interevent time using the original (not resampled) data sets, a deep slip-rate of 33 mm/yr, and a transition depth of 14 km is shown by the green line. The calendar years corresponding to each interevent time (Δt) are also shown.

The resulting bounds on interevent time range from 7 to 21 years at 95% confidence. In other words, the strain released in 1966 recovered sometime between 1973 and 1987. The expected earthquake has yet to occur, demonstrating that the time predictable model has failed at Parkfield.

Implications

There are several possible reasons for the inability of the time-predictable model to forecast the Parkfield earthquake. A central premise of the model is that an earthquake occurs when the fault reaches a critical stress. However, modern theories of fault failure postulate that earthquake nucleation depends on the elastic loading system and the frictional properties of the fault rather than a characteristic failure stress. Therefore, variations in pore fluid pressure or stress perturbations may affect the time to the next earthquake [*Dieterich*, 1994]. For example, *Toda and Stein* [2002] suggest that the 1983 Coalinga event (fig. 1a) could have delayed the next Parkfield earthquake into the mid 1990's, however they could not explain the length of delay that has been observed. The M ~ 4.7 Parkfield events in the early 1990s (fig. 1b, [*Fletcher and Spudich*, 1998]) likely increased the static stress in the expected nucleation zone, increasing the probability of a repeat of the 1966 event. Another questionable assumption of the model is that stress accumulates at a constant rate between earthquakes. Slight changes in the interseismic slip-rate could lead to significant changes in stressing-rate in the expected nucleation zone.

We conclude that the reaccumulation of the strain released in the last earthquake is a necessary but not a sufficient condition for another event to occur. The time-predictable model is too simple to accurately characterize the conditions necessary for moderate to large earthquakes, although it appears to fare better in describing recurrence in some clusters of microseismicity. The time-predictable model is used in earthquake probability calculations. Because multiple models for earthquake recurrence are employed in such assessments and uncertainty is assigned to each, we do not believe that our findings negate the existing hazard forecasts. However, our findings could conceivably lead to reassessment of the uncertainty attributed to the time-predictable model. An alternative description of the earthquake cycle also proposed by *Shimazaki and Nakata* [1980] is termed the slip-predictable model. This model states that the size of an earthquake depends on the elapsed time since the previous earthquake.

This model shares many assumptions with the time-predictable model, however it cannot be tested at Parkfield until another earthquake occurs on the 1966 rupture plane. If such an event were to happen today, based on the slip-predictable model and using our estimates of interseismic moment deficit rate, the earthquake would be expected to be of M_w 6.6 – 6.9, considerably larger than previous Parkfield earthquakes.

PROJECT 2: TIME-DEPENDENT DEFORMATION

The second aspect of the earthquake cycle that we proposed to investigate is transient deformation. Several studies [e.g., *Gao et al.*, 2000 and references therein] have noted a possible transient event at Parkfield characterized by an increase in microseismicity, the occurrence of four $4 < M < 5$ earthquakes in the Middle Mountain area, and anomalous signals on the two-color laser and borehole tensor strainmeter (BTSM) networks in the early 1990s. We propose to use a nonparametric method for modeling two-color laser, GPS, and strainmeter data based on a Kalman filtering strategy called the Network Inversion Filter (NIF) [*Segall and Matthews*, 1997; *McGuire and Segall., in review*]. Currently we are further developing the filtering algorithm and using synthetic tests to assess how small a signal (in magnitude and duration) may be accurately modeled given realistic measurement noise and station distribution.

NONTECHNICAL SUMMARY

The time-predictable earthquake recurrence model, which is often used in earthquake probability forecasts, states that an earthquake will occur when a fault reaccumulates the strain released in the most recent earthquake. Using measurements of surface displacement near the San Andreas fault in central California we estimated rigorous bounds on the recurrence time predicted by this model for a M~6 earthquake. The model predicts that this event should have happened by 1987, but to date it has not occurred. This implies that the time-predictable model is too simple to account for the many processes that influence earthquake occurrence.

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DATA AVAILABILITY

The trilateration and GPS data may be obtained in ASCII format from the USGS at: http://quake.wr.usgs.gov/research/deformation/gps/index.html. The sinex files used in this study may be obtained from Jessica Murray (jrmurray@pangea.stanford.edu; 650-723-5485).

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