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Source Parameters of the October 1, 1987 Whittier Narrows Earthquake From Crustal Deformation Data

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Offsets in the regional strain field, generated by the October 1, 1987 Whittier Narrows earthquake, were recorded with large amplitudes on two deep-borehole dilational strainmeters at distances of 46.7 and 65.5 km from the hypocenter and marginally on instruments at greater distances in the Parkfield area and at Pinon Flat, where laser extensometers also recorded small offsets. These data are insufficient to solve for the location and physical parameters of the earthquake, but by also using the measured elevation changes in the epicentral area, we are able to invert for source models consistent with all available observations of crustal deformation. The source models obtained indicate that slip extends to a depth of about 30 km, well below the recorded aftershock zone. The requirement for deeper (and presumably aseismic) slip derives from the large negative dilatation experienced by the nearest strainmeter (PUBS), but high-frequency data from the same site exclude any significant slow component of moment release. By ignoring PUBS we obtain a moment of about 0.7 × 10^{18} N m on a fault that has a strike and dip of about N60°W and 40° down to the north, respectively, and extends to a depth of about 16 km. The most likely reason for the anomalous offset at PUBS appears to be sympathetic slip triggered on a nearby fault by the main shock. Precursive strain during the month prior to the earthquake is not apparent at the nanostrain level in the data from the closest instrument, but the event was accompanied by a change in strain rate at the two nearer sites.

INTRODUCTION

The Whittier Narrows earthquake occurred at about 1442 UT on October 1, 1987, about 10 km NW of the town of Whittier (Figures 1*a* and 1*b*). *Hauksson and Jones* [this issue] report a magnitude M_L of 5.9, for a west striking earthquake with a dip of 27° (north down), a rake of 90°, at a depth of 14±1 km. *Bent and Helmberger* [this issue], using long-period data, report a somewhat different solution; strike N80°W, dip 40°N, a rake of 98°, moment 10^{18} N m, and a focal depth of 14 km. By combining both long-period and short-period surface seismic data, Bent and Helmberger propose that the earthquake was a double source with a total moment of 1.4 × 10^{18} N m. The earthquake was recorded on borehole dilational strainmeters installed throughout California (Figure 1*a*). While these partly completed instrument arrays are designed to provide information about critical tectonic regions (e.g., Parkfield, San Juan Bautista, Mojave, Long Valley caldera, etc.), the strain sensitivity and resolution are often sufficient to allow determination of independent constraints on source parameters (such as seismic moment and source geometry) for earthquakes in other areas [*Johnston et al.*, 1987*a*].

In this paper we determine the range of possible models for the Whittier Narrows earthquake that satisfy all the available coseismic deformation data. These data comprise the strain offsets recorded on the two dilatometers in the Mojave desert, on a group of similar instruments in the Parkfield area, on a dilatometer at Pinon Flat Observatory, on the three laser extensometers at Pinon Flat [*Wyatt*, 1988], together with the elevation changes in the epicentral area reported by *Lin and Stein* [this issue]. We are indebted to them for generously allowing us to use their data in advance of publication. We also look for evidence of short-term and intermediate-term preseismic failure for this earthquake, even though the closest instrument is at a distance of more than 40 km.

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BOREHOLE INSTRUMENTATION

The Sacks-Evertson dilational strainmeters [*Sacks et al.*, 1971] used in this study are installed at a depth of about 200 m below the surface at the sites shown in Figure 1*a*. The sensors, installed as part of a cooperative program between the U.S. Geological Survey and the Carnegie Institution of Washington, are cemented in the borehole with expansive grout having physical characteristics approximating those of granite or sandstone host material. The boreholes are 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 data from the dilatometers are transmitted with a 16-bit digital telemetry system through the GOES satellite to Menlo Park, California, at one sample every 10 min [*Silverman et al.*, 1989]. The sensors, the installation, and the telemetry system are calibrated together against the theo-

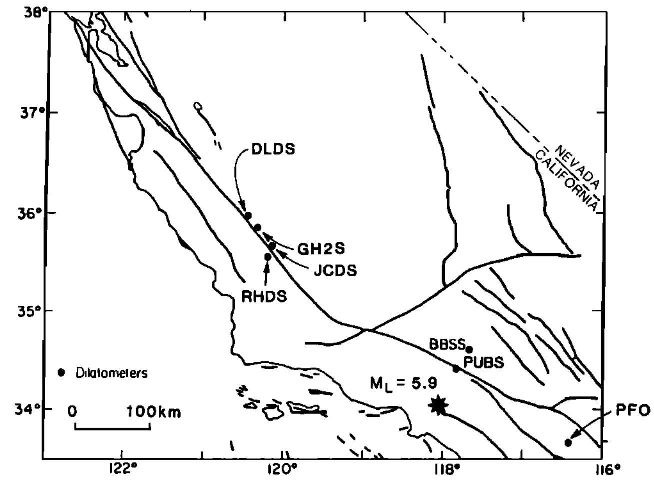

Fig. 1*a*. Dilatometer strain sites in California that recorded coseismic strain offsets at 1442 hours during the October 1, 1987 Whittier Narrows earthquake (M_L 5.9). Data from the three laser extensometers at PFO, kindly provided by F. Wyatt and D.C. Agnew of the Institute of Geophysics and Planetary Physics, San Diego, are also used. The epicenter of the earthquake is shown as a star.

retical ocean-load corrected solid earth tides. This calibration is repeatable to better than 5%. The data are also recorded on-site with low-speed analog recorders and, for some sites, at different gains on 16-bit digital recorders, sampling at 200 s^{-1}, together with data from colocated three-component seismic velocity transducers [*Borcherdt et al.*, 1985]. The event triggering mode was used to record simultaneous seismic and strain data during the Whittier Narrows earthquake and its many aftershocks.

