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A MEDIUM TERM PRECURSOR TO THE LOMA PRIETA EARTHQUAKE ?

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Abstract. The Loma Prieta earthquake (M_S=7.1, 17 October 1989) provided unique near field borehole tensor strain observations. The medium term data at the San Juan Bautista site showed a clear anomalous change in the fault parallel shear strain rate beginning about a year before the event. The anomaly ultimately reached 30% of the coseismic offset. The signal shows similarities with changes in strain rates reported from the geodetic record, suggesting a broad regional anomaly. The limited spacial sampling available prevents determination of a causal link useful for prediction between these data and the earthquake.

INTRODUCTION

Measurements of earth strain within several source dimensions of an earthquake in the years prior to the event should yield information about the processes of strain accumulation and concentration leading to failure, and may contribute to specific prediction of earthquakes.

As the expected strain rates are of order 1 $\mu\varepsilon$ per annum or less, strain data are potentially contaminated by spurious signals from ground coupling problems and non-tectonic effects from thermal, groundwater or cultural sources (*Agnew,1986*). Early near surface point measurements provided little useful insight. Significant improvements in signal quality and stability have been achieved with the deployment of borehole strainmeters at depths of about 200 meters. Quality borehole strain data have been taken at such depths in Japan for nearly 20 years.(*Sacks et al., 1971*) Instruments provide almost continuous data at sensitivities more than three orders of magnitude greater than quality geodetic network data, and, depending on the borehole depth and the complexity of local geology, operate in a relatively noise free environment. Limitations on the data focus on the representative nature of the small sample of the rock surrounding the instrument, and on the reliability of the coupling of the instrument to the rock mass. Measurements indicate that performance is not limited by the intrinsic sensitivity or stability of the instrument package itself (*Agnew, 1986, Gladwin et al., 1987*). The borehole tensor strainmeter used here (*Gladwin, 1984*) measures both hydrostatic and shear strain in the ground with sub-nanostrain resolution and long term stability better than 100nε per year (*Gladwin et al., 1987*). These stability data are also evidenced in the present data.

Two borehole instruments (a Sacks-Evertson dilatometer and a Gladwin tensor strainmeter) were operating in the region of the San Andreas fault recently involved in the magnitude 7.1 Loma Prieta earthquake of October 17, 1989, (see Figure 1). High resolution recordings were made on each of these instruments before, during and after the event (*Johnston et al., 1990*). The San Juan Bautista tensor strainmeter was located 40 km south-east of the epicentre and within perhaps 10 km of the southern extent of the rupture. The data obtained over the four years prior to this event provides a rare opportunity to observe local strain processes prior to a large magnitude earthquake.

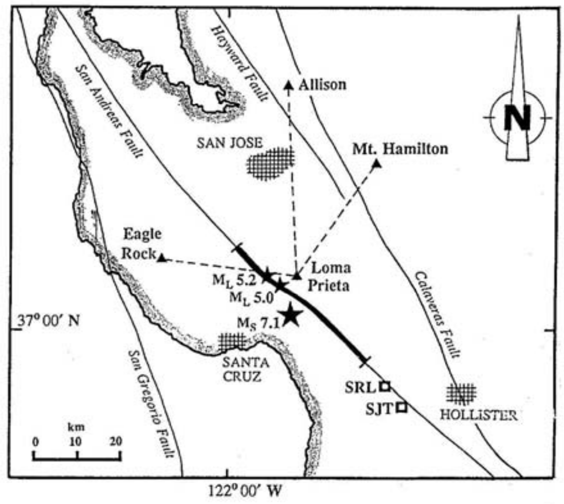

Fig. 1. Borehole strain sites in Northern California. Site SJT is the tensor instrument reported here, and SRL is the Sacks-Evertson dilatometer. Relevant geodetic lines are shown. The section of the San Andreas involved in the Loma Prieta event is shown.

DATA AND PROCESSING

The San Juan site was installed in late September, 1983 at a depth of 150 m using an expansive grout. Day averages for the three components of the strainmeter are shown in figure 2. Immediate post-installation observations are dominated by grout compression of the instrument and by thermally controlled decay as the instrument site re-establishes equilibrium with its surroundings. The installation immediately followed drilling, so that this grout cure was then followed by an exponential recovery of the virgin stress field relieved during the drilling process.

