GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 10, PAGES 1777-1780, SEPTEMBER 1990

Near-Field High Resolution Strain Measurements Prior to the October 18, 1989, Loma Prieta M_S 7.1 Earthquake.

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Abstract. High resolution strain recordings were made in deep boreholes throughout California prior to, during, and following, the October 18, 1989, M_S 7.1 Loma Prieta earthquake. The nearest dilational strainmeters (sensitivity 10^{-10}) and 3-component tensor strainmeters (sensitivity 10^{-9}) were 37 km to 42 km, respectively, from the main shock. High quality data, including details of strain offsets, were recorded on both instruments through the earthquake. These data have been searched for indications of short-, intermediate-, and long-term strain redistribution and/or fault slip that might have indicated imminent rupture. Short- and intermediate-term changes in both tensor strain and dilational strain (≤ several nanostrain, if any) during the minutes to months before the earthquake are at least 1000 times smaller than that generated by the earthquake itself. If short-term preseismic slip did occur at the nucleation point of the earthquake during the previous week, and if the type of slip is similar to that during the earthquake, its moment could not be more than 10^{24} dyne-cm. Stated another way, slip equivalent to that expected for a M 5.3 earthquake could have occurred in the hypocentral region without the strainmeters detecting it at these distances and azimuthal positions. Long-term strain changes appear to have occurred in mid-1988 and mid-1989. These changes were both followed by M_L 5 earthquakes in the hypocentral region on June 27, 1988, and August 8, 1989, respectively, and, since they correspond approximately to changes in geodetic strain rate over the epicenter, may indicate precursory strain redistribution in the epicentral region. Minor post-seismic strain recovery (≈ 14%) occurred in the month following the main shock.

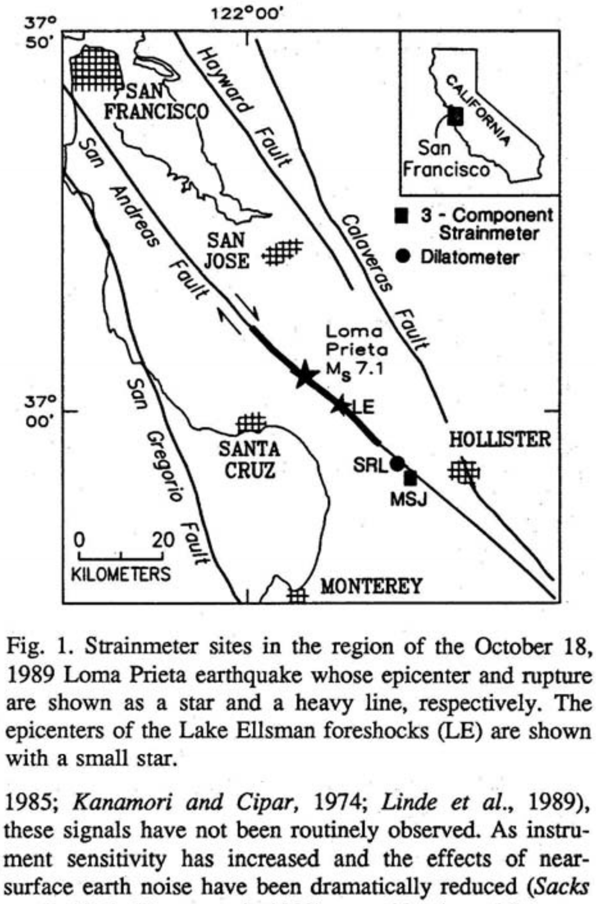

Fig. 1. Strainmeter sites in the region of the October 18, 1989 Loma Prieta earthquake whose epicenter and rupture are shown as a star and a heavy line, respectively. The epicenters of the Lake Ellsman foreshocks (LE) are shown with a small star.

Introduction

Changes in the state of crustal stress and strain in the epicentral region of moderate to large earthquakes have long been expected to precede the main shock (*Mogi,* 1985) but, while some intriguing indications of impending fault failure have been reported (eg *Rikitake,* 1976; *Mogi,* 1985; *Kanamori and Cipar,* 1974; *Linde et al.,* 1989), these signals have not been routinely observed. As instrument sensitivity has increased and the effects of near-surface earth noise have been dramatically reduced (*Sacks et al.,* 1971; *Wyatt et al.,* 1982), quantification of "precursive" strain and tilt changes and identification of the underlying physics of failure, has proven illusive (*Johnston et al.,* 1987). Arrays of borehole instruments have been installed in Japan (see summary of the Japanese Program in Mogi, 1981) and at several critical locations within the San Andreas fault system (*Johnston et al.,* 1987) to provide insight into these issues.