Deformation Data

We have used strain offset data from all of the instruments which were in operation at the time of the earthquake and which were close enough to register the strain field change. The largest values were obtained at the closest dilatometers PUBS and BBSS (Figure 1*b*) in the Mojave desert at hypocentral distances of 46.7 and 65.5 km, respectively. At greater distances, such as at Pinon Flat (157 km) and in the Parkfield region (≈ 300 km), small offsets were observed although these were all close to or below the measurement uncertainties of about 0.2 to 0.5 nstrain. The coseismic off-

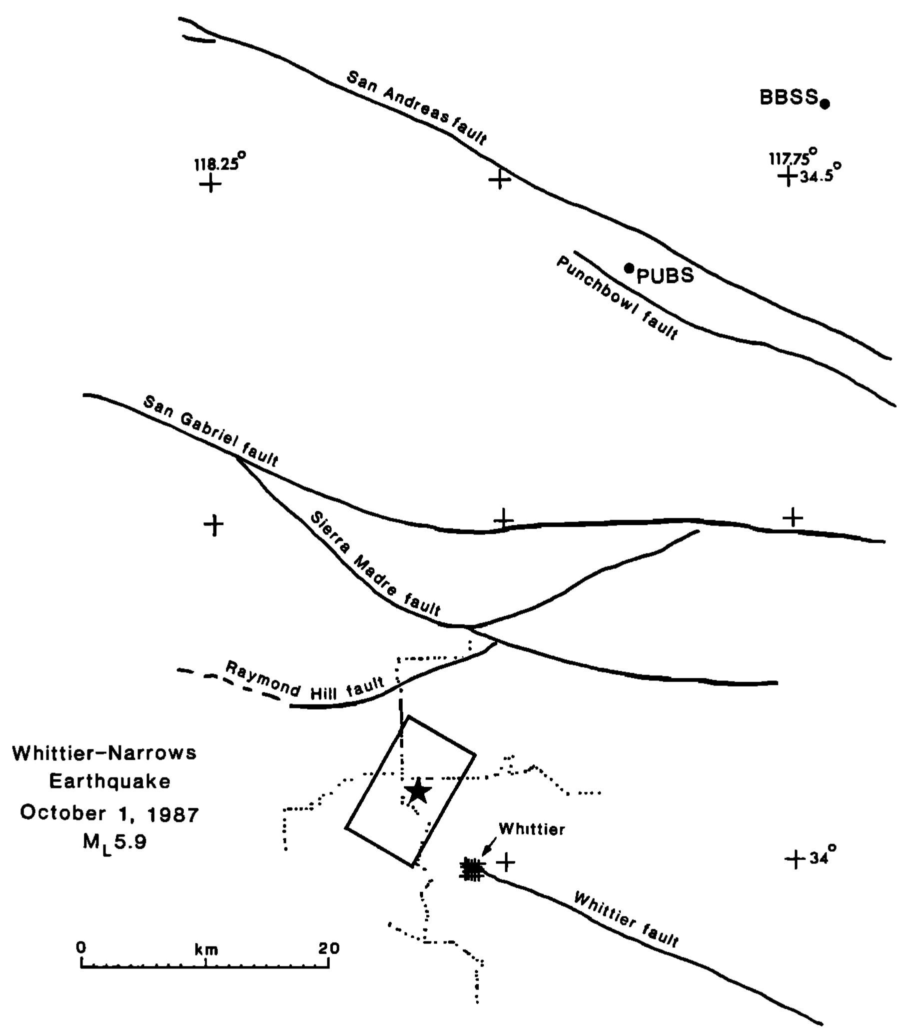

Fig. 1*b*. Expanded map of the region surrounding the epicenter (star). Fault locations are taken from the geologic map of California (scale 1:250,000). Whittier is shown by hatching. The dashed rectangle is the surface projection of our preferred model LJB (see text), which dips to the north. Dotted lines show the location of the level lines reported by *Lin and Stein* [this issue].

TABLE 1. Comparison of Observed Coseismic Strains and Various Model Calculations

Station	Latitude, °N	Longitude, °W	Type	Observed	LJA*	LJB*	BH†	LSA‡	LSB‡
PUBS	34.43	−117.87	DIL	−27.5±3.0	−28.2	24.7	41.6	29.7	32.7
BBSS	34.57	−117.73	DIL	11.0±1.0	11	11.2	16.6	12.1	13.8
RHDS	35.54	−120.25	DIL	−0.07±0.1	−0.07	−0.03	0.07	0.08	0.09
DLDS	35.94	−120.42	DIL	−0.02±0.1	−0.03	−0.00	0.07	0.07	0.08
GH2S	35.83	−120.34	DIL	−0.02±0.1	−0.04	−0.01	0.08	0.08	0.09
PFO	33.61	−116.46	DIL	−0.2 ±0.5	−0.5	−0.4	−0.5	−0.3	−0.3
PFO	33.61	−116.46	N-S	−0.32±0.25	−0.3	−0.2	−0.7	−0.4	−0.6
PFO	33.61	−116.46	E-W	−0.36±0.3	−0.5	−0.4	−0.07	0.01	0.08
PFO	33.61	−116.46	NW-SE	−0.39±0.25	−0.3	−0.3	−0.4	−0.2	−0.3

*Present work.
†*Bent and Helmberger* [this issue] (point source calculation used).
‡*Lin and Stein* [this issue].

sets from all sites are given in Table 1. The offsets for the instruments in the Parkfield region are consistent in that all appear to be contractions. A similar statement holds for the data from Pinon Flat, where we have independent estimates of the dilatation and the horizontal extensions. As will become apparent below, our discussion is concerned more with the well-observed values at the Mojave sites and, in particular, with the relative values at these sites.

Figure 2*a* (upper) shows the strain time history from the dilatometer PUBS on the day of the earthquake. The sinusoidal-like signal results from the earth tides. The offset from the earthquake can be more clearly seen (Figure 2*a*, lower) when tidal frequencies are removed from the data and when the strain generated by atmospheric pressure loading of the Earth's surface is also removed. The offset at PUBS is -27.0±0.5 nstrain. Negative values denote contraction. Similar data from BBSS for the same time period are shown in Figure 2*b*. Here the offset is +11.2 nstrain, opposite in polarity to that at PUBS. Independent data from the laser strainmeters at PFO for the few hours before and after the earthquake are shown in Figure 2*c*. Intermediate-term data from the two dilatometer sites in the Mojave Desert covering the 5-day period before and 3-day period after the earthquake are shown in Figures 3*a* and 3*b* for PUBS and BBSS, respectively. The upper plot in both figures again displays the "raw" data, while the lower plots show the data after removal of the signal at tidal frequencies and correcting for atmospheric loading by calculating a frequency independent transfer factor. The absolute values that we quote for the offsets at these sites depend on our knowledge of the tidal amplitudes, but because of the site locations, any errors in our procedures will make little or no difference to the relative offsets at PUBS and BBSS.

