A shear-strain anomaly following the Loma Prieta earthquake

R. L. Gwyther, M. T. Gladwin* & R. H. G. Hart

Department of Physics, University of Queensland, 4072, Australia

BOREHOLE tensor strain instruments deployed along the San Andreas fault for the past ten years have provided sufficient resolution and stability to sample regional tectonic processes, potentially enhancing earthquake prediction capability. Data obtained from the instrument at San Juan Bautista, in the near-field region of the 17 October 1989 Loma Prieta earthquake ($M_s = 7.1$) provide the first opportunity to observe shear strain processes associated with a large earthquake. We previously reported[1] a prominent shear-strain anomaly in those data for more than a year before the earthquake. This anomaly ceased immediately after the earthquake, but, as we report here, a new and higher rate of fault-parallel shear accumulation (2 microstrain per year) was established about four months later and has continued to the present. Associated changes in creep rate are apparent at a number of sites on the surface trace of the fault within 30 km of the strain meter. We propose that the observed strain accumulation results from increased slip around a nearby locked section of the fault, this slip arising from loading by the failed Loma Prieta source region to the north. This model is consistent with suggestions of an increased probability of a moderate earthquake near San Juan Bautista[9,10], and with evidence[12] that interactions between fault regions are important in earthquake processes.

A Gladwin borehole tensor strain meter[2] installed near the San Andreas fault at San Juan Bautista in late 1983 has provided continuous areal and shear strain data with sub-nanostrain (nε) resolution and long-term stability better than 100 nε per year[3]. Raw data from the instrument consist of diameter changes in three directions at 120° to each other in the horizontal plane. These are reduced to areal strain ε_a, and engineering shear strains γ_1 and γ_2 (roughly parallel to and at 45° to the fault, respectively). The strain meter is grouted into the surrounding rock, and this instrument inclusion is softer to shear than to compression. Observed strain components are therefore scaled by hole coupling parameters[4] determined by tidal calibration.

Data from borehole inclusions are initially dominated by grout compression of the instrument, by thermally controlled decay as the instrument site re-establishes equilibrium with its surroundings and by an exponential recovery of the virgin stress field relieved at the borehole during the drilling process[5,6]. The exponential signals have no relevance to the monitoring of regional strain changes and were removed by an exponential least-squares fit over the interval January 1984 to February 1988 (ref. 1). These residuals were then reduced to the strains ε_a, γ_1 and γ_2 shown in Fig. 1*a*.

The dominant signals present are the coseismic strain steps of the Loma Prieta earthquake which in Fig. 1*b* are removed from the data to make long-term trends more apparent. As previously reported, an anomalous change in γ_1 is apparent by late 1988, showing a remarkably linear strain accumulation of 1 $\mu\varepsilon$ per year[1]. A smaller change of ~0.3 $\mu\varepsilon$ per year was also evident from mid-1988. The azimuth of maximum shear for the accumulating shear strain was roughly parallel to the local San Andreas strike.

Immediately after the earthquake, the strain rate returned for ~10 days to its value before the anomaly, then decreased for two months. By May 1990, following the Chittenden aftershock sequence, the present linear shear accumulation rate of ~2 $\mu\varepsilon$ per year with the original sense had been established. During the whole of the period since mid-1988, medium-term changes in ε_a and γ_2 have been less than 250 nε per year. The strain data indicate that by May 1990, the accumulating strain was predominantly shear strain with a maximum azimuth of 318°, close to the local San Andreas fault strike of 310°.