The exponential signals have no relevance to the monitoring of the strain *changes* which may be occurring in the region, and were removed from the raw data by a least squares analysis to produce residual component data used

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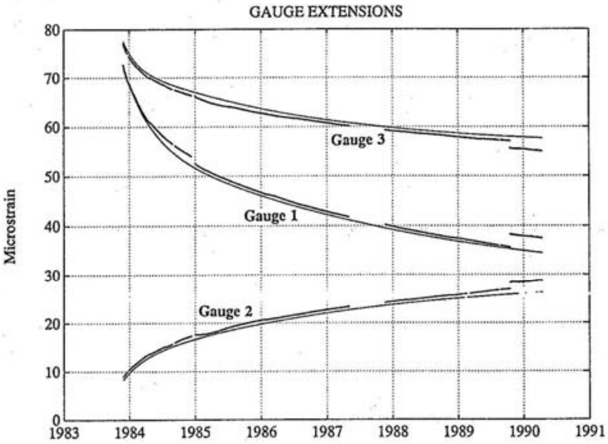

Fig. 2. Three component raw data from the San Juan Bautista site. Data are expressed in microstrain measured within the instrument, and are simple day averages. The fitted exponentials are included on the diagram, offset for clarity.

in subsequent strain analysis. The residuals for the three gauge components are shown in figure 3, for the period from July 1986. No smoothing has been applied.

The residuals thus produced are sensitive to the details of the exponential removal procedure. For meaningful residuals in the present context of a search for possible precursive signals, it is necessary to exclude from the fit regions of data which are contaminated by obvious non-exponential processes or which are themselves involved in the time window of the precursors to be identified. Disturbances of the record associated with the Morgan Hill earthquake, and experiments at the site resulting in large transients due to downhole heating, necessitated exclusion of data from April, 1984 to mid 1986. All data subsequent to March, 1988, which could potentially relate to the change of gradient evident on the raw records, were also excluded. The same exclusion regions were used for all components. A

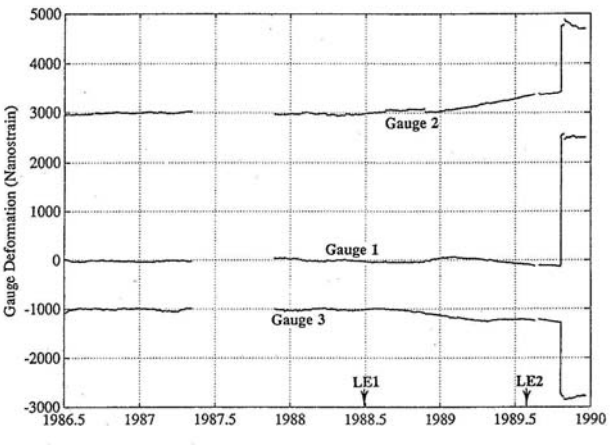

Fig. 3. Three component residuals after removal of exponentials. Data after March, 1988 were excluded from the fit. The change of slope under discussion is evident on all of the components, and represents nearly 20% of the co-seismic amplitude for gauge 3, 25% for gauge 2, and less than 10% for gauge 1.

wide range of data windows were investigated to verify that the strain rate change was not an artifact of the detrending procedure. The onset and character of the linear strain rate anomaly was always evident even if the fit region was extended into 1989. The exponentials determined are shown (offset for better visibility) in figure 2. These exponential processes are to be expected from all standard rheological models. The residuals prior to mid 1988 are remarkably flat, indicating that the determined exponentials adequately describe the long term recovery of the hole. The measured grout curing exponential time constants ranged from about 90 to 110 days, and the hole recovery exponentials ranged from approximately 800 to 1000 days.

These residuals are combined to produce shear and areal strains, which are scaled by hole coupling parameters to account for shear and areal strain response of the instrument inclusion (*Gladwin and Hart, 1985*). The parameters are determined by a calibration procedure involving, for each gauge, a comparison of individual tidal components of the theoretical earth tide strains(corrected for ocean loading) with tidal components of the strains observed on the instrument. The procedure by which individual channels are tidally calibrated is described in detail elsewhere (*Hart et al., in preparation*)

The resulting areal and shear strain records are shown in figure 4. These completely specify the strain field in the horizontal plane defined with the x axis east and the y axis north, γ_1 and γ_2 being shears with the maximum shear across NW-SE/NE-SW planes, and N-S/E-W planes respectively. They are related to the strain tensor components e_{ij} by $e_a=(e_{xx}+e_{yy})$, $\gamma_1=(e_{xx}-e_{yy})$, and $\gamma_2=2e_{xy}$. The convention of extension positive is used. To facilitate comparison