In addition to the strain data, we have incorporated the elevation change data of *Lin and Stein* [this issue], provided

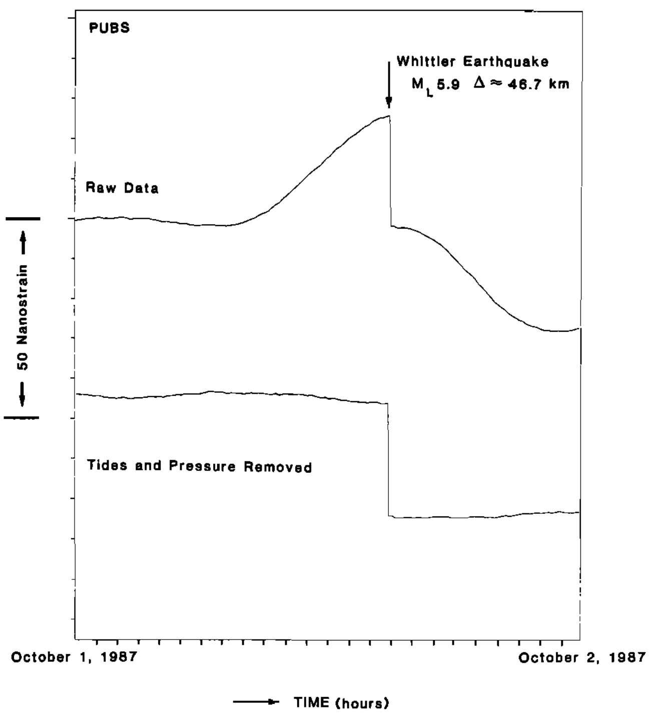

Fig. 2*a*. Raw (upper) and earth tide and atmospheric pressure-corrected (lower) dilational strain data from the dilatometer PUBS during October 1, 1987. The occurrence time of the Whittier Narrows earthquake is shown by the arrow.

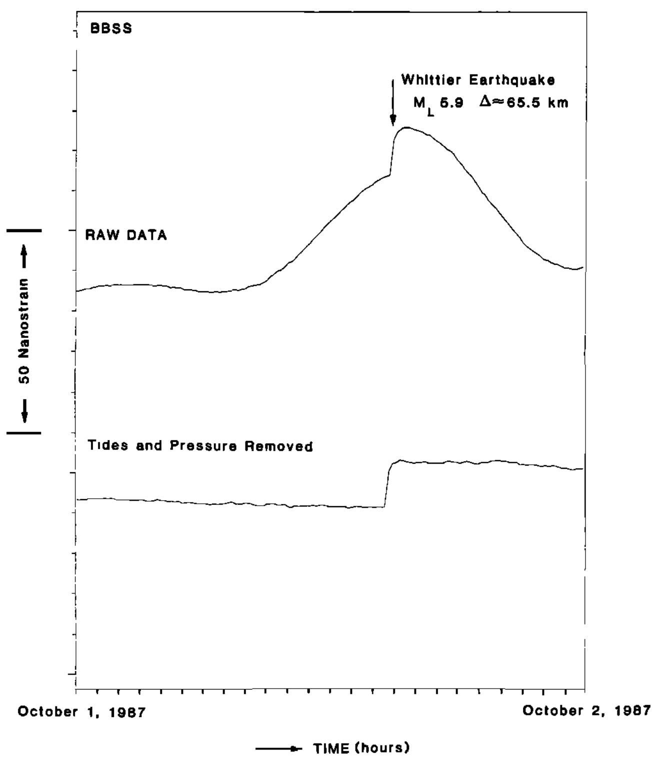

Fig. 2*b*. As for Figure 2*a*, but for site BBSS.

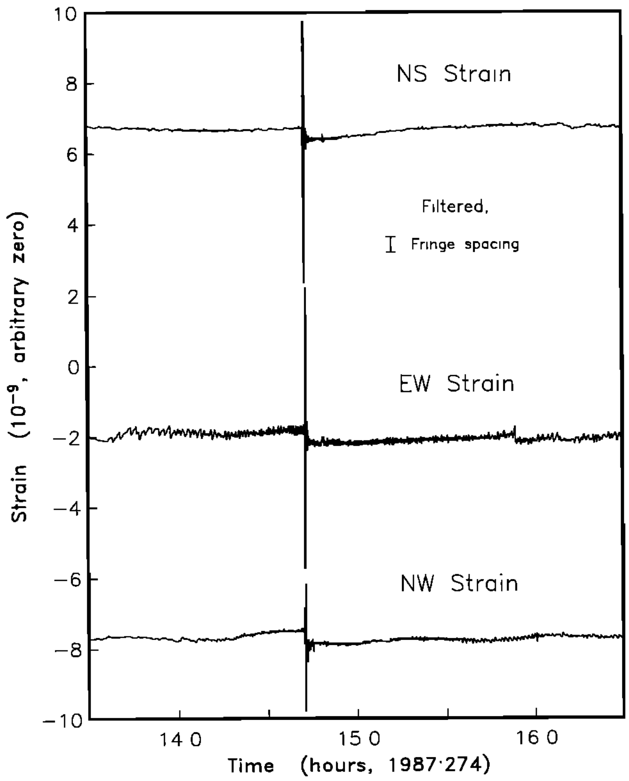

Fig. 2c. Coseismic data from the three 732-m laser extensometers at PFO, after filtering to remove the earth tides and also seismic energy with frequencies above 0.1 Hz. The original data were sampled at 10 s^{-1}. Vertical traces in the data mark the time of the Whittier Narrows earthquake.

by them in advance of publication. A full description of these data are given in that paper. The survey lines are shown in Figure 1b. Note that the survey data allow measurements of the relative changes in elevation.

We have also examined the strain data for noncoseismic variations in the strain record which may be associated with the earthquake. It is evident from Figures 2 and 3 that there are no indications of accelerating strain at these epicentral distances during the last few days to last few minutes before the earthquake. Similar results have been reported for other moderate earthquakes in California [*Johnston et al.*, 1987*a*] where the instrument locations were only a few source lengths from the earthquake. The data from BBSS and, to a lesser extent, PUBS show some indications of postseismic strain changes for several hours following the earthquake. These strain changes are in the same sense as the coseismic offset but most likely result from perturbation of the near-instrument aquifer system by the passage of large-amplitude seismic waves. Similar time constants of several hours were observed throughout North America in water wells following the 1964 Alaskan earthquake [*Cooper*, 1968].

