PRESEISMIC OBSERVATIONS

NEAR-FIELD HIGH-RESOLUTION STRAIN MEASUREMENTS

By Malcolm J.S. Johnston,
U.S. Geological Survey; and
Alan T. Linde,
Carnegie Institution of Washington

CONTENTS

ABSTRACT

High-resolution strain recordings were made in deep boreholes throughout California before, during, and after the earthquake. The nearest dilatational strainmeters (sensitivity, 10^{-10}) and three-component tensor strainmeters (sensitivity, 10^{-9}) were 37 to 42 km, respectively, from the main-shock epicenter. High-quality data, including details of strain offsets, were recorded on both instruments through the earthquake. We have searched these data 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 dilatational strain (not more than several nanostrain if any) during the minutes to months before the earthquake are at least 1,000 times smaller than that generated by the earthquake itself. If any short-term preseismic slip did occur at the nucleation point of the earthquake during the previous week, and if the type of slip was similar to that observed during the earthquake, its moment could be no more than 10^{24} dyne-cm. Stated another way, slip equivalent to that expected for an earthquake with a magnitude of 5.3 could have occurred in the hypocentral region without the strainmeters detecting it at these distances and azimuthal positions. Longer-term changes in strain rate appear to have occurred in mid-1988 and mid-1989 at about the time of two M_L=5 earthquakes in the hypocentral region on June 27, 1988, and August 8, 1989. Because regional strain redistribution in the epicentral area is not apparent in large-scale surface-displacement data over this region, these changes probably resulted from adjustment of nearby fault-slip rates at these times. Minor postseismic strain recovery (≈14 percent) occurred in the month after the main shock.

INTRODUCTION

Although changes in the state of crustal stress and strain in the epicentral regions of moderate to large earthquakes have long been expected to precede the main shock (Mogi, 1985) and some intriguing indications of impending fault failure have been reported (for example, Kanamori and Cipar, 1974; Rikitake, 1976; Mogi, 1985; Linde and others, 1988), these signals have not been routinely observed. As instrumental sensitivity has increased and the effects of near-surface earth noise have been dramatically reduced (Sacks and others, 1971; Wyatt and others, 1982), quantification of "precursory" strain and tilt changes and identification of the underlying physics of failure have proved elusive (Johnston and others, 1987). Arrays of borehole instruments have been installed in Japan (see summary by Mogi, 1981) and at several critical locations within the San Andreas fault system (Johnston and others, 1987) to investigate these issues.

In expectation of a moderate to large earthquake in the Santa Cruz Mountains/San Juan Bautista section of the San Andreas fault, installation of an array of six deep-borehole dilatational strainmeters (Sacks and others, 1971) and two tensor strainmeters (Gladwin and others, 1987) was planned for this region in the early 1980's. However, only three of these eight instruments were actually installed (in 1982 and 1983), of which only two (one dilatometer and one tensor strainmeter) were operating at the time of the Loma Prieta earthquake (U.S. Geological Survey staff, 1990). High-resolution strain recordings were made on both of these instruments through the time of the earthquake (Johnston and others, 1990). The closest dilatometer (site SRL, fig. 1) and tensor strainmeter (site MSJ, fig. 1) are 37.5 and 41.6 km, respectively, to the southeast along strike from the hypocenter of the earthquake but only about 6 and 9.5 km, respectively, from the probable south end of the final rupture zone (fig. 1).

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

INSTRUMENTATION

The dilatational (Sacks and others, 1971) and tensor strainmeters (Gladwin and others, 1987) used in this study are both installed at about 200-m depth below the surface