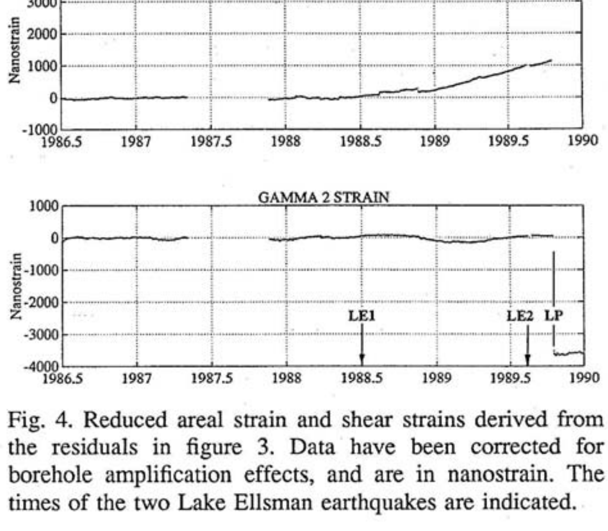

Fig. 4. Reduced areal strain and shear strains derived from the residuals in figure 3. Data have been corrected for borehole amplification effects, and are in nanostrain. The times of the two Lake Ellsman earthquakes are indicated.

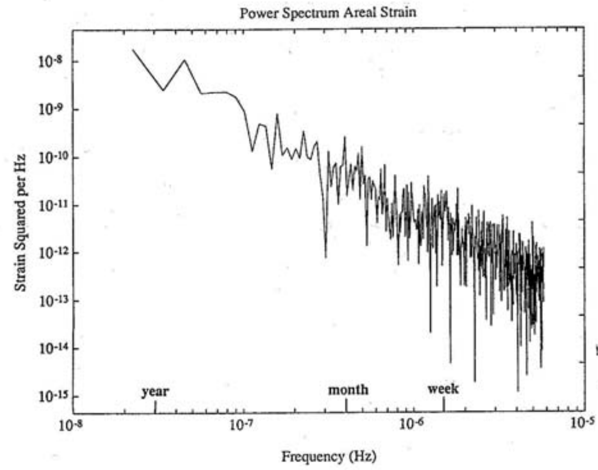

Fig. 5. Power spectrum for 1024 days of areal strain data beginning approximately 1986.5.

of our data with geodetic records in the region, we have here chosen to use engineering strains rather than tensor definitions used in our previous publications. For the areal strain, we have used the symbol e_a rather than Δ (areal dilatation) of Prescott et al., 1979, since Δ commonly refers to volumetric dilatation. No other processing or filtering has been applied to these records. The data show negligible response to rainfall, and no hydrological studies of the region have been investigated.

DISCUSSION OF STRAIN RECORDS

The co-seismic areal strain step seen in figure 4 is +2140 nε, γ_1 is +1840 nε, and γ_2 -3790 nε. Strain axes on this figure differ from those previously reported in *Johnston et al., 1990* which were in non-engineering units and were derived without the gauge-specific calibration procedure here used. As noted in *Johnston et al., 1990*, dislocation models based on the large scale geodetic data appear inappropriate for the south-eastern end of the rupture zone, and do not at this stage predict the coseismic areal strain steps for both Searle Road and San Juan Bautista, which recorded comparable expansions. No short term (seconds to days) precursory signals were evident (*Johnston et al., 1990*).

Apart from the coseismic step, these records are notable for their overall stability. The areal strain, for example, is constant at the 50 nε level from 1986 to early 1989. Investigation of the instrument response to the M_2 and O_1 tidal components indicates that coupling conditions have not changed significantly since 1986.

The most significant feature is the onset of a change in strain rate in γ_1 clearly identified over three months in late 1988. A steady additional strain rate of 1140 nε per year was established, ultimately accumulating more than 30% of the coseismic step. Since e_a is essentially constant, this change in the strain field is predominantly a shear. Further, γ_1 is dominant so the maximum shear is approximately parallel to the San Andreas Fault (strike N50W here) and is consistent with increased shear stress across the fault in the direction of subsequent failure. The data imply a change of strain rate of approximately 370 nε compression per year for e_{yy}, and for the early part of 1989, an extension of approximately 570 nε for e_{xx}.

The power spectrum of three years of the areal strain data shown in figure 5 provides a reasonable estimate of the lowest anomalous signal detectable in any period range. Integration of the spectrum over the period band above three months indicates a standard deviation of approximately 20 nε for assumed stationary data. This same standard deviation would be produced by a single three month ramp excursion of amplitude 100 nε at an arbitrary point in our 34 month record. A signal excursion of similar character to our anomaly can thus be identified as anomalous if it exceeds approximately 100 nε in three months. Under this criterion, the γ_1 record was identifiably anomalous by November 1988, almost a year before the earthquake (Figure 6).

