PRESEISMIC OBSERVATIONS

BOREHOLE STRAIN MEASUREMENTS OF SOLID-EARTH-TIDAL AMPLITUDES

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ABSTRACT

The Loma Prieta earthquake provided an opportunity for a sensitive test of suggestions that earthquakes may be preceded by variations in earth-tidal strain amplitudes. Such variations have been proposed as providing an advantageous technique for detecting precursory changes in elastic parameters within a seismogenic zone. We have analyzed the data from two borehole strainmeters continuously operating within 40 km of the epicenter and within about 10 km of the south end of the rupture zone. We are unable to identify any precursory changes in tidal components M2 and O1 and estimate that any large-scale changes in Young's modulus must have been less than about 2 percent. If these results apply generally, we conclude that variations in elastic material properties before earthquakes do not occur throughout substantial volumes of the subsequent hypocentral region.

INTRODUCTION

Nishimura (1950) first suggested that changes in earth-tidal response might be a useful method for monitoring crustal elastic properties and, possibly, predicting earthquakes. Several other studies have been made on the temporal variations of tidal amplitudes in seismically active regions (for example, Mikumo and others, 1978; Kato, 1979; Mao and others, 1989), but none of these studies has provided strong evidence to support or refute the usefulness of the technique for earthquake prediction. Finite-element analysis has been used (Beaumont and Berger, 1974; Tanaka, 1976) to calculate tidal-response anomalies as a function of changes in the elastic properties of various-shaped source regions.

The Loma Prieta earthquake was the largest California earthquake in recent years and the largest to occur relatively close to any of the continuous strain-monitoring stations in California. Elsewhere (Johnston and others, 1990), we have reported on the absence of observed short-term strain precursors to this earthquake. Johnston and Linde (1990), in a preliminary analysis of the data from one of these stations, reported on a precursory tidal-amplitude anomaly for this earthquake, but their analysis included then-undetected artifacts in the data. We have now analyzed the data from two stations to determine whether any significant changes in tidal amplitudes occurred during the several years before the earthquake.

Initial plans for borehole strain instrumentation in the San Juan Bautista, Calif., area, just south of the Loma Prieta rupture zone (fig. 1), called for the installation of a modest network of five to seven stations. Owing to various constraints, however, only three instruments were installed, two of which were in operation during the study period: a tensor (three component) strainmeter (Gladwin and others, 1986) and a Sacks-Evertson strainmeter (dilatometer) (Sacks and others, 1971). The locations of these two stations in relation to the Loma Prieta rupture zone are mapped in figure 1; the tensor strainmeter (sta. SJT) is 38 km from the epicenter, and the dilatometer (sta. SRL) 33 km.

The instrumental data are collected at the U.S. Geological Survey offices in Menlo Park, Calif., via satellite digital telemetry (Silverman and others, 1989); station SJT is sampled every 18 minutes, and station SRL every 10 minutes. Both instruments have more than adequate sensitivity and frequency response to ensure that Earth tides can be detected and recorded with good precision.

ANALYSIS

We concentrate our analysis on the strain data from the approximately 2-year period before the earthquake. Our conclusions apply to earlier data also, but for various technical reasons (postinstallation effects, various instrument modifications, and less reliable telemetry) the earlier data vary more widely. For the period shown in figures 2 and 3, station SJT has been operating without modification, and the data stream has been consistently reliable and undisturbed by site visits. Several problems, however, have complicated the record from station SRL. We have removed from the record any artifacts introduced by site visits, although we suspect that, after mid-March 1989, the data from station SRL may have been subjected to a slowly decreasing effective gain, apparent during 1990.

The tidal analyses have been carried out by using two independent procedures: a linear least-squares inversion (Gladwin and others, 1985), and the BAYTAP(G) routine based on Bayesian statistics (Ishiguro and others, 1984). Excellent agreement was obtained for the calculated tidal amplitudes. We have performed various tests with both real and synthetic data to ensure that the results are reliable and robust. Temporal variations in tidal components M2 and O1 at the two stations are plotted in figure 2. We have used 60-day windows for our analysis, with sequential windows sliding forward by 30 days. The time tag associated with each analysis is taken as the midpoint of the window. From station SRL we obtain estimates of the dilatational strain. The instrument at station SJT records three components of strain, defined by

