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THE LOMA PRIETA EARTHQUAKE, 1989 AND EARTH STRAIN TIDAL AMPLITUDES: AN UNSUCCESSFUL SEARCH FOR ASSOCIATED CHANGES

Alan T. Linde

Department of Terrestrial Magnetism, Carnegie Institution of Washington

Michael T. Gladwin

Physics Department, University of Queensland

Malcolm J. S. Johnston

U. S. Geological Survey, Menlo Park

Abstract. The Loma Prieta earthquake of 1989 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 in a seismogenic zone. We have analyzed data from two borehole strainmeters continuously operating within 40 km of the epicenter and within about 10 km of the southern end of the rupture. We are unable to identify any precursory changes in M2 and O1 tidal amplitudes and estimate that any large scale changes in Young's modulus must have been less than about 2%. If these results apply generally, we would conclude that variations in elastic material properties prior to 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 perhaps predicting earthquakes. A number of other studies have been made on time variations of tidal amplitudes in seismically active regions (e.g. Mikumo *et al.*, 1978; Kato, 1979; Mao *et al.*, 1989) but none of these has provided strong evidence to support or refute the usefulness of the technique for earthquake prediction. Finite element analysis techniques have been used (Beaumont and Berger, 1974; Tanaka, 1976) to calculate tidal response anomalies as a function of changes in elastic properties of various shaped source regions.

The Loma Prieta earthquake (M_L 7.1) of October 18, 1989 is the largest California earthquake in recent years, and is the largest to occur relatively close to any of the continuous strain monitoring sites in California. Elsewhere (Johnston *et al*, 1990) we have reported on a lack of observed short term strain precursors to this earthquake. Johnston and Linde (1990), in preliminary analysis of data from one of these sites, have reported on a precursory tidal amplitude anomaly for this earthquake but that earlier analysis included then undetected artifacts in the data. We have now analyzed the data from both sites in order to determine if any significant changes in tidal amplitudes occurred during the several years preceding the earthquake.

Initial plans for borehole strain instrumentation in the San Juan Bautista area, just to the south of the Loma Prieta break, called for the installation of a modest network of 5 to 7 sites. Unfortunately, due to a variety of constraints, only 3 sites were installed; 2 were in operation during the period studied here. These instruments are a tensor (three component) strainmeter (Gladwin *et al*, 1986) and a Sacks-Evertson strainmeter (dilatometer) (Sacks *et al*, 1971). The instrument sites and their relation to the earthquake fault are shown in Figure 1. The tensor instrument (SJT) is 38 km from the epicenter and the dilatometer (SRL) is a little closer (33 km).

The data from the instruments are collected in Menlo Park via satellite digital telemetry (Silverman *et al*, 1989). SJT is sampled every 18 minutes, SRL every 10 minutes.

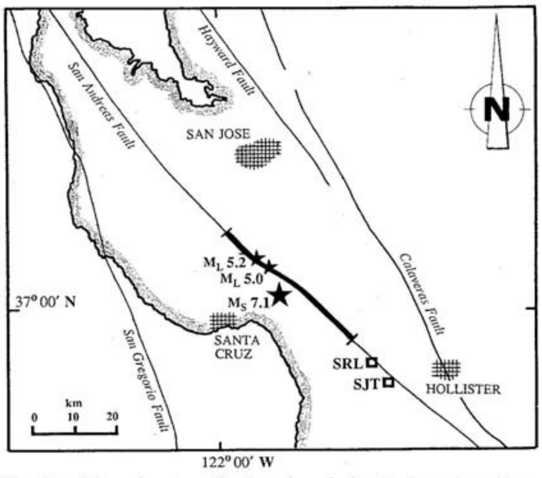

Fig. 1. Map showing the two borehole strainmeter sites SRL and SJT in relation to the fault break of the Loma Prieta earthquake. The two smaller earthquakes marked are the Lake Ellsman events of 1988 and 1989.

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Both instruments have more than adequate sensitivity and frequency response to ensure that the Earth tides can be detected and recorded with good precision.

Analysis

We have concentrated our analysis of the strain data on the approximately two years preceding the earthquake. Our conclusions apply to earlier data also but for a variety of technical reasons (post installation effects, various instrument modifications and less reliable telemetry) the earlier data exhibit greater variability. For the period shown in the plots, SJT has been operating without modification and the data stream has been consistently reliable and undisturbed by site visits. A number of problems have complicated the record from SRL; we have removed from the data artifacts introduced by various site visits, although (see below) we have reason to believe that, after mid March 1989, the data from SRL may have been subjected to a slowly decreasing effective gain; during 1990 a steady decrease in gain became apparent.