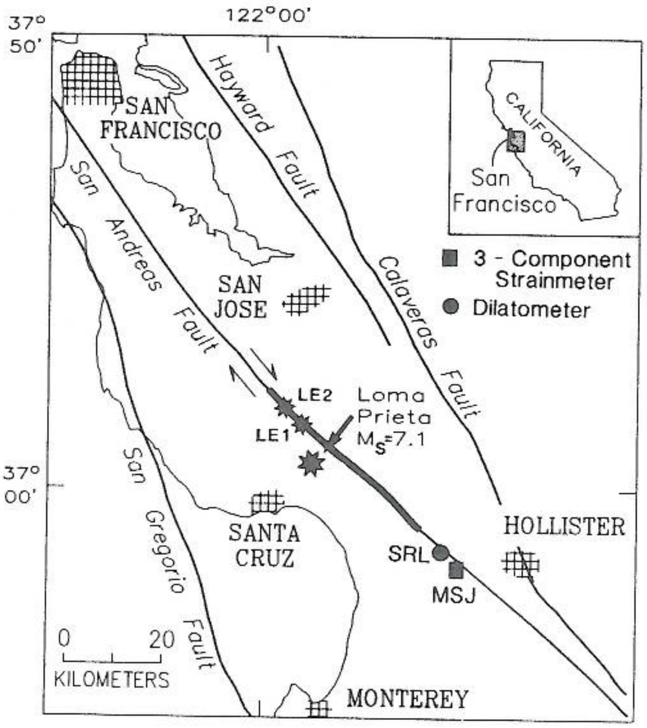

Figure 1.—San Francisco Bay region, showing locations of strainmeter sites SRL and MSJ. Large star, epicenter of Loma Prieta earthquake; small stars, epicenters of two Lake Elsman foreshocks (LE1, LE2). Heavy line, Loma Prieta rupture zone. Arrows denote direction of fault movement.

at the locations 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 reequilibration of the aquifer system. The instruments operate at sensitivities of better than 10^{-10} and 10^{-9}, respectively.

Data from the dilatational and tensor strainmeters are transmitted with 16- and 12-bit digital telemetry through the Geostationary Orbit Environmental Satellite (GOES) to the U.S. Geological Survey offices in Menlo Park, Calif., at 1 sample every 10 minutes and 1 sample every 18 minutes, respectively (Silverman and others, 1989). The sensors, the installation, and the telemetry system are all calibrated together against the theoretical ocean-load-corrected solid-earth tides; this calibration is repeatable to better than 5 percent and remained stable through the earthquake to better than 1 percent.

OBSERVATIONS

The primary features of the data from the dilatometer at site SRL (fig. 1) during the periods 1 month, 1 year, and 4.5 years, respectively, before and 1 month after the earthquake (LP) are shown in figure 2, where positive dilation implies extension. The occurrence times of the Lake Elsman M_L=5.0 (LE1) and M_L=5.2 (LE2) foreshocks on June 27, 1988, and August 8, 1989, respectively (see Olson, 1990, for details), are shown in figure 2*C*.

The three strain components from the tensor strainmeter at site MSJ (fig. 1) have been combined, first, to determine strains in east-west (e_{11}) and north-south (e_{22}) directions and, second, to determine (1) tensor shear strain γ_1 [$=(e_{11}-e_{22})/2$] across a plane in a northwest-southeast direction, or approximately parallel to the San Andreas fault; (2) tensor shear strain γ_2 ($=e_{12}$) across a plane in a north-south direction, or approximately 45° to the San Andreas fault; and (3) dilatational strain Δ [$=0.66(e_{11}+e_{22})$]. Note that this terminology (for tensor shear strain) differs by a factor of 2 from the engineering shear-strain terminology used by Gladwin and others (1991), and that the scale on these figures differs slightly from that used by Johnston and others (1990) because the gage-specific calibration factors used by Gladwin and others (1991) have been invoked.

The shear strains γ_1 and γ_2 and the dilatational strain Δ during the periods 4 years before and 1 month after the earthquake are plotted in figure 3, and detrended versions of these same data in figure 4. The primary features of figures 2 through 4 are (1) absence of significant short-term strain changes during the minutes to months before the earthquake; (2) indications of longer term changes in strain rate in mid-1988 at sites SRL (fig. 2*C*) and MSJ (fig. 4*B*) and in mid-1989 at site SRL (fig. 2*C*); (3) coseismic strain offsets of 1.4 microstrain (dilation at site MSJ) to 5 microstrains (dilation at site SRL); and (4) relatively minor postseismic strain recovery (≈14 percent) in the month after the earthquake, evident in all the strain data.

