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Slip-rate increase at Parkfield in 1993 detected by high-precision EDM and borehole tensor strainmeters

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Abstract. On two of the instrument networks at Parkfield, California, the two-color Electronic Distance Meter (EDM) network and Borehole Tensor Strainmeter (BTSM) network, we have detected a rate change starting in 1993 that has persisted at least 5 years. These and other instruments capable of measuring crustal deformation were installed at Parkfield in anticipation of a moderate, M6, earthquake on the San Andreas fault. Many of these instruments have been in operation since the mid 1980s and have established an excellent baseline to judge changes in rate of deformation and the coherence of such changes between instruments. The onset of the observed rate change corresponds in time to two other changes at Parkfield. From late 1992 through late 1994, the Parkfield region had an increase in number of M4 to M5 earthquakes relative to the preceding 6 years. The deformation-rate change also coincides with the end of a 7-year period of sub-normal rainfall. Both the spatial coherence of the rate change and hydrological modeling suggest a tectonic explanation for the rate change. From these observations, we infer that the rate of slip increased over the period 1993-1998.

Introduction

Following the forecast by *Bakun and Lindh* [1985] of a M6 earthquake nucleating under Middle Mountain on the San Andreas fault near Parkfield, CA, many types of instruments were installed to measure crustal properties prior, during, and after this anticipated event [*Bakun and McEvilly,* 1984 and *Roeloffs and Langbein*, 1994]. Although the M6 earthquake has not occurred, we have established a baseline of measurements from which we should be able to detect any subtle changes in crustal properties that might occur. We have observed a significant change in the rate of strain that we infer to have resulted from an increase in the rate of right-lateral slip on the San Andreas fault at Parkfield, CA. The data come from two independent instrument networks shown in Figure 1: the Borehole Tensor Strainmeter (BTSM) network [*Gwyther et al.,* 1996] and the two-color Electronic Distance Meter (EDM) network [*Langbein et al.*, 1990].

We show here that data from the two-color EDM network support the claim of *Gwyther et al.* [1996] for a change in the deformation rate at Parkfield. These data are from independent measurements that do not have the same noise sources as the borehole strainmeters. The combined EDM and strainmeter data provide additional constraints on the source of deformation. In addition, our analysis incorporates a noise model of the data such that the statistical significance of the rate changes can be estimated.

The strain changes measured at Parkfield are significant since they document changes in strain accumulation and fault slip over periods of less than a decade. Although much effort has been spent looking for changes in rates of crustal deformation (*eg. Savage and Lisowski,* 1995), it is rare to find a report where the

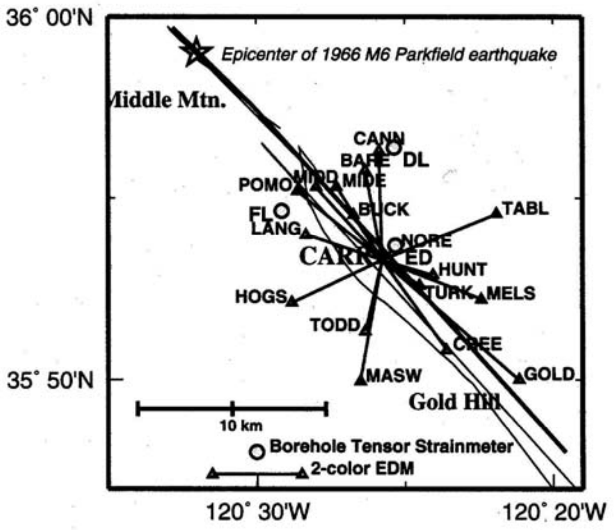

Figure 1. Location of the two-color EDM network and the BTSM network with respect to the San Andreas fault and other localities at Parkfield, CA. The monuments at POMO and MIDE have nearby monuments POMM and MIDA (not identified in the figure). POMM and MIDA are deeply anchored and are described by *Langbein et al.* [1995].