The tidal analyses have been carried out using two independent procedures; a linear least square inversion (Gladwin *et al*, 1985) and the BAYTAP(G) routine based on Bayesian statistics (Ishiguro *et al*, 1984). Excellent agreement was obtained for the calculated tidal amplitudes. We have performed a variety of tests with both real and synthetic data to ensure that the results are reliable and robust. Time variations of the M2 and O1 tidal amplitudes from the two sites are shown in Figure 2. We have used 60 day windows for the 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 the SRL site we get estimates of the dilatational strain. The SJT instrument gives three components of strain; as plotted these are defined by:

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

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

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

with x axis east and y axis north. Note that all of the traces are characterized by long term constancy of both the M2 and O1 amplitudes. Formal error bars (1 standard deviation) are given for all points and in some cases, particularly for the larger amplitude signals, the error bars are obscured by the point symbol. In general, as one would expect, the errors are larger for the smaller amplitude signals, which are all shown at their absolute levels. Confidence in the reliability of our measurements is also enhanced from the fact that the amplitude ratios of M2 to O1 for all components are in good agreement with the theoretically calculated ratios. For all the tidal amplitude signals, there are no variations which can be considered significant in the 2 years preceding the earthquake. The standard deviations of these values are about 1% for the M2 e_a and ∇ amplitudes, about 2% for the corresponding O1 amplitudes and somewhat larger for the lower amplitude tidal components. We estimate the threshold for detecting departures from constant values as being at about the 2% level.

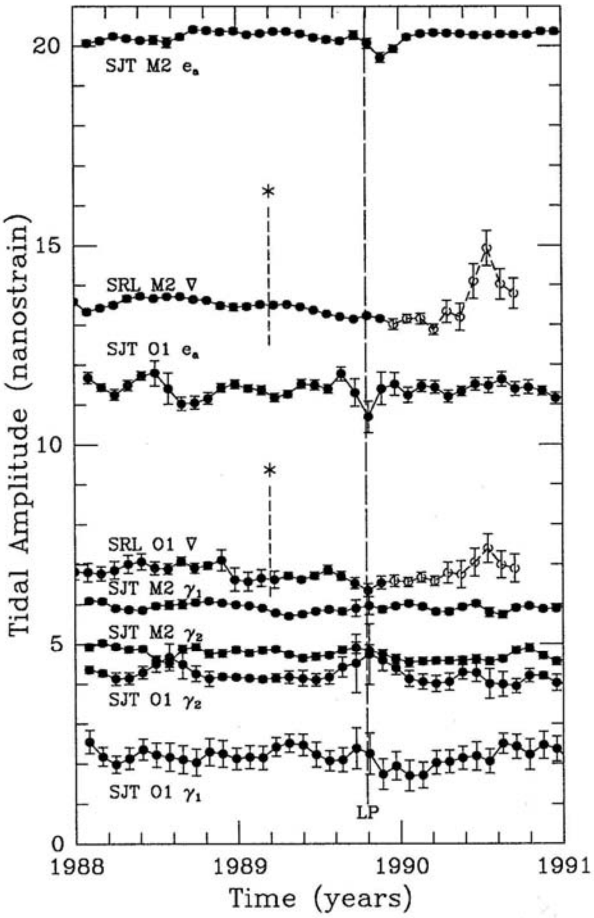

Fig. 2. Earth tidal strain amplitudes, for tidal components M2 and O1, as a function of time at the sites SRL and SJT shown in Figure 1. Error bars are for one standard deviation. The long vertical dashed line marked LP indicates the time of the Loma Prieta earthquake. The shorter dashed lines, marked *, show the time of an electronic change at SRL (see text). From 1990, SRL data have been gain corrected (using atmospheric pressure response) and are shown dashed with open circles (also see text). The larger values near the end of the SRL traces apparently result from an overcorrection. We find no significant variations in these amplitudes preceding the earthquake. Note also that the earthquake has not produced any significant coseismic or postseismic effect on tidal amplitudes.