Longer-term data from the nearest instrument PUBS for 21 months prior to, and 10 months after, the Whittier Narrows earthquake are shown in Figure 4. A long-term trend (contraction) of 1.10 μstrain/yr has been removed from these data. This trend was determined from data during the 21 months prior to the earthquake. Although some strain perturbations at the 0.2 μstrain level are apparent, we do not ascribe any tectonic significance to these changes. On the other hand, a reduction in compressive strain rate is associated with the earthquake. This, and the offset generated by the earthquake, are the primary earthquake related features in the strain data at PUBS. The decrease in strain rate, obtained by linear regression fits to the data before and after the earthquake, is 1.15 μstrain/yr. A similar but smaller change in rate (-0.36 μstrain/yr) occurred at BBSS. These data are also shown in Figure 4. We note that for both sites, the change in strain rate is opposite in polarity to the coseismic offset. We do not have an explanation for such changes, but similar records have been obtained in as-

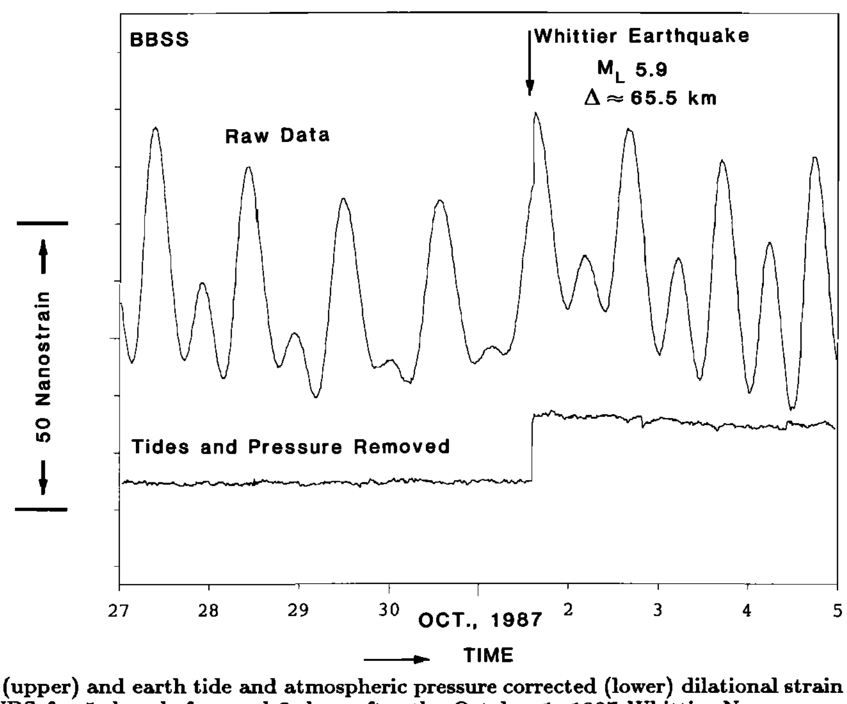

Fig. 3a. Raw (upper) and earth tide and atmospheric pressure corrected (lower) dilational strain data from the dilatometer PUBS for 5 days before and 3 days after the October 1, 1987 Whittier Narrows earthquake. The occurrence time of the earthquake is shown by the arrow.

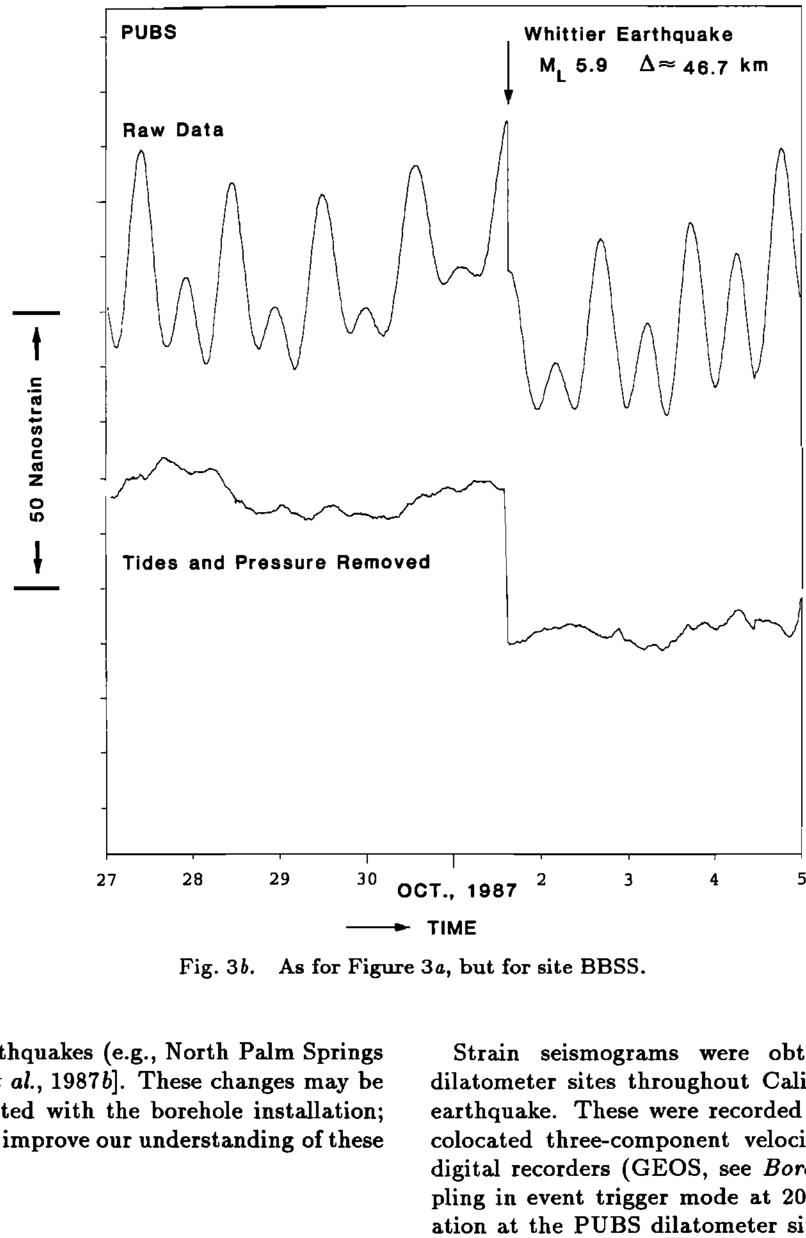

Fig. 3*b*. As for Figure 3*a*, but for site BBSS.

sociation with other earthquakes (e.g., North Palm Springs earthquake [*Johnston et al.*, 1987*b*]. These changes may be local site effects associated with the borehole installation; future observations may improve our understanding of these effects.