$$e_a = e_{xx} + e_{yy}$$

$$\gamma_1 = e_{xx} - e_{yy}$$

$$\gamma_2 = 2e_{xy}$$

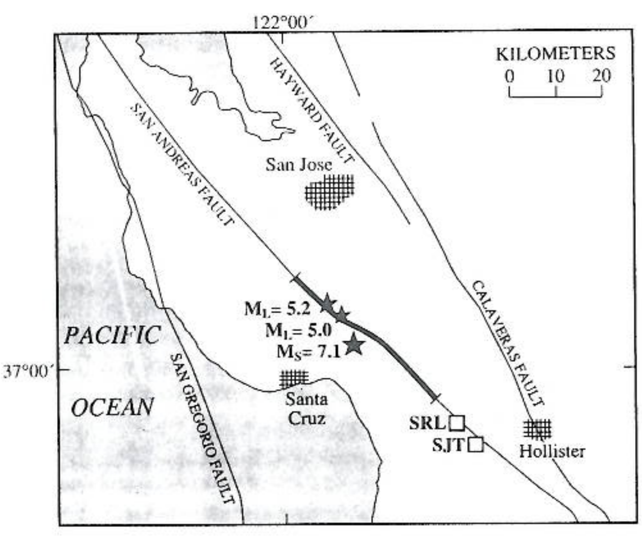

Figure 1.—Loma Prieta region, Calif., showing locations of monitoring stations (squares) and major faults (lines). Heavy line, Loma Prieta rupture zone; stars, epicenters of Loma Prieta earthquake (large) and Lake Elsman foreshocks of 1988 and 1989 (small).

where the x-axis is east and the y-axis north. Note that all of the traces are characterized by long-term constancy of both tidal components M2 and O1. Formal error bars (1σ) are given for all points, and in some places, particularly for the larger-amplitude signals, these error bars are obscured by the data points. In general, as we would expect, the errors are larger for smaller-amplitude signals, which are all shown at their absolute levels. Confidence in the reliability of our measurements is also enhanced by the fact that the M2-to-O1 tidal-amplitude ratios for all strain components agree well with the theoretically calculated ratios. For all the tidal-amplitude signals, no variations are evident that can be considered significant in the 2-year period before the earthquake. The standard deviations of these values are about 1 percent for the M2 components of e_a and ∇ (dilatation) amplitudes, about 2 percent for the corresponding O1 components, and somewhat larger for the lower-amplitude tidal components. We estimate the threshold for detecting departures from constancy at about the 2-percent level.

During 1990, the instrument at station SRL has been characterized by a clear, steady decrease in gain due to the accumulated effects of a 1987 downhole leak in the cable or at the cablehead. A modification in the electronics allowed stable operation of the instrument, as evidenced by the constancy of the tidal admittance during 1988, but an inadvertent modification in March 1989 (asterisks, fig. 2) partly restored the pre-1987 configuration. (The instantaneous gain change caused by this modification has been removed from the data.) This instrument measures dilatational strain, and because variations in atmospheric pressure cause corresponding changes in dilatational strain in the near-surface rock, we can check for changes in instrumental gain by calculating the pressure admittance versus time. The pressure admittance and tidal components M2 (fig. 3*A*) and O1 (fig. 3*B*) versus time at station SRL after the March 1989 modification are plotted in figure 3; a faulty pressure transducer was also replaced at that time. Although we do not expect the pressure admittance and tidal amplitudes to track precisely (the effective bulk modulus of near-surface material varies with, for example, ground-water content), starting at about 1990 both the pressure admittance and tidal amplitudes clearly show similar and consistent decreases. We have used the pressure admittance as a gain correction to the tidal amplitudes (circles and dashed curves, fig. 2). This correction results in nearly constant tidal amplitudes until about mid-1990, when a real decrease in the pressure admittance may have occurred, and so the correction produces larger tidal amplitudes. The need for correcting these post-1990 tidal amplitudes somewhat decreases the weight we can give to these measurements from station SRL, but it appears that the postseismic tidal components M2 and O1 at station SRL did not change significantly, consistent with their constancy at station SJT. (Note that these reservations do not apply to the preseismic and coseismic data from station SRL.)

We do not detect any coseismic change in Earth tidal-strain amplitudes (at the 2-percent level), and the tidal amplitudes after the earthquake are at the same levels as before. Thus, any changes in elastic parameters introduced as a result of rock fracturing during the earthquake were also quite small or localized to a small volume. If we had reported a precursory effect without noticing any coseismic change, we might have questioned the validity of that result, although for this type of phenomenon the absence of such change does not necessarily exclude the possibility of recording any precursory effect.