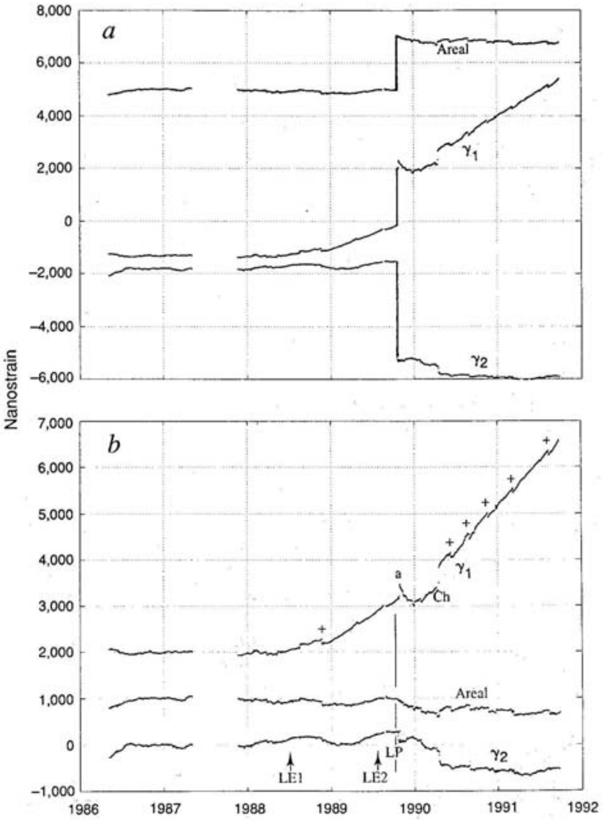

FIG. 1 *a*, Areal strain and shear strains from the SJT borehole tensor strain meter at San Juan Bautista near the San Andreas fault in northern California. Exponential trends have been removed. The dominant feature is the coseismic strain step from the Loma Prieta earthquake. *b*, Removal of this step reveals the details of the strain records, in particular the striking anomaly in the γ_1 component, the relative constancy of the other two strain components and trend reversal on γ_1 for three months following the Loma Prieta earthquake. All steps in the data can be associated with seismic events or nearby creep events: for example, the times of the two Lake Elsman earthquakes are indicated (LE1, LE2), as are the times of the Loma Prieta earthquake (LP), a Loma Prieta aftershock (A), the Chittenden earthquake sequence (Ch) and creep events also monitored on a nearby creep meter (+).

To verify the stability of the instrument and coupling, we investigated the response to earth strain tides using the dominant, thermally uncontaminated tidal components O_1 and M_2. Results are shown in Fig. 2 for the ε_a and γ_1 data sets. It is clear that there have been no significant or systematic changes of tidal admittance on this instrument over the whole period under discussion. In particular, the admittance anomalies before the earthquake suggested for Searle Road dilatometer data[7] are absent in these tensor strain observations.

Several explanations for the strain anomaly following the Loma Prieta earthquake need to be examined. A non-tectonic source from the instrument or its immediate vicinity is unlikely because of the stability of the tidal response, consistency of our internal instrument checks, stability of the areal strain record

---

* To whom correspondence should be addressed.

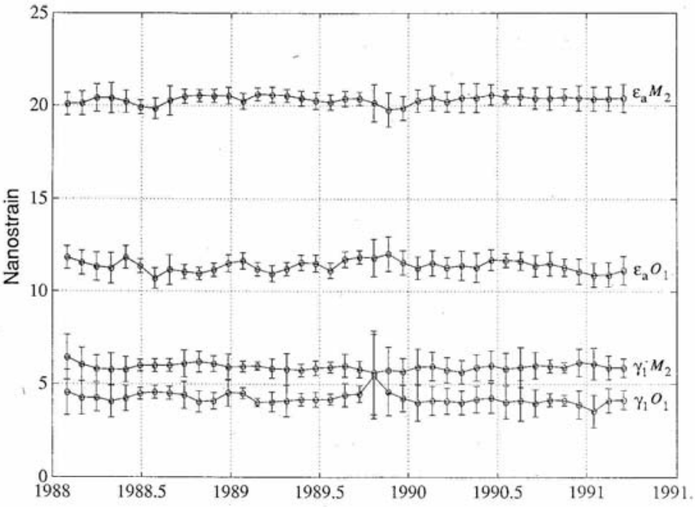

FIG. 2 Amplitude of the M_2 and O_1 tidal components of areal strain ε_a and shear strain γ_1 for the period 1988 to the present. Sixty-day windows of 90-min data were used to provide the amplitude of the normalized tidal component every 30 days. The strain step of the Loma Prieta event and other easily identifiable strain steps were removed from the record. Error bars indicate the precision of determination, assuming gaussian noise. There is no significant change in instrument performance for any component.

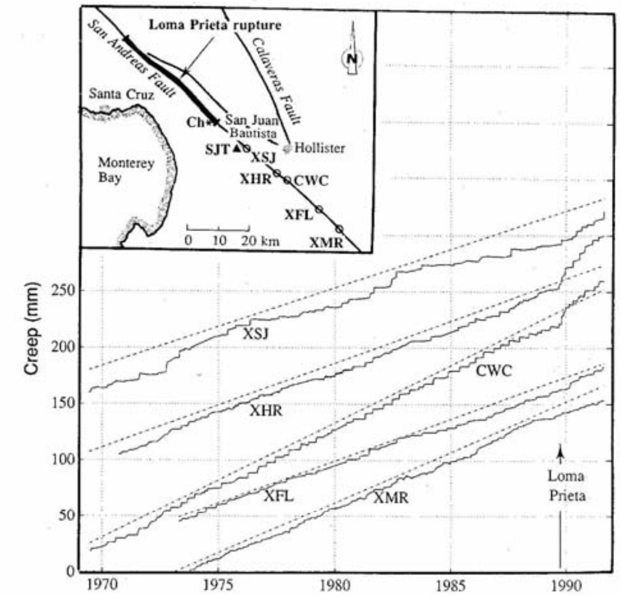

FIG. 3 Surface creep data (provided by K. Breckenridge of United States Geological Survey, Menlo Park) from creep meters along the fault south of San Juan Bautista, with positions of creep meters XSJ, XHR, CWC, XFL and XMR, tensor strain meter SJT, and Chittenden aftershock Ch indicated in the inset map. The trend lines indicated are from Burford[8]. Note that the XMR data have been halved for convenience of plotting.

and detailed correspondence in time of all observed strain steps with either earthquakes or creep events on nearby creep meters.