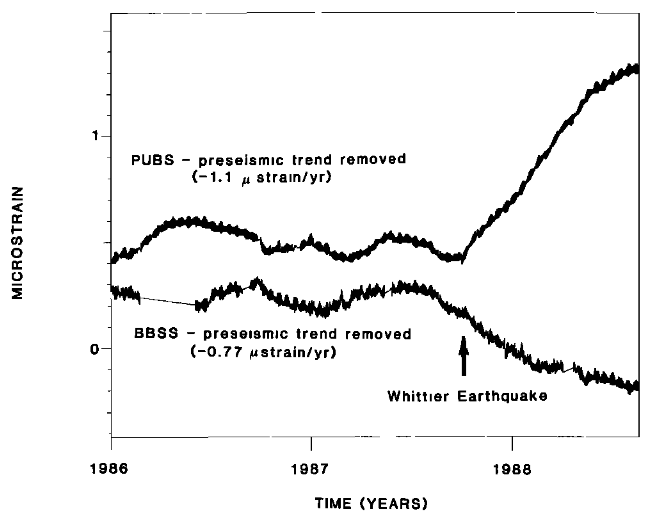

Fig. 4. Detrended, pressure-corrected strain data during the 21 months prior to the October 1 Whittier Narrows earthquake and 10 months following the earthquake from the closest dilatometers PUBS and BBSS.

Strain seismograms were obtained at many of the dilatometer sites throughout California for the October 1 earthquake. These were recorded together with data from colocated three-component velocity transducers on 16-bit digital recorders (GEOS, see *Borcherdt et al.* [1985]) sampling in event trigger mode at 200 s^{-1}. The seismic radiation at the PUBS dilatometer site is shown in Figure 5*a*, while that observed at the GH2S site is shown in Figure 5*b*. Careful inspection of the strain record in the seconds before rupture indicates no precursory strain release above the resolution limit (0.05 nstrain, see Figure 5*a* insert). This is consistent with other observations in California [*Johnston et al.*, 1987*a*].

STATIC DISLOCATION MODELS

We have too few strain coseismic observations to determine the source parameters, but by using them together with the elevation changes, we are able to invert the data. We model the source as a single rectangular plane with uniform slip and use *Okada*'s [1985] formulation for the surface deformations due to a dislocation embedded in an elastic half-space. Results from these calculations were verified independently by comparison with those from other programs. We use the method of *Marquardt* [1963], as described by *Bevington* [1969], for least squares estimation of nonlinear parameters. We also carried out a grid point search over a generous range of parameters in order to verify the va-

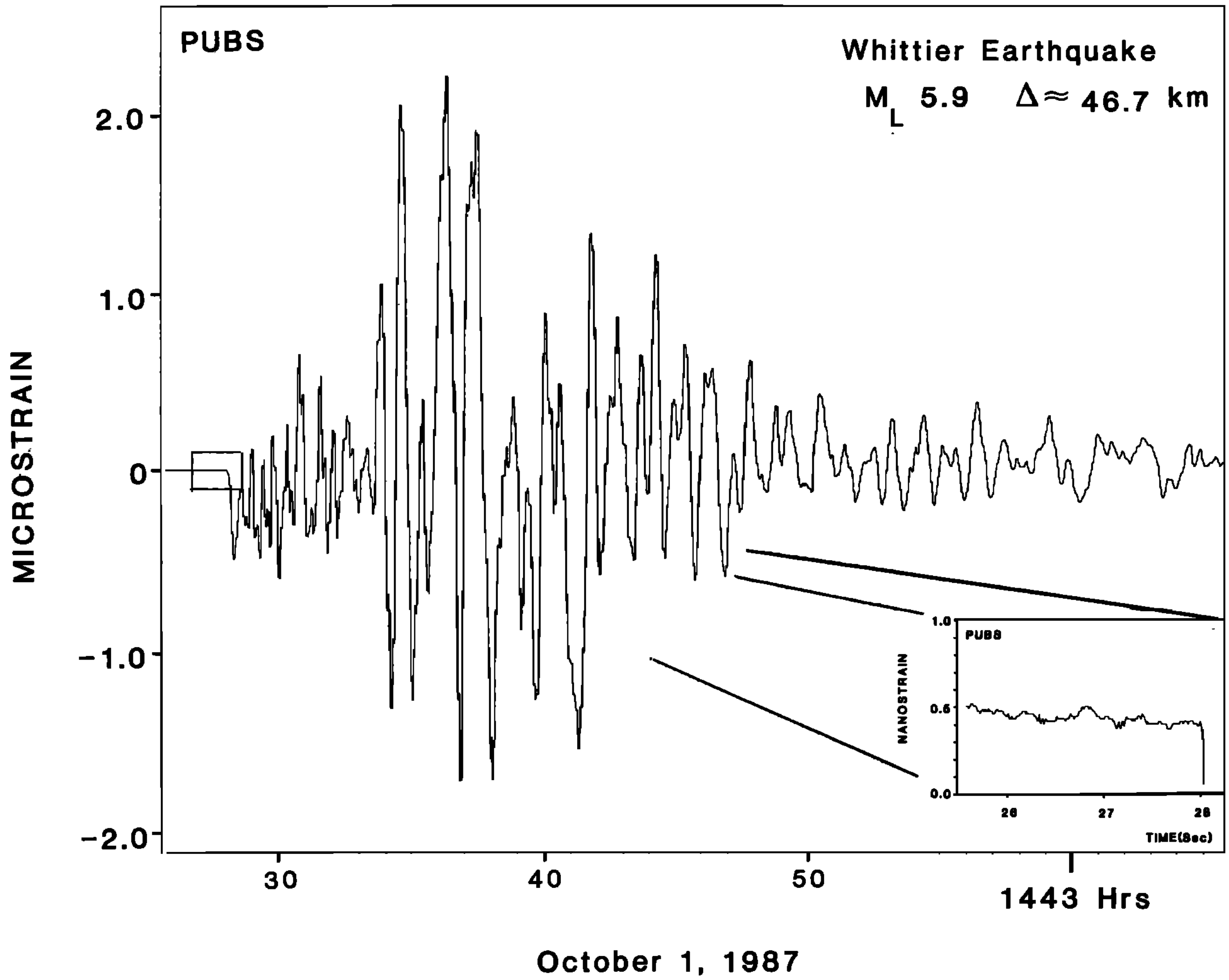

Fig. 5*a*. Record of volumetric strain sampled at 200 s^{-1} obtained at the dilatometer PUBS (hypocentral distance of 46.7 km) during the Whittier Narrows earthquake. An expanded section for 2.5 s prior to the arrival of the *P* wave is shown in the inset. Note that contraction is positive.