During 1990, 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 change in March 1989 (marked by * on the plot) partially restored the pre-1987 configuration. (The instantaneous gain change caused by this has been removed from the data.) This instrument measures dilatational strain and since variations in atmospheric pressure produce 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. Figure 3 shows the pressure admittance and M2 (Figure 3a) and O1 (3b) tidal amplitudes for SRL following the March 1989 modification; a faulty pressure transducer was also replaced at that time. While we do not expect the admittance and tidal amplitude values to track precisely (the effective bulk modulus of near surface material varies with, for example, ground water content), it is clear that starting at about the beginning of 1990 both the admittance values and the tidal amplitudes show similar and consistant decreases. We have used the pressure admittance values to provide a gain correction for the tidal amplitudes and those corrected values are shown in Figure 2 with dashed lines and open circles. This correction results in rather constant values for the tidal amplitudes until about mid 1990 when there may have been a real decrease in the pressure admittance and thus the correction produces larger tidal amplitudes. The need for correcting these post 1990 tidal values somewhat decreases the weight we can give to these values from SRL, but it appears that there were no significant changes in the post-seismic M2 and O1 tidal amplitudes at SRL, consistent with the lack of any change at SJT. (Remember also that these reservations do not apply to the pre- and co-seismic SRL data.)

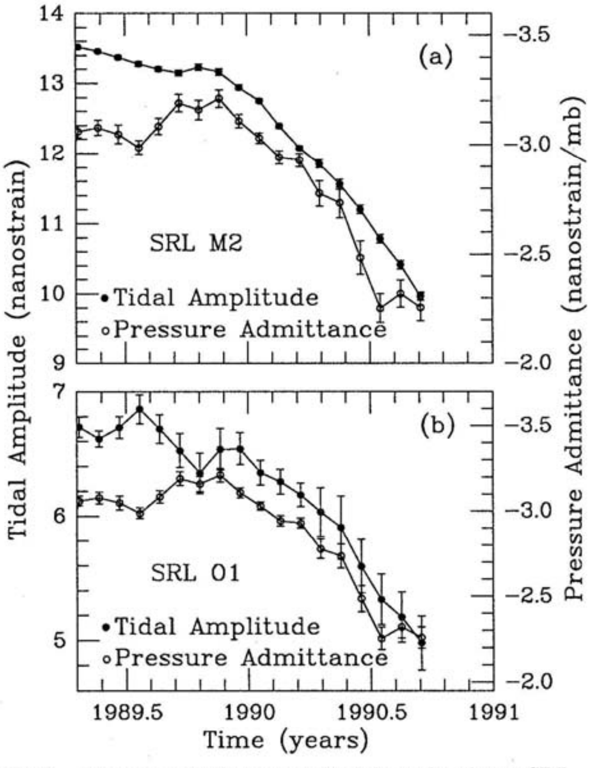

Fig. 3. Pressure admittance and tidal amplitudes at SRL following the March 1989 electronic modification. M2 amplitudes are shown in (a) and O1 in (b). Pressure admittance is negative since an increase in atmospheric pressure produces contraction (negative strain) in the near surface rock. While the admittance undergoes real changes with time, it is clear that both tidal amplitudes and the admittances systematically decrease during 1990. This is attributed to a slowly decreasing effective gain of the instrument during that period.

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

Discussion

The finite element modeling papers of Beaumont and Berger (1974) and Tanaka (1976) were written at a time when dilatancy was thought to be a wide scale precursory phenomenon. The modeling estimates by Beaumont and Berger of variations up 60% in strain tides were based on large dilatant zones in which the seismic compressional wave velocity was reduced by 15%. Such large effects are no longer considered likely but we can use our results to place upper constraints on precursory strain induced variations in elastic properties of the seismogenic zone for the Loma Prieta earthquake. The modeling in Beaumont and Berger indicates that our sites are favorably located for detection of any significant variations in elastic properties in the site region. If such changes occurred before the Loma Prieta earthquake, our monitoring sites would surely have been within about 30 km of such a zone and could have been as close as 10 km or 15 km. Beaumont and Berger's work shows the latter situation would provide near maximum sensitivity for detection and, even for a more remote source, our sites would be well placed to experience the resultant tidal amplitude changes. If such changes did take place, then changes in Young's modulus over any large (kms) spatial extent had to have been less than about 2%. The corresponding change in V_p would be less than about 1%, a limit lower than that which has been set from travel time residuals for local earthquakes (Steppe *et al*, 1977) or for teleseismic events (Robinson and Iyer, 1976). The alternative possibility, which we cannot exclude, is that significant modulii changes occurred in a small preparation zone. This may remain an important issue in the mechanics of rupture, but appears to be academic in terms of precursor detection since we do not know the location of initiation of a future earthquake and, in many cases, cannot physically locate instruments very close to such a location even if we did know where it would be.

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

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M. T. Gladwin, Physics Department, University of Queensland, Queensland 4072, Australia.

M. J. S. Johnston, U. S. Geological Survey, 345 Middlefield Rd, Menlo Park, CA 94025.

A. T. Linde, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd. NW, Washington DC 20015.

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