DISCUSSION

The finite-element models of Beaumont and Berger (1974) and Tanaka (1976) were published when dilatancy was thought to be a wide-scale precursory phenomenon. The modeling estimates by Beaumont and Berger of variations as large as 60 percent in tidal strain were based on large dilatant zones in which the seismic compressional-wave velocity was reduced by 15 percent. Although large effects are no longer considered likely, we can use our results to place upper constraints on any precursory strain-induced variations in the elastic properties of the seismogenic zone for the earthquake. The modeling by Beaumont and Berger indicates that our stations are favorably located for detection of any significant variations in elastic properties within the site region. If such changes occurred before the earthquake, these stations would surely have been within about 30 km of such a zone, possibly as close as 10 or 15 km. Beaumont and Berger's work shows that this situation would provide near-maximum sensitivity for detection

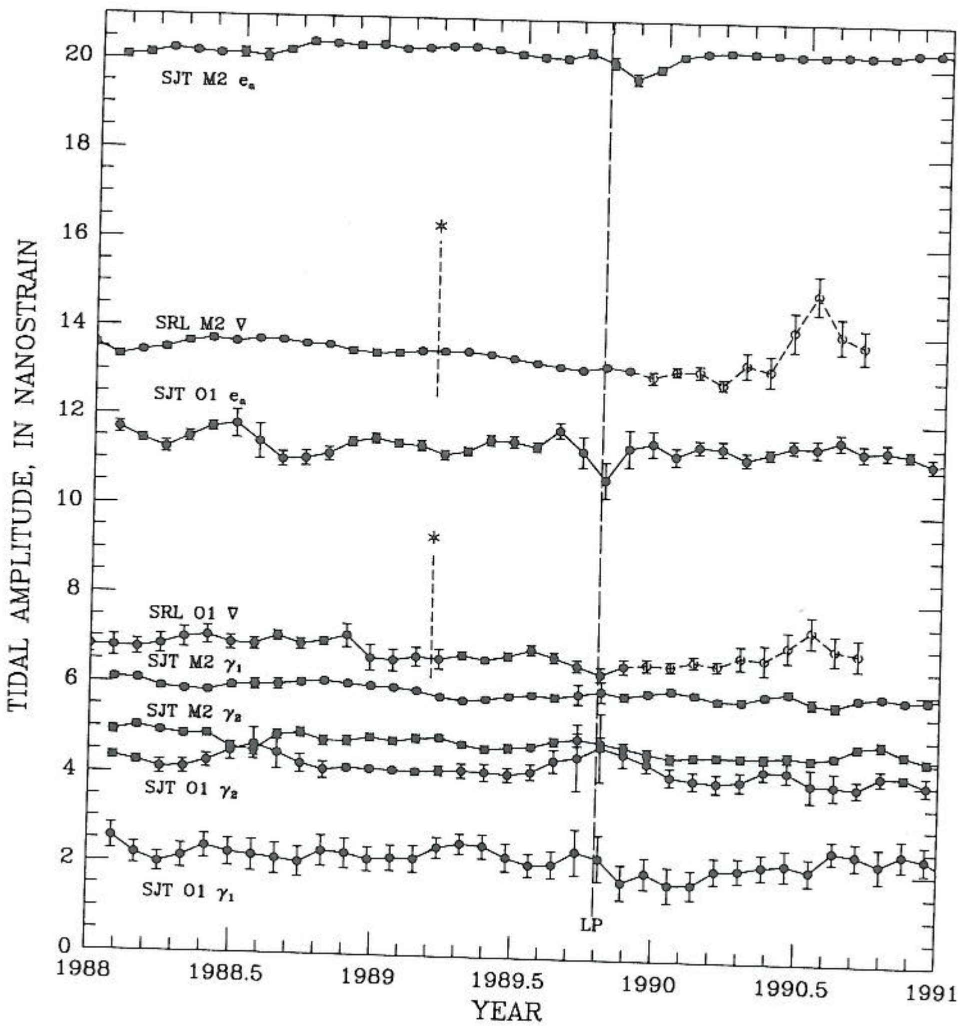

Figure 2.—Earth-tidal strain amplitudes of components M2 and O1 as a function of time at stations SRL and SJT (see fig. 1 for locations). Error bars are 1σ. LP, time of Loma Prieta earthquake; stars, time of an electronic change at station SRL (see text). Since 1990, data from station SRL have been gain corrected, using atmospheric-pressure response (dashed curves with circles). Larger values near end of station SRL traces apparently result from an overcorrection. We find no significant variations in these amplitudes before earthquake. Note also that earthquake has not had any significant coseismic or postseismic effect on tidal amplitudes.