lidity of the inversion solutions. Eleven parameters are required for a complete description of our problem: three for the source location; two (strike and dip) for its orientation; four (length, width, strike slip dislocation, dip slip) for the source dimensions, and two for the absolute levels of the two survey lines.

In the inversion procedure, weighting of the various data points varies with the reciprocal of the error estimates. For the elevation changes, we have used the errors as tabulated by *Lin and Stein* [this issue]; for the strains we have used a range of error estimates to see how different weights perturb the solution parameters. These error estimates were varied systematically over a wide range. For the two Mojave sites (PUBS, BBSS), which have large well-determined offsets, we used errors ranging from 2% to 20% of the observed signals; for the Parkfield sites (small offsets), we used 25% to 200%; for Pinon Flat data, we allowed errors from 2% to about 100%. In general, the solution parameters are fairly robust (in the sense that the geophysical significance is unaltered) with respect to these different weightings. This is also true if instead of using all the leveling data, we use every third, fifth, or tenth value, which decreases the ratio of the combined weight of the leveling data to the strain data from 5 to 1.6, 1, and 0.5, respectively, for the strain errors of the preferred model LJB discussed below.

Table 1 shows the observed strain offsets and those calculated from several models. Model LJA is representative of solutions obtained by inverting all of the available data; similarly for model LJB, except that the station PUBS is omitted; model BH is the *Bent and Helmberger* [this issue] solution; LSA and LSB are the solutions given by *Lin and Stein* [this issue]. For models LJA and LJB, we have chosen sample solutions in which the same weighting for the data was used. The solution parameters for these models are in Table 2. Different relative weightings for the strain data result in a suite of models for both classes LJA and LJB. The LJA models have strikes which range from N60°W to N70°W; dips between 30° and 40°; fault lengths from about 2-4 km; widths from 40 to 50 km; right-lateral strike slip less than 10 cm; thrust slip from 45 to 70 cm. The moments varied between 1.1 and 1.9 x 10^{18} N m. All these models have slip penetrating to depths between 28 and 32 km. Chi-square values range from 2 to 3. For models in the LJB class, strikes range between N65°W and N60°W;

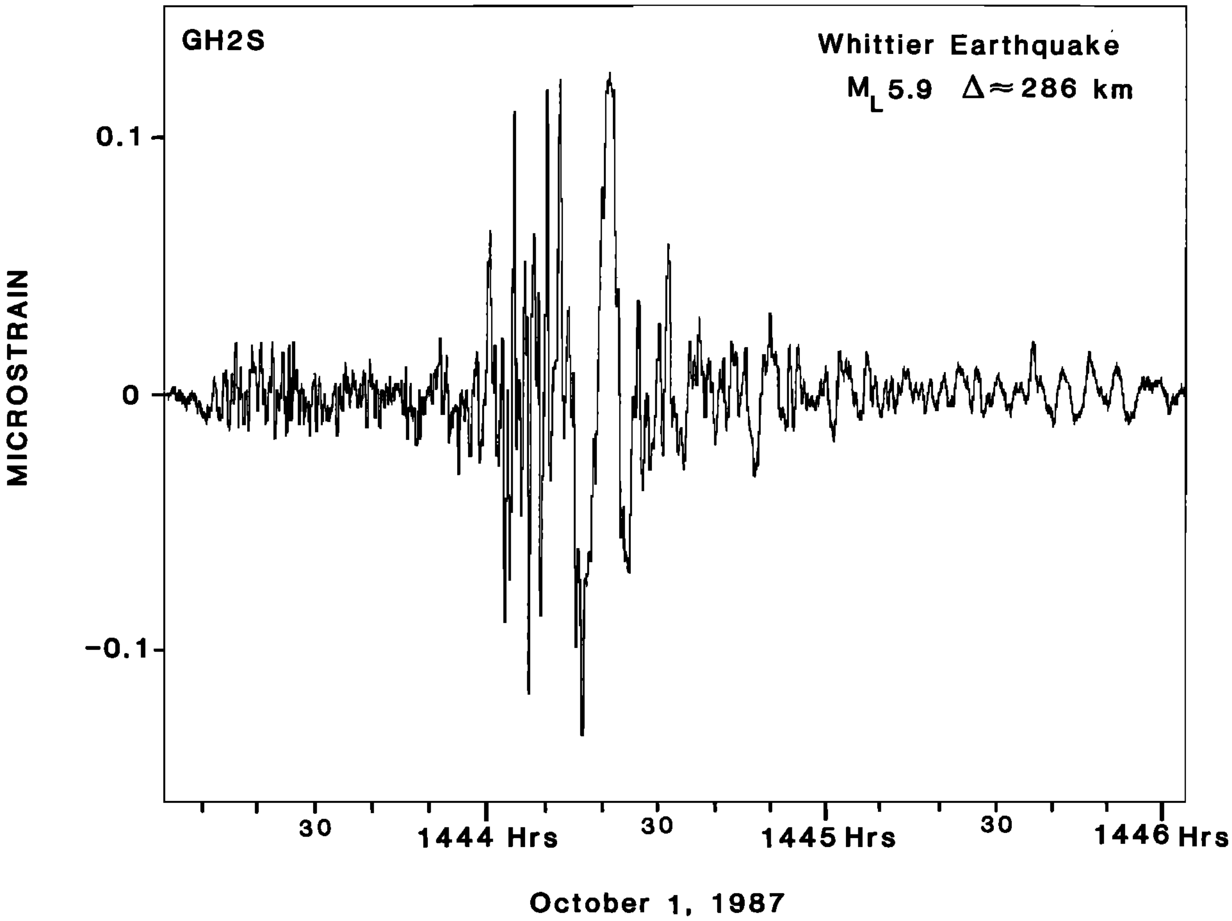

Fig. 5*b*. As for Figure 5*a*, but for dilatometer GH2S at a distance of 285 km.