In expectation of a moderate to large magnitude earthquake in the Santa Cruz mountains/San Juan Bautista section of the San Andreas fault, an array of eight deep borehole dilational strainmeters (*Sacks et al.,* 1971) and

Paper number 90GL01494
0094-8276/90/90GL-01494$03.00

tensor strainmeters (*Gladwin et al.*, 1987) was planned for for this region in the early 1980's. Unfortunately, only three of the eight instruments in the plan were installed (in 1982 and 1983) and only two of these instruments were operating at the time of the October 18, 1989, M_S 7.1 Loma Prieta earthquake (*U.S.G.S. Staff*, 1990). High resolution strain recordings were made on both of these instruments through the earthquake. The closest dilatometer, SRL, and tensor strainmeter, MSJ, are 37.5 km and 41.6 km, respectively, to the southeast along strike from the hypocenter of the earthquake but only about 6 km and 9.5 km, respectively, from the probable southern end of the final rupture (Figure 1).

These near-field data collected during the Loma Prieta earthquake provide us with our best opportunity yet to: 1) identify precursive changes in both dilational and tensor strain during the years to minutes before this earthquake, 2) estimate the maximum possible precursive slip (if any) at the nucleation point of the earthquake assuming it has a form similar to that during the earthquake, 3) compare the observed coseismic strain offsets with those calculated from simple models of the earthquake, 4) identify and characterize the post-seismic strain/slip behavior, and 5) compare the longer-term borehole strain data with geodetic strain data (*Lisowski et al*, 1990a) over the same time period.

Instrumentation

The dilational strainmeter (*Sacks et al.*, 1971) and the tensor strainmeter (*Gladwin et al.*, 1987) used in this study are both installed at a depth of about 200-m below the surface at the sites shown in Figure 1. The sensors are cemented in boreholes with expansive grout and each borehole is then filled to the surface with cement to avoid long-term strain changes due to hole relaxation effects and re-equilibration of the aquifer system. The instruments operate at sensitivities of better than 10^{-10} and 10^{-9}, respectively.

The dilatometer and tensor data are transmitted with 16-bit and 12-bit digital telemetry through the GOES satellite to Menlo Park, California, at 1 sample every 10 minutes and 1 sample every 18 minutes, respectively (*Silverman et al.*, 1988). The sensors, the installation, and the telemetry system are calibrated together against the theoretical ocean-load corrected solid earth tides. This calibration is repeatable to better than 5% and remained stable through the earthquake to better than 1%.

Observations

The primary features of the data from the SRL dilatometer during the periods 1 month, 1 year, and 4.5 years, respectively, before the earthquake and one month after the earthquake (LP) are shown in Figure 2, where positive dilation implies extension. The occurrence times of the the Lake Ellsman M_L 5.0 (LE1) and M_L5.2 (LE2) foreshocks on June 27, 1988, and August 8, 1989, respectively, (see *Olsen*, 1990, for details) are also shown in Figure 2c. Orthogonal shear strains γ_1 $\{=(e_{11} - e_{22})/2\}$ and γ_2 $\{=(e_{12})\}$, and dilational strain $\{=0.66(e_{11} + e_{22})\}$ derived from the tensor strain data for the period 4 years before and and 1 month after the earthquake are shown in Figure 3 and detrended versions of these same data are shown in Figure 4. The primary features of Figure's 2, 3, and 4 are:

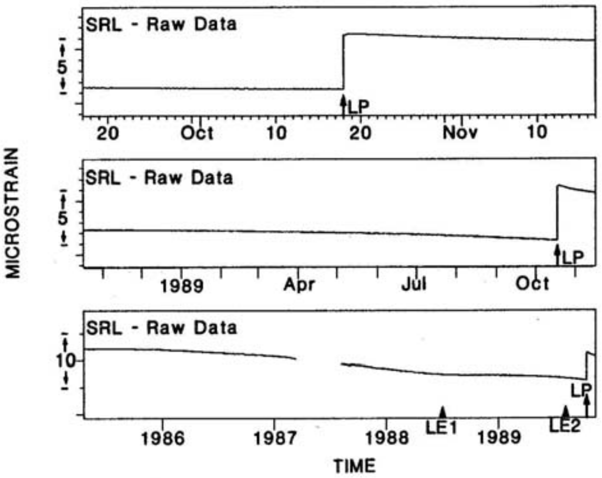

Fig. 2. a) Dilational strain data at SRL one month before and after the Loma Prieta earthquake (LP). b) Dilational strain data at SRL one year before and one month after the Loma Prieta earthquake. 2c) Dilational strain data at SRL 4.5 years before and 1 month after the Loma Prieta earthquake. The occurrence times of the the Lake Ellsman M_L 5.0 (EL1) and M_L5.2 (EL2) foreshocks on June 27, 1988, and August 8, 1989, respectively, are shown with arrows.