Although the strain signals could arise from small-scale processes in a nearby section of the fault, observations of anomalous creep at three sites up to 30 km away indicate a more extended source. Figure 3 shows long-term data from creep meters for 5 sites covering 40 km of the fault south of San Juan Bautista, with long-term trends from ref. 8. A distinct increase in creep rate following the Loma Prieta earthquake is evident on sites XSJ, XHR and CWC, spanning 16 km of the fault. The XFL site (29 km from XSJ) shows only a marginal increase, and the more remote site XMR (40 km) shows no effect.

The creep anomalies in Fig. 3 are atypical, especially for CWC and XHR, and begin at the time of the Loma earthquake. The creep anomaly at XSJ begins about the time of the establishment of the new shear-strain anomaly at SJT. This strongly suggests that these signals are not just the consequence of normal interactions between fault sections in this creeping section, but are linked to the earthquake. We conclude that the failure of the Loma Prieta source region transferred load to the San Juan Bautista region just to its south, resulting in increased creep rate. The simplest explanation of an increased creep rate is frictional response to the increased shear loading parallel to the fault indicated by the coseismic γ_1 step at San Juan Bautista (see Fig. 1*a*).

But slip through creep does not itself result in linearly increasing elastic strain. We suggest that our linear shear-strain anomaly is best explained by continued aseismic slip around a nearby locked section of the fault, the slip being associated with loading transferred from the Loma Prieta source region, particularly after the Chittenden aftershock sequence (April 1990). The area near San Juan Bautista is known to experience moderate earthquakes ($M_L \approx 5$) 4–8 km deep, and an earthquake has recently been predicted there after a locked section was identified by seismic quiescence[9] and creep retardation[10]. The shear-strain data are consistent with increased loading on a locked section in this region, and thus an increased probability of a moderate earthquake in the San Juan Bautista region.

We have previously suggested[1] that the strain changes occurring before Loma Prieta were related to a broad regional effect, arguing this from the timing of the Lake Elsman foreshock and a marginal geodetic anomaly[11] near the Loma Prieta source. Creep retardation preceding moderate earthquakes in adjacent regions has been observed[8]. The creep data in Fig. 3 also show some evidence for a regional creep anomaly (at XSJ, XHR and CWC) in the two years before Loma Prieta. This provides support, independent of the geodetic data, for our suggestion[1] of a pre-Loma Prieta strain anomaly, at least in the San Juan region. The disappearance of the strain anomaly immediately following the earthquake has further strengthened the case that these anomalous changes were directly associated with the Loma Prieta event. ☐

Received 1 September 1991; accepted 16 January 1992.

1. Gladwin, M. T., Gwyther, R. L., Higbie, J. W. & Hart, R. *Geophys. Res. Lett.* **18,** 1377–1380 (1991).
2. Gladwin, M. T. *Rev. scient. Instrum.* **55,** 2011–2016 (1984).
3. Gladwin, M. T., Gwyther, R. L., Hart, R. & Francis, M. *J. geophys. Res.* **92,** 7981–7988 (1987).
4. Gladwin, M. T. & Hart, R. *Pure appl. Geophys.* **123,** 59–88 (1985).
5. Berry, D. S. *Int. J. Rock Mech. Min. Sci.* **4,** 181–187 (1967).
6. Berry, D. S. & Fairhurst, C. *Am. Soc. Testing Mat. STP* **402,** 190–206 (1966).
7. Johnston, M. J. S. & Linde, A. T. *Eos* **71,** 1461 (1990).
8. Burford, R. O. *Pure appl. Geophys.* **126,** 499–529 (1988).
9. Wyss, M. & Burford, R. A. *Nature* **329,** 323–325 (1987).
10. Sylvester, A. G., Burford, R. O. & Schultz, S. S. *Eos* **71,** 290 (1990).
11. Lisowski, M., Prescott, W. H., Savage, J. C. & Svarc, J. L. *Geophys. Res. Lett.* **17,** 1211–1214 (1990).
12. Marko, G. M. *J. geophys. Res.* **87,** 7807–7816 (1982).

ACKNOWLEDGEMENTS. We thank R. Liechti for maintenance, K. Breckenridge for data retrieval and assistance with creep meter data, and A. Linde and M. Johnston for support in the program. The work was supported by a grant from the US Geological Survey, Department of the Interior. Contents do not represent policy of that agency, and no endorsement of the agency is to be assumed. The instruments were previously developed under awards of the Australian Research Grants Scheme, and fabricated by R. Willoby and staff in house.