An expanded-scale plot of dilatational strain during the week before the earthquake (fig. 5*A*) shows more detail of the short-term strain immediately before the earthquake, and the same data with earth tides and atmospheric-loading effects removed are plotted in figure 5*B*. The 95-percent-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

An important issue concerns the amount of precursory slip that might have occurred in the hypocentral region before the earthquake. If we make the reasonable assumption that, if preseismic slip did occur, it had the same rupture mechanism as the subsequent earthquake, we can estimate the maximum precursory slip moment M_p generating strains of less than 1 nanostrain at the two strainmeter sites during the minutes to weeks before the earthquake. Thus, taking the geodetically determined source mechanism (Lisowski and others, 1990a) and the seismically determined depth (Dietz and Ellsworth, 1990) of the earthquake to indicate precursory source type and location, and using Okada's (1985) dislocation-model formulation, we obtain $M_p \leq 10^{24}$ dyne-cm. Using Aki's (1987) magnitude/moment relation, the largest allowable precursory slip moment at the earthquake source is equivalent to an earthquake of M=5.3.

We are less certain about our measurements of strain-rate changes at periods of years or longer. Long-term changes in the geodetic lines were initially reported as a precursor to the earthquake by Lisowski and others (1990b). However, these changes have since been shown not to be significant (Lisowski and others, 1992). Nevertheless, we have checked our borehole strainmeter data during the same period and note that strain-rate changes did occur in mid-1988 (shown for dilatometer data in fig. 2*C* and detrended fault-parallel shear strain γ_1 in fig. 4*B*). These changes correspond approximately to the time of the first Lake Elsman foreshock (LE1), as shown in figures 2*C* and 4*B*. A less significant change in long-term strain rate occurred in mid-1989 at about the time of the second

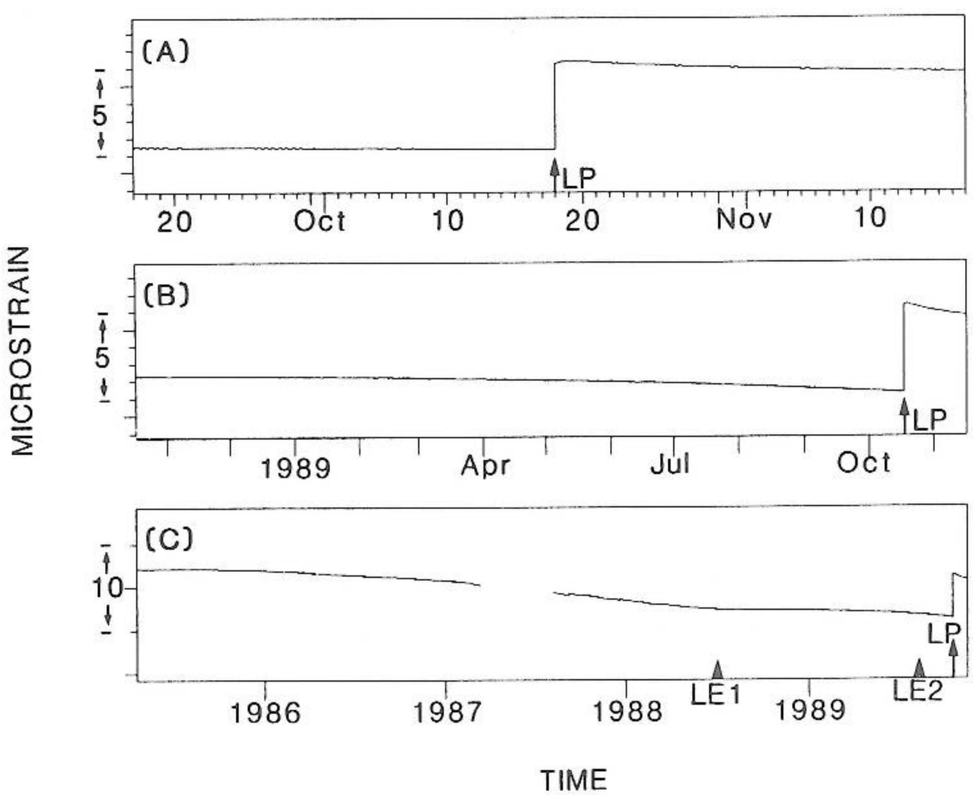

Figure 2.—Dilatational strain recorded at site SRL (fig. 1) 1 month before and 1 month after (*A*), 1 year before and 1 month after (*B*), and 4.5 years before and 1 month after (*C*) Loma Prieta earthquake. Arrows denote occurrence times of Lake Elsman M_L=5.0 (LE1) and M_L=5.2 (LE2) foreshocks of June 27, 1988, and August 8, 1989, respectively, and of Loma Prieta earthquake (LP).