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changes are both statistically significant and observed on more than a single instrument type (eg. *Wakita et al.,* 1988)

Data

The measurements and rate changes in the BTSM network through 1995 have been described by *Gwyther et al.*, [1996]. An additional 3 years of measurements are included in the analysis here. We processed the data as follows: Each BTSM consists of three independent extensometers oriented 120°apart. For each extensometer gauge, the data have a background noise process that is closely related to a random walk, and an exponential term arising from long-term readjustment of the instrument inclusion. We have investigated a number of approaches to determine the underlying tectonic rate changes in the data. Here we take the first derivative of the data after low-pass filtering and decimating to 10-day intervals so that the transformed data are more

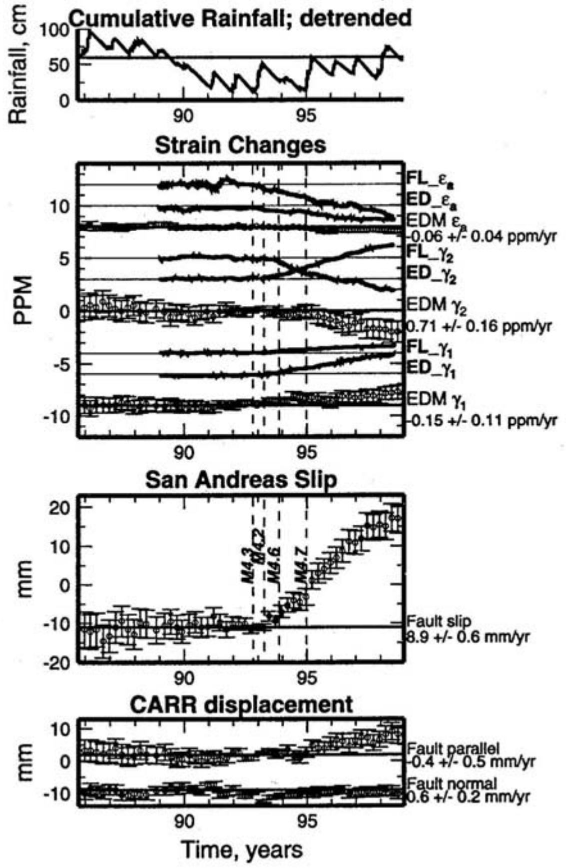

Figure 2. Results of fitting a model of fault slip and strain accumulation to the EDM data. The strain changes inferred from the EDM data are compared with the strain changes deduced from two of the strainmeters. The standard error changes with time because the EDM data have temporal correlations that are modeled by a random-walk process. The times and size of 4 earthquakes, with $M > 4$, under Middle Mountain are shown. In addition, cumulative rainfall is shown (detrended by an annual rate of $38cm/yr$).

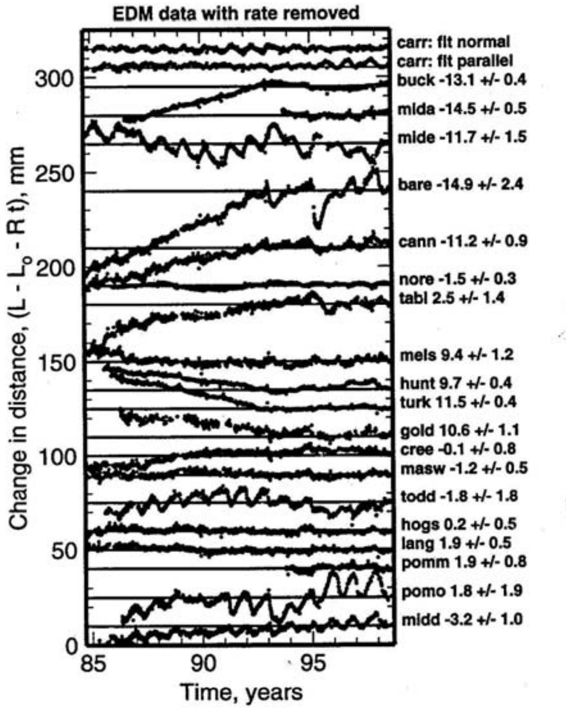

Figure 3. Residual changes in line length from 19 baselines measured by the two-color EDM at Parkfield. The data have been adjusted for possible changes in the position of the central monument (shown on the top two traces). In addition, a lengthening rate has been estimated for the 1993 to 1998.7 interval and that trend has been removed from the data. The rate and its standard error are shown adjacent to the trace of the residuals.

closely related to a Gaussian process with a normal distribution. Then, for the derivative time series, we fit the function $Ae^{(t-t_0)/\alpha} + B + C$ where the exponential terms A and α model the installation process after t_0 [*Gwyther et al.* 1996], constants B and C represent the background secular rate and the change in rate after 1993, respectively. The root mean square (RMS) of the residuals to this function represents the data error and it can be propagated through the least-squares procedure to estimate the standard errors of the four parameters.