As shown in figure 1, the region to the north of the epicenter is covered by a geodetic network of three lines radiating from Loma Prieta to Allison, Mt. Hamilton and Eagle Rock (*Lisowski et al., 1990*). Lisowski *et al.* report a marginally significant change of gradient for the Allison and and Mt. Hamilton lines following the June 1988 Lake Ellsman "foreshock". The least squares determined change of gradient of the Allison line (-15.1 +/- 2.6 mm per year) appears better defined than that for the Hamilton line (-8.1 +/- 2.2 mm per year). Lower rates are suggested from the GPS data for the Allison line. The dominant effect is on the Allison line which runs roughly North-South and measures the integral of e_{yy} along its length. The geodetic data show an increased compressional rate through 1989 which is equivalent to 300 nε per year averaged over the line. This is comparable to the borehole measurement. The Mt. Hamilton data indicate an averaged compression strain rate of approximately 250 nε per annum compared with the implied value of 180 nε from the borehole data for the period mid 1988 to March 1989.

As noted above, our data imply an extension of 570 nε in e_{xx} which would be expected to show on the Loma to Eagle Rock line. No such extension is evident in the geo-

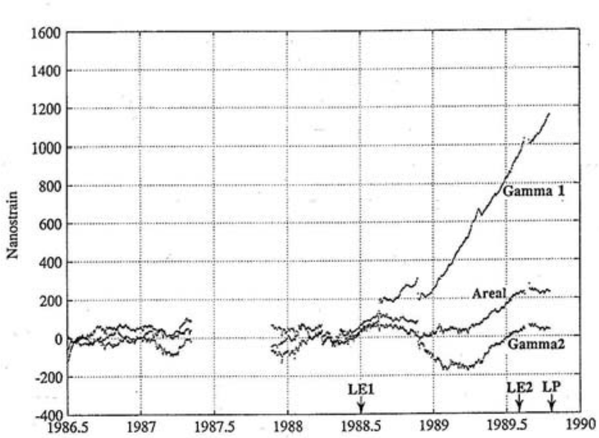

Fig. 6. Areal and shear strain data for the three and a half years up to but not including the Loma Prieta event. The change of character of the shear records is evident.

detic data for the interval. The GPS data, however, appear to indicate an extension which could be as large as 650 nε per annum over the same interval.

The similarity of the borehole data with major features of the geodetic measurement may only be coincidental. Though other models are not excluded, the data could imply a regional increase in shear strain rate acting to increase shear stress across the fault in the direction of failure occurred approximately one year before the Loma Prieta earthquake. The increase is remarkably linear, with no evidence of accelerating failure. However, with such sparse coverage of the region, the temptation to identify this anomaly as a precursor must be resisted.

CONCLUSIONS

A well established change of shear strain rate has been observed at the San Juan tensor strainmeter site, occurring almost a year prior to the Loma Prieta earthquake, with ultimate amplitude of more than 30% of the final coseismic event. Together with geodetic data, this observation may indicate a regional loading of the fault in a direction consistent with final failure. No causal link to the event can be established because of inadequate spatial sampling.

Though the anomaly may have been produced by a source in the immediate instrument vicinity, the similarity in amplitude, sense of shear and time signature with the geodetic observations argue for a regional strain disturbance. Anomalous strain changes reported at the Searle Road dilatometer (*Johnston et al., 1990*), may also confirm this conclusion, though no compatible areal strain effects are evident on our data.

The character of the anomaly is not well described by any of the current theoretical precursor modelling studies, which predict short term tertiary creep phenomena. It is better described as indicative of a process of regional stress concentration caused by a localised departure from the regional tectonic strain rates as determined by geodetic studies. A similar anomaly has been reported (*Wyss et al., 1990*) for the active region of the San Andreas at Parkfield.

As a case study, this observation strongly underlines the need to deploy adequately sized arrays of strain instruments, the importance of measuring the total strain field at each site rather than single components, and the importance and interdependence of short baseline, high resolution data and the absolute long baseline data provided in this case by the geodetic array. The results obtained demonstrate that minimal processing of borehole data to remove borehole equilibration processes produces residuals with stability adequate for short to intermediate term tectonic monitoring relevant to precusor studies. In this context, the observations reported here are the only objective pointer to performance expectations for a future array of borehole strain data.

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