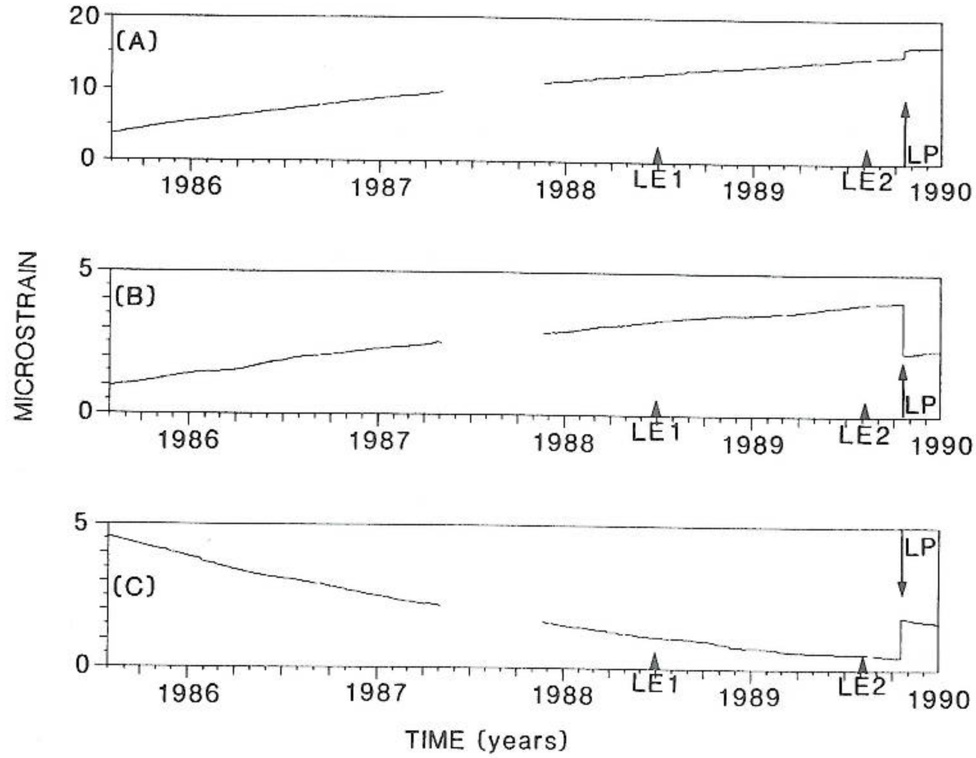

Figure 3.—Tensor shear strains γ_1 (*A*) and γ_2 (*B*) and dilatational strain (*C*) derived from tensor-strain data at site MSJ (fig. 1) 4 years before and 1 month after Loma Prieta earthquake. Arrows denote occurrence times of Lake Elsman M_L=5.0 (LE1) and M_L=5.2 (LE2) foreshocks of June 27, 1988, and August 8, 1989, respectively, and of Loma Prieta earthquake (LP).