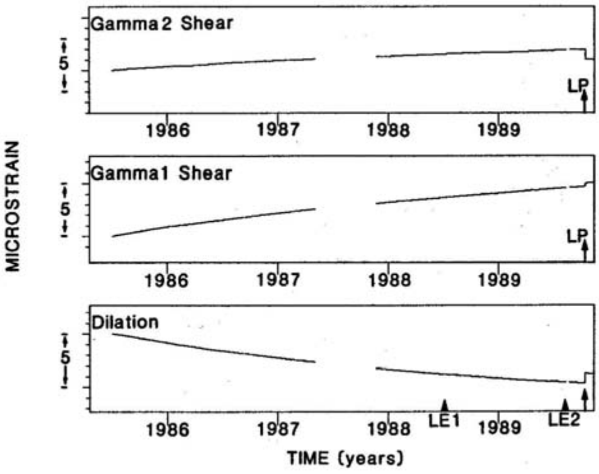

Fig. 3. Orthogonal shear strains γ_1 and γ_2 and dilational strain derived from tensor strain data at MSJ 4 years before and one month after the Loma Prieta earthquake.

1) Absence of significant short-term strain changes during the months to minutes before the earthquake.
2) Indications of longer-term changes in strain rate in mid-1988 (SRL - Figure 2c and MSJ - Figure 4b) and in mid-1989 (SRL - Figure 2c).
3) Coseismic strain offsets of 1.3 microstrain (dilation at MSJ) to 5 microstrain (dilation at SRL).
4) Relatively minor postseismic strain recovery (≈ 14%) in the month following the earthquake evident in all strain data.

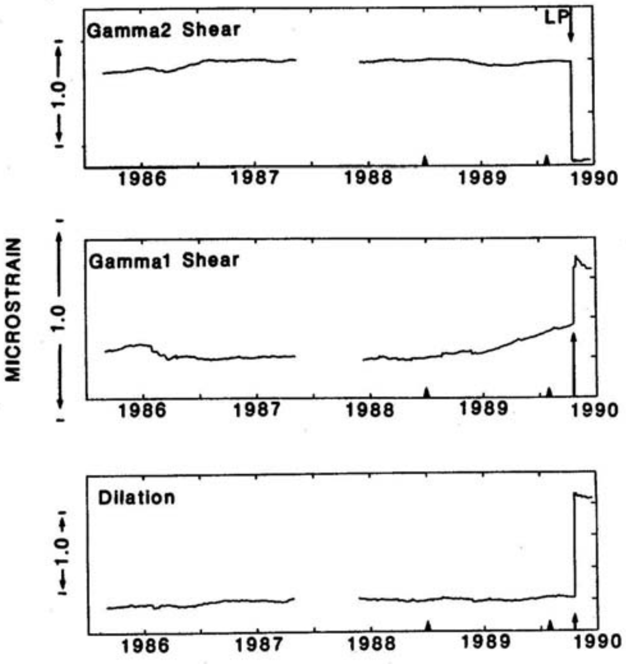

Fig. 4. Residuals of the shear and dilational data in Figure 3 following the removal of exponential functions determined by least-square analysis. The exponentials result from the curing of the grout used to emplace the instrument and to the recovery of borehole stresses relieved during drilling. They are not related to tectonic processes.

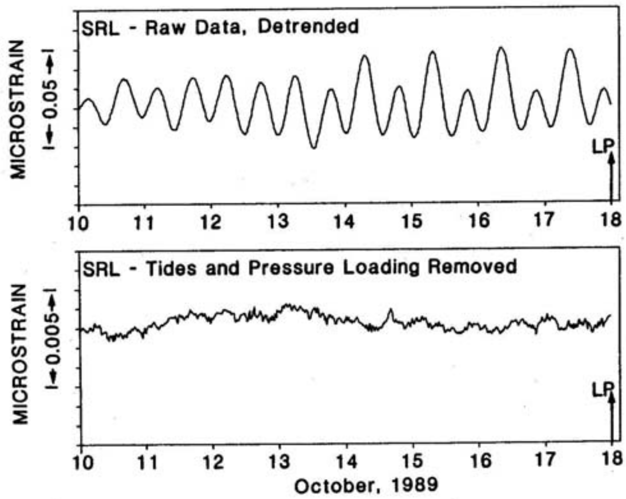

Fig. 5. Dilational strain (upper) during the week before the Loma Prieta earthquake. The lower plot shows the same data at an expanded scale with earth tides and atmospheric loading removed.