and that, even for a more remote source, the stations would be well placed to record the resulting tidal-amplitude changes. If such changes did occur, then changes in Young's modulus over any large (kilometers) spatial extent must have been less than about 2 percent. The corresponding change in V_p would be less than about 1 percent, a limit lower than that set from traveltime residuals for local earthquakes (Steppe and others, 1977) or for teleseismic events (Robinson and Iyer, 1976). The alternative possibility, which we cannot exclude, is that significant changes in Young's modulus occurred within a small preparation zone. Although this issue may remain important in the mechanics of rupture, it appears to be academic in terms of precursor detection because we do not know the location of initiation of a future earthquake and, in many cases, cannot physically locate instruments near such a location even if we did know it exactly.

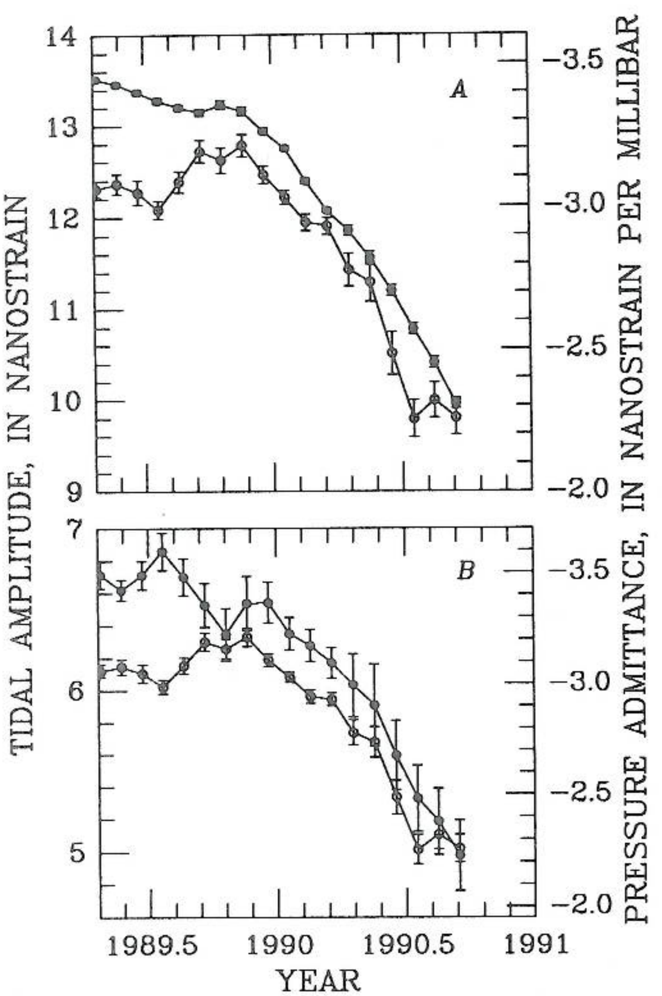

Figure 3.—Pressure admittance (circles) and tidal amplitudes (dots) of components M2 (*A*) and O1 (*B*) versus time at station SRL (fig. 1) after March 1989 electronic modification. Pressure admittance is negative because an increase in atmospheric pressure causes contraction (negative strain) in near-surface rock. Although pressure admittance changes over time, both tidal amplitudes and pressure admittances clearly decrease systematically during 1990, owing to a slowly decreasing effective gain of instrument during that period.

We conclude that no identifiable (greater than 2 percent) precursory changes in solid-earth-tidal amplitudes occurred in the area about 35 km to the south of the epicenter. This result places a significant constraint on such precursory effects and corrects an earlier report of a positive result for this effect: the preliminary work by Johnston and Linde (1990) was in error, principally because not all the effects of electronic modifications to the instrument at station SRL were recognized and removed from the data at that time. The results obtained here are consistent with the report by Gladwin and others (1991), who noted the constancy of earth-tidal strain amplitudes before the earthquake. To the extent that our observations at the two stations can be generalized, it now appears less likely that variations in earth-tidal strain amplitudes can serve as earthquake precursors.

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