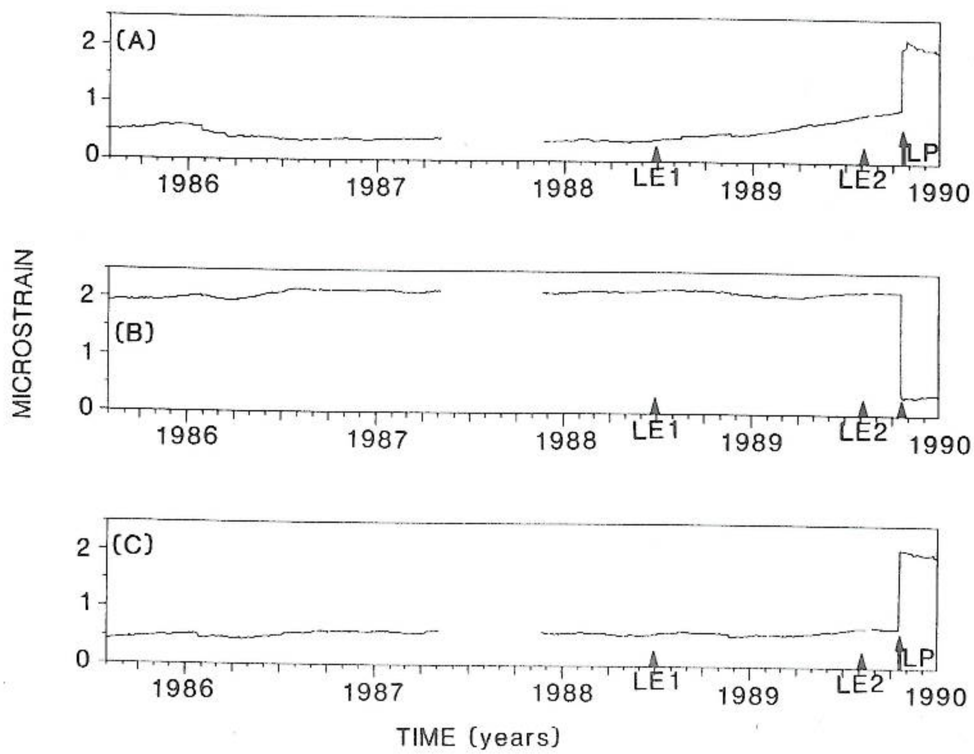

Figure 4.—Residuals of tensor shear strains γ_1 (*A*) and γ_2 (*B*) and dilatational strain (*C*) plotted in figure 3, after removal of exponential functions determined by least-squares analysis. Exponentials result from curing of grout used to emplace instruments and from recovery of borehole stresses relieved during drilling, not from tectonic processes.

Lake Elsman foreshock on August 8, 1989 (fig. 2*C*). With so few data, however, it is difficult to place much significance on these long-term strain changes.

Although the measurements of coseismic strain offsets are too few to determine the source parameters of the earthquake, we can compare the observed offsets with those calculated from a best-fit static model of the earthquake constrained by inversion of the surface geodetic data (Lisowski and others, 1990a). This comparison can be made by modeling the source as rectangular fault planes with uniform slip, using Okada's (1985) formulation for surface deformations due to a dislocation embedded in an elastic half-space. The calculated strain values at sites SRL and MSJ are quite sensitive to the details of complex fault geometry at the south end of the rupture zone (fig. 1), although this geometry is poorly constrained by the large-scale geodetic data (Lisowski and others, 1990a) at this stage of analysis. Until a better fault-slip model for the south end of the Loma Prieta rupture zone is obtained, we cannot easily compare the observed and calculated strain offsets at sites SRL and MSJ.

The simplest interpretation of the immediate postseismic strain data is in terms of rebound following slight overshoot of the fault rupture. Such an interpretation, however, is probably too simple because the geometry of fault rupture near and beneath these instruments is still changing, as indicated by continuing seismicity (aftershocks) and varying surface displacements throughout this region (Lisowski and others, 1990a).

CONCLUSIONS

Short-term precursory strain changes are not apparent in the data from a dilatational strainmeter (located 37.5 km downstrike from the main-shock epicenter) and a tensor strainmeter (located 41.6 km from the main-shock epicenter). If precursory strains actually occurred, they are less than 0.1 percent of the strain offset generated on these instruments by the earthquake. These observations constrain the preseismic moment release at the nucleation point of the earthquake to less than 10^{24} dyne-cm. In other words, any aseismic slip in the hypocentral region greater than that which commonly occurs during an M=5.3 earthquake would have been detected on the strainmeters at these distances and azimuthal positions. Using Kanamori and Anderson's (1975) relations between magnitude and source size for an M=5.3 earthquake, the amount of slip that might have occurred on a 7- by 7-km patch at the hypocenter could not have been more than about 7 cm. Though better positioned over the hypocentral region, geodetic measurements also would not detect this amount of fault slip by inversion of surface-displacement data because of poorer resolution (≈1 cm in horizontal-displacement measurements; Lisowski and others, 1990a).