An expanded-scale plot of dilational strain during the week immediately before the earthquake Figure 5 (upper) shows more detail of short-term strain prior to the earthquake. The same data with earth tides and atmospheric loading effects removed is shown in the lower plot. The 95% confidence limits of these data are 1.1 nanostrain. Thus, if short-term precursory strain changes occurred during the week before the earthquake, they could not have been more than a nanostrain, or so. Similarly, during the month before the earthquake precursory strain excursions could not have been more than about 5 nanostrain.

Discussion

A most important issue concerns the amount of precursive slip that might have occurred in the hypocentral region prior to the earthquake. If we make the reasonable assumption that, if preseismic slip occurs, it had the same rupture mechanism as the subsequent earthquake, we can estimate the maximum precursive slip moment M_p generating strains of less than 1 nanostrain at the two instrument locations during the weeks to minutes before the earthquake. Thus, taking the geodetically determined source mechanism (*Lisowski et al.*, 1990) and the seismically determined depth (*Deitz and Ellsworth*, 1990) of the Loma Prieta earthquake to indicate precursive source type and location and using *Okada's* (1985) dislocation model formulation, we obtain:

$$M_p \leq 10^{24} dyne-cm$$

Using *Thatcher and Hanks* (1973) magnitude/moment relation, the largest allowable precursive slip moment at the earthquake source is equivalent to an earthquake with a magnitude M=5.3.

We are less certain about our strain change measurements at periods of years or longer. Nevertheless, since long-term changes in the geodetic lines have been reported (*Lisowski et al.,* 1990b) as being precursive to the Loma Prieta earthquake, we have checked our borehole strain data during the same period. We note that the change in strain rate in mid-1988 shown for the dilatometer data in Figure 2c and the detrended fault parallel shear strain (γ_1) in Figure 4 corresponds approximately to the time when the changes in line length occurred.

Unfortunately, there are not enough coseismic strain offset measurements to determine the source parameters of the earthquake. We can, however, compare the observed offsets with those calculated from the best-fit static model of the earthquake constrained by inversion of the surface geodetic data (*Lisowski et al.,* 1990a). This can be done by modeling the source as rectangular fault planes with uniform slip by using *Okada's* (1985) formulation for surface deformations due to a dislocation embedded in an elastic half-space. The calculated strain values at SRL and MSJ are quite sensitive to the details of complex fault geometry at the southern end of the fault rupture. Unfortunately, this geometry is poorly constrained by the large-scale geodetic data (*Lisowski et al.*, 1990a) at this stage of analysis. Until a better fault slip model for the southern end of the Loma Prieta fault rupture is obtained, we cannot compare the observed and calculated the strain offsets at SRL and MSJ.

The simplest interpretation of the immediate postseismic strain data is in terms of rebound following slight overshoot of the fault rupture. However, such an interpretation is probable too simple since the geometry of fault rupture near and beneath these instruments is continuing to change, as indicated by continued seismicity (aftershocks) and changing surface displacements through this region (*Lisowski et al.*, 1990a).

Conclusions

Short-term precursory strain changes are not apparent in data from a dilational strainmeter (located 37.5 km down strike from the Loma Prieta earthquake) and a tensor strainmeters (located 41.6 km from the earthquake). If these precursory strains occurred, they are less than 0.1% of the strain offset generated on these instruments by the earthquake. These observations constrain preseismic moment release at the nucleation point of the earthquake to be less than 10^{24} dyne-cm. In other words, slip greater than that expected for a M 5.3 earthquake in the hypocentral region would have been detected on the strainmeters at these distances and azimuthal positions. Although better positioned over the hypocentral region, geodetic measurements also would not detect this fault slip because of poorer resolution ($\approx$ 1 cm (*Lisowski et al.*, 1990a)).

Long-term strain changes, such as might be expected from strain redistribution in the epicentral area, occurred in mid-1988 and mid-1989. These changes were both followed by M_L 5 earthquakes in the hypocentral region on June 27, 1988, and August 8, 1989, respectively, and correspond approximately in time with possible changes in geodetic strain rate near the epicenter (*Lisowski et al.*, 1990b). A more complete array of instruments was clearly needed around the epicenter of this earthquake to resolve this long-term strain issue and other issues such as determination of the best co-seismic slip models and the details of post-seismic slip growth and geometry.

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(Received March 9, 1990;
Revised June 25, 1990;
Accepted June 26, 1990.)