dips between 38° and 44°; fault lengths from 4 to 6.5 km; widths from 12 to 14.5 km; right-lateral strike slip between 10 and 16 cm; thrust slip from 20 to 45 cm. The corresponding moments are all about 0.7 × 10^{18} N m, and the maximum slip depths are about 16 km. Chi-square values are about 1.2. A contour plot of the dilatational strain due to this model is shown in Figure 6*a*. Comparison of the leveling data with calculated vertical displacements due to model LJB (our preferred model, see below) is shown in Figure 7. If we restrict solutions to be pure thrust slip (and omit PUBS), we fit the data almost as well as with the LJB model. A representative solution strikes at N72°W, dips 50° to the north, and is 10.5 km long and 5.4 km wide with 57 cm of slip.

All of these models (LJA through LSB) are different in various aspects, but many of these differences, such as relatively small variations in location, are not geophysically significant. Our model LJA does, however, have a strik-

TABLE 2. Source Parameters of Models in Table 1

Parameter	LJA	LJB	BH	LSA	LSB
Latitude,* °N	34.01	34.01	34.05	34.03	34.03
Longitude,* °W	−118.11	−118.12	−118.08	−118.07	−118.07
Depth,* km	3.6	6.4	12	12	12
Strike, W of N	57.1	56.1	80	90	90
Dip, N down	30	42	40	30	34
Length, km	1.7	6.2	#	4.5	12
Width, km	47.7	14.5	#	6	4
Slip, m	0.44	0.25	#	1.1	0.71
Rake, deg	102	114	98	90	90
Moment†	1.3	0.67	1.2	0.96	1.09

* Midpoint of top edge, except for BH (hypocenter).
† These moments have units of 10^{18} N m.
# Not determined by *Bent and Helmberger* [this issue].

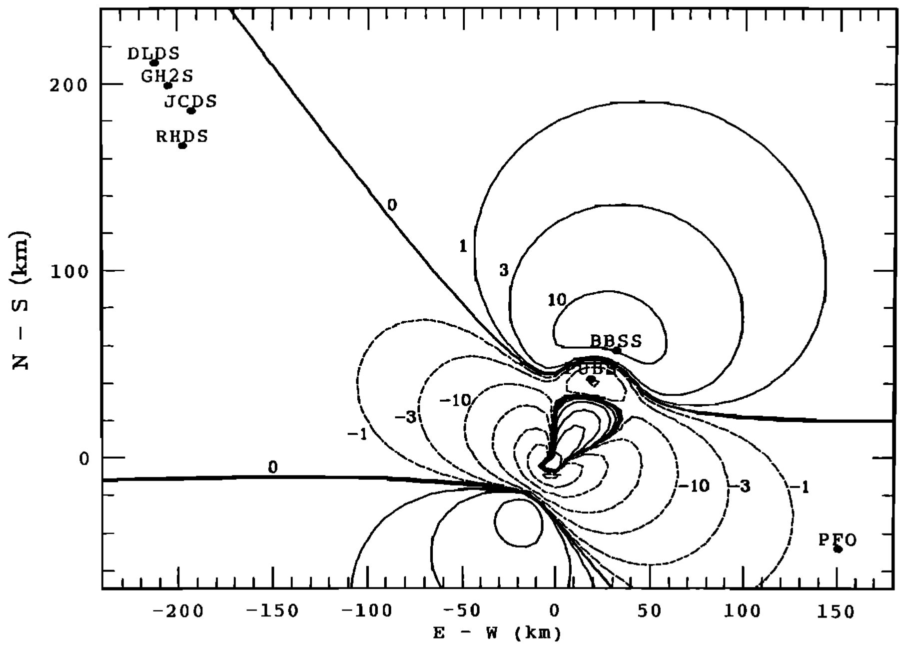

Fig. 6*a*. Contour plot of dilational strain due to model LJB (see text and Tables 1 and 2) in which data from PUBS are omitted in the inversion. The coordinate origin is 34.058°S, 118.077°W. Contour levels are in nanostrain. Solid and dashed lines represent positive and negative dilatations, respectively.

ing difference in that it requires slip at depths greater than the seismogenic zone; for this to be correct, the deeper slip presumably must take place over a longer time scale. It is obvious from the calculated values for our model LJB (in which PUBS is omitted from the inversion) that this deep slip is required to satisfy the data at PUBS; in fact, any of the source models proposed elsewhere for this earthquake result in positive dilatations at PUBS (about 30 nstrain) in contrast to the −27 nstrain observed. The contour plot in Figure 6*b* illustrates the need for deep slip in order to satisfy the PUBS observation. This conclusion is not modified by the choice of different shapes (elliptical or circular rather than rectangular) for the fault plane. The anomaly cannot be resolved by supposing that we have a significant error in our absolute calibrations. If this were the case, such an error would scale both PUBS and BBSS equally so that the ratio of the observed offsets cannot be significantly in error. (We are confident of this because the tidal amplitudes must be