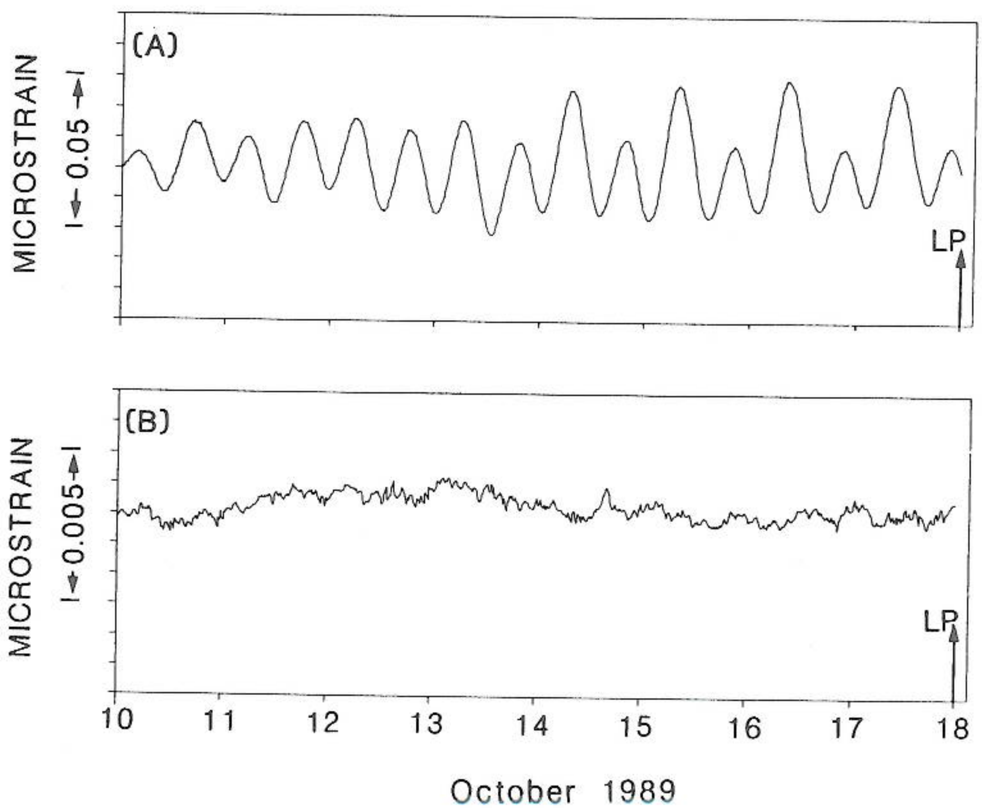

Figure 5.—Dilatational strain. *A*, Data during week before Loma Prieta earthquake (LP). *B*, Same data at an expanded scale, with earth-tidal and atmospheric-loading effects removed.

Long-term strain changes, such as might be expected from strain redistribution in the epicentral region, occurred in mid-1988 and mid-1989, at about the time of the two M_L=5 Lake Elsman foreshocks in the hypocentral region on June 27, 1988, and August 8, 1989. However, because these changes are not clearly observed on geodetic lines over this area, they most likely resulted from more local changes in the spatial pattern of fault slip and are not related directly to the Loma Prieta source region, or from larger scale regional strain, as proposed by Gladwin and others (1991). A more complete array of instruments was clearly needed around the epicenter of this earthquake to resolve this long-term-strain issue and such other issues as determination of the best coseismic-slip models and the details of postseismic-slip growth and geometry.

ACKNOWLEDGMENTS

We thank M.T. Gladwin for tensor strain data and Doug Myren for careful maintenance of the instruments.

REFERENCES CITED

Aki, Keiiti, 1987, Magnitude-frequency relation for small earthquakes; a clue to the origin of f_{max} of large earthquakes: Journal of Geophysical Research, v. 92, no. B2, p. 1349–1355.