Once the rate-change parameter and its error are quantified for each gauge, then the equivalent tensor-strain quantities, $\epsilon_a = \epsilon_{xx} + \epsilon_{yy}$, $\gamma_1 = \epsilon_{xx} - \epsilon_{yy}$, and $\gamma_2 = 2\epsilon_{xy}$ [*Gladwin and Hart,* 1985], are computed where x and y are directed east and north, respectively. The estimates of rate change in $\mu strain/yr$ are: $\gamma_1 = -0.34 \pm 0.12$, $\gamma_2 = 0.56 \pm 0.11$ for ED and $\gamma_1 = 0.12 \pm 0.16$, $\gamma_2 = -0.54 \pm 0.16$ for FL. The residual strain changes (assuming $C = 0$) are shown in Figure 2. Although the statistics indicate that the strain-rate changes for DL are significant, examination of the character of the short-term fluctuations indicates that this instrument is affected by localized deformation due to hydrology [*Gwyther et al.,* 1996].

The residual changes in line lengths as measured by the two-color EDM [*Langbein et al.,* 1990 and *Langbein et al.,* 1995] are shown in Figure 3. These data have been adjusted for localized motion of the central monument CARR and their secular rates have been removed. The localized motion of CARR is estimated as follows: line-length changes from all of the baselines are filtered such that only the fluctuations with periods shorter than 1.5 years remain. With the exception of the four baselines, with high random-walk noise (TODD, POMO, MIDE, and BARE) [*Langbein and Johnson,* 1997], the length-change residuals from each baseline for each day are used to estimate the motion of the central monument by fitting $P\cos\theta_i + N\sin\theta_i$ where θ_i is the azimuth of the i^{th} baseline with respect to the fault. The estimated fault-parallel and fault-normal displacements of CARR, P and N, are also plotted in Figure 3. The values P and N as functions of time are used to adjust the raw length-change measurements from each baseline. A linear trend with time is fit and removed from the adjusted data. These residuals are plotted in Figure 3 and their secular rates are listed in the figure. The standard deviation in rate incorporates the results of the analysis of *Langbein and Johnson* (1997), where they show that EDM data have both Gaussian and random-walk noise in the background.

Three fault-crossing baselines, BUCK, HUNT, and TURK, show a change in rate that appears significant. The sign of these changes is consistent with the rate of fault slip increasing in 1993. Further, the two non-fault crossing baselines that are nearly fault-parallel, MIDD and CREE, do not show any obvious change in rate. Thus, it is likely that the rate change on the fault-crossing baselines is due to fault slip rather than fault-parallel motion of CARR.

Comparison of the data shown in Figures 2 and 3 suggests that both the EDM and BTSM networks detected a rate change during 1993. The delayed change for the BTSM data is resolved when the random-walk character of both data sets is taken into account. The change in rate of deformation coincides with two other events: rainfall and seismic activity. The rainfall for early 1993 was the largest seasonal rain since 1987. The rate of seismic moment release near Parkfield peaked in the interval between late 1992 and late 1994.

Table 1. Estimated slip and strain-rate changes from EDM data

Component	Rate 1986.0-1998.7	Rate change 1993.0-1998.7
Rigid block slip on SAF, mm/yr	8.9±0.6	4.6±0.9
ϵ_a $\mu strain/yr$	-0.06±0.04	-0.1±0.1
γ_1 $\mu strain/yr$	-0.15±0.11	0.1±0.2
γ_2 $\mu strain/yr$	0.71±0.16	-0.3±0.2
Carr displacement		
Fault normal mm/yr	0.6±0.2	0.3±0.4
Fault parallel mm/yr	-0.4±0.5	1.3±0.7

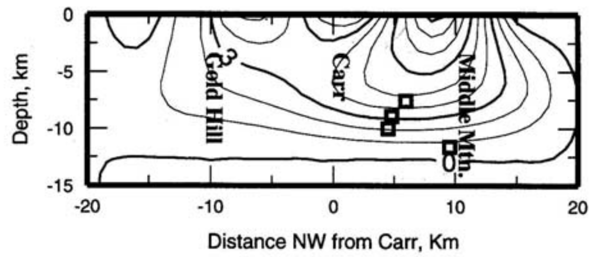

Figure 4. A cross section of inferred changes in the rate of slip using the EDM and BTSM shear-strain data. The rate changes are from comparing post 1993 measurements to those prior to 1993. The contour intervals are in mm/yr. The locations of $M > 4$ earthquakes after December 1992 are plotted as squares and the positions of local geography are shown for cross referencing with Figure 1.