Dietz, L.D., and Ellsworth, W.L., 1990, The October 17, 1989, Loma Prieta, California, earthquake and its aftershocks; geometry of the sequence from high-resolution locations: Geophysical Research Letters, v. 17, no. 9, p. 1417–1420.

Gladwin, M.T., Gwyther, R.L., Hart, R.H.G., Francis, M.F., and Johnston, M.J.S., 1987, Borehole tensor strain measurements in California: Journal of Geophysical Research, v. 92, no. B8, p. 7981–7988.

Gladwin, M.T., Gwyther, R.L., Higbie, J.W., and Hart, R.H.G., 1991, A medium term precursor to the Loma Prieta earthquake?: Geophysical Research Letters, v. 18, no. 8, p. 1377–1380.

Johnston, M.J.S., Linde, A.T., and Gladwin, M.T., 1990, Near-field high resolution strain measurements prior to the October 18, 1989, Loma Prieta M_S 7.1 earthquake: Geophysical Research Letters, v. 17, no. 10, p. 1777–1780.

Johnston, M.J.S., Linde, A.T., Gladwin, M.T., and Borcherdt, R.D., 1987, Fault failure with moderate earthquakes: Tectonophysics, v. 144, no. 1–3, p. 189–206.

Kanamori, Hiroo, and Anderson, D.L., 1975, Theoretical basis of some empirical relations in seismology: Seismological Society of America Bulletin, v. 65, no. 5, p. 1073–1096.

Kanamori, Hiroo, and Cipar, J.J., 1974, Focal processes of the great Chilean earthquake, May 22, 1966: Physics of the Earth and Planetary Interiors, v. 9, p. 128–136.

Linde, A.T., Suyehiro, Kiyoshi, Miura, Satoshi, Sacks, I.S., and Takagi, Akio, 1988, Episodic aseismic earthquake precursors: Nature, v. 334, no. 6182, p. 513–515.

Lisowski, Michael, Prescott, W.H., Savage, J.C., and Johnston, M.J.S., 1990a, Geodetic estimate of coseismic slip during the 1989 Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, no. 9, p. 1437–1440.

Lisowski, Michael, Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990b, A possible geodetic anomaly observed prior to the Loma Prieta earthquake: Geophysical Research Letters, v. 17, no. 8, p. 1211–1214.

Mogi, Kiyoo, 1981, Earthquake prediction program in Japan, *in* Simpson, D.W., and Richards, P.G., eds., Earthquake prediction; an international review: Washington, D.C., American Geophysical Union, p. 635–666.

———1985, Earthquake prediction: Tokyo, Academic Press, 355 p.

Okada, Yoshimitsu, 1985, Surface deformation due to shear and tensile faults in a half-space: Seismological Society of America Bulletin, v. 75, no. 4, p. 1135–1154.

Olson, J.A., 1990, Seismicity in the twenty years preceding the Loma Prieta, California earthquake: Geophysical Research Letters, v. 17, no. 9, p. 1429–1432.

Rikitake, Tsuneji, 1976, Earthquake prediction: Amsterdam, Elsevier, 357 p.

Sacks, I.S., Suyehiro, Shigeji, Evertson, D.W., and Yamagishi, Yoshiaki, 1971, Sacks-Evertson strainmeter, its installation in Japan and some preliminary results concerning strain steps: Papers in Meteorology and Geophysics, v. 22, p. 195–207.

Silverman, Stan, Mortensen, C.E., and Johnston, M.J.S., 1989, A satellite-based digital data system for low-frequency geophysical data: Seismological Society of America Bulletin, v. 79, no. 1, p. 189–198.

U.S. Geological Survey staff, 1990, The Loma Prieta, California, earthquake; an anticipated event: Science, v. 247, no. 4940, p. 286–293.

Wyatt, F.K., 1988, Measurements of coseismic deformation in southern California; 1972–1982: Journal of Geophysical Research, v. 93, no. B7, p. 7923–7942.

Wyatt, F.K., Beckstrom, Kent, and Berger, Jon, 1982, The optical anchor—a geophysical strainmeter: Seismological Society of America Bulletin, v. 72, no. 5, p. 1707–1715.