Modeling

To enhance the resolution of this possible rate change in the EDM data, we construct a simple model of deformation as a function of time. The model consists of 6 time-varying parameters. Fault slip is represented by simple, rigid-block motion on the San Andreas. Since the procedure used to adjust the data for motion of CARR is not exact, two parameters are used to account for motion of CARR. Since we know from *Segall and Harris* [1987] that the slip distribution on the San Andreas is more complex than rigid-block motion, we add three components of strain to model for part of the complexity. The basic method to estimate these parameters with time is discussed by *Langbein* [1989]. Here it is modified to incorporate a data covariance with a combination of random-walk and white noise as documented by *Langbein and Johnson* [1997].

The results shown in Figure 2 and listed in Table 1 demonstrate that the rate of fault slip on the San Andreas increased. The uncertainty in slip-rate change of $0.9mm/yr$ includes the high statistical correlation (0.9) between slip and fault-parallel motion of CARR.

The BTSM and EDM data can be combined to model the distribution of slip-rate changes on the San Andreas fault. We can only model slip-rate change rather than slip rate because the strainmeter data are only sensitive to changes in strain rate. A map of the distribution of slip-rate changes is constructed using the methodology of *Matthews and Segall* [1993]. After partitioning the fault into many small slip patches (*Okada,* 1992), a Laplacian smoothness constraint is imposed on the distribution of slip. Cross validation is used to select a slip-rate distribution that fits the data but is relatively smooth. The localized motion of CARR is an additional parameter that is estimated along with the slip distribution.

The result for a model that fits the data is shown in Figure 4. Other slip-rate distributions can be tested by specifying regions of zero slip. Results from inverting the data for these extreme models suggest that the slip-rate changes extend to at least 5 *km* depth and span the fault zone from 5 to 10 *km* northwest of CARR. This concentration of slip northwest of CARR is apparent in the slip-rate distribution shown in Figure 4 where only the smoothness constraint was used.

Summary and Conclusions

Data from two different types of instruments near Parkfield suggest a change in the rate of slip on the San Andreas fault. The rate changes coincide both with a 2-year period of $M > 4$ earthquakes and the cessation of sub-normal rainfall at Parkfield. Closer examination of the results presented in Figure 2 suggests that the slip rate during the past year, 1997.5 to 1998.5, has returned to its pre-1993 rate, but that the strain rates from the BTSM network have not changed over the past year.

The rate changes coincide with the cessation of a 5-year drought. Some of the EDM baselines are strongly affected by seasonal wetting and drying of the soil adjacent to these shallow monuments [*Langbein et al.*, 1990 and 1995]. Longer-period changes due to a multiple-year drought are more difficult to reconcile. However, the three baselines that contribute most to the apparent rate change are only minimally influenced by the seasonal rainfall and these baselines have the small values of random-walk noise compared to the other Parkfield baselines [*Langbein and Johnson,* 1997].

With the cessation of the drought, we would expect that the water table would be recharged, which is the case at Parkfield [*Roeloffs and Quilty*, personal communication 1998]. *Roeloffs* [1997] has modeled water table changes likely to result in the observed strain-rate changes. Her conclusion is that the three mechanisms which might lead to associated strain change, namely water table loading, poro-elastic coupling, and localized percolation to depth, are all unlikely in the case of the Parkfield data. However, we can not rule out the possibility that the shear-strain changes reported here are influenced by the local hydrology.

Local seismicity at Parkfield suggests that a tectonic origin for these rate changes. The sequence of four $M > 4$ earthquakes under Middle Mountain in the two-year interval from late 1992 are the largest events near Middle Mountain since we started intensive geodetic monitoring in 1985. In addition, ***Nadeau and McEvilly*** [1999] present evidence from micro-earthquakes suggesting that there was an increase in slip under Middle Mountain for the 2 to 3 year interval starting in 1993. We believe that the data from seismicity and the two deformation networks are important since it is the first case where earth scientists have documented an increase in fault slip over a small part of the fault zone using independent data sets.

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