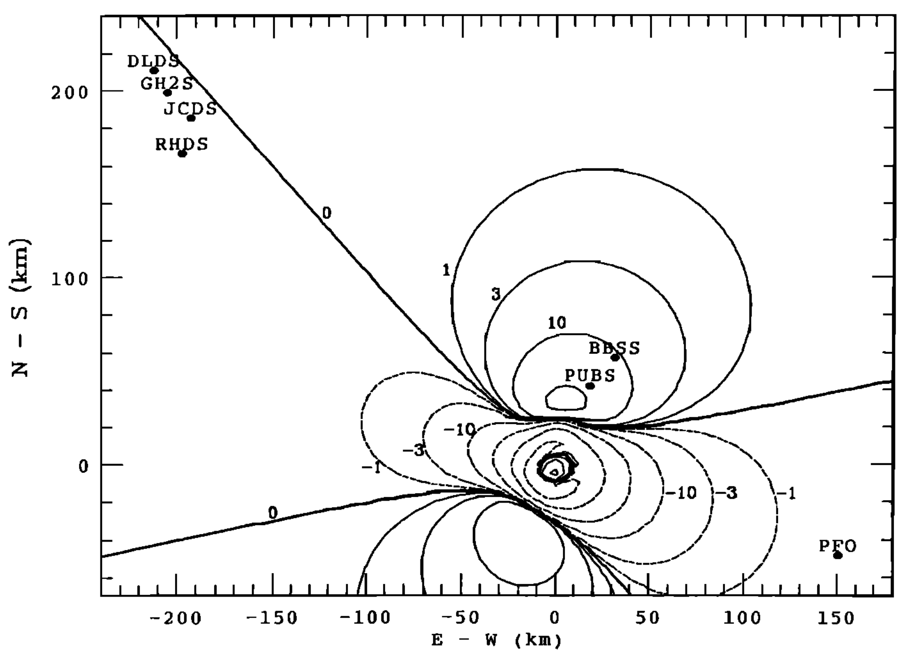

Fig. 6*b*. Same as for Figure 6*a* but for all deformation data (model LJA). An increase in depth of slip is required to produce negative dilatation at PUBS.

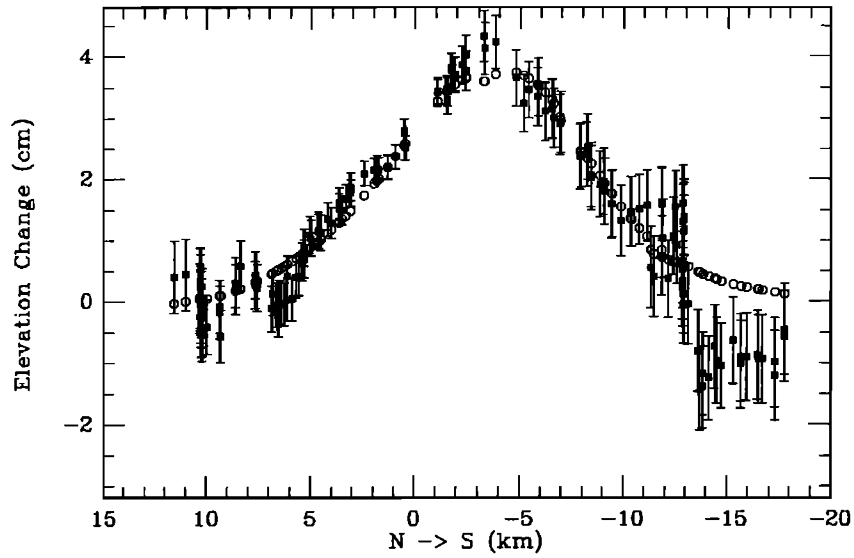

Fig. 7*a*. Comparison plot of predicted level changes (open circles) for the preferred model (LJB) derived from the strain and uplift data with the observed changes (solid squares) reported by *Lin and Stein* [this issue] for the north-south line. The coordinate origin is the same as in Figure 6. The zero level is that derived from the model calculation. Both the quality of the fit and the zero levels are comparable to those of Lin and Stein.

almost equal at both sites and so the offset ratio is readily determined.) Inversions in which we allow the absolute values at PUBS and BBSS to vary by up to ±50% (a generous estimate for our errors in determining tidal amplitudes) all result in models which require deep slip. The amplitudes at Pinon Flat and in the Parkfield area are all quite small; inversions in which one or both sets of these data are omitted again result in models similar to model LJA in that deep slip is required.

DISCUSSION

The seismic data require that any deep slip must take place slowly, presumably over an interval of a minute or more. We are able to place a limit on the duration of any such slow slip on the basis of the high-frequency data from the dilatometer at PUBS (Figure 5*a*). The strain offset within 15 or 20 s after the *S* arrival can be estimated by low-pass filtering the data later in the record and comparing those values with the preevent level. This yields a value of about −29 nstrain which agrees very well with the −27 nstrain obtained from the continuous data sampled every 10 min. We conclude that the Whittier Narrows earthquake was not associated with any significant aseismic slip and that therefore the strain offset value recorded at PUBS is not directly due to the main shock. This conclusion is consistent with the inversion results in that the family of solutions obtained when PUBS is omitted has a lower spread in the parameter range and that the chi-square test indicates a better fit to the data.

This is the first time that we have found significant disagreement between coseismic offset observations from Sacks-Evertson borehole instruments and the calculations based on values for the seismically determined solutions. It is therefore important to attempt to isolate the cause of the spurious value in this case. We have indicated above that the discrepancy cannot be due to errors in site calibration. Since the acceptable source models, with slip penetrating to depths about 16 km, produce dilatation with polarity opposite to that observed, we have to question the reliability of this site. Unfortunately, we have no independent reason to suspect that PUBS should provide unreliable coseismic data for this particular earthquake. The host rock (sandstone) is, relative to that at other sites, both homogeneous

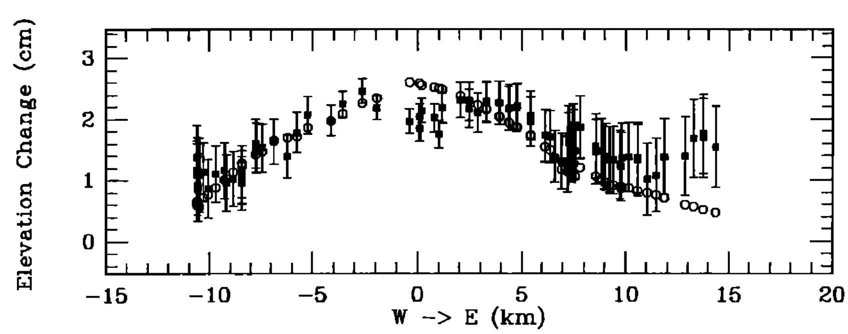

Fig. 7*b*. As for Figure 7*a*, but for the east-west line.

TABLE 3. Observed and Calculated Strain Steps at PUBS for Other Nearby Earthquakes: 1986–1989

Earthquake	Time, UT	Latitude,°N	Longitude,°W	Magnitude	Reference*	Observed Strain	Calculated Strain
Oceanside	86J1841347	32.9783	−117.8583	5.3	R1	0.6	0.7
Whittier	87J2771059	34.0600	−118.1035	5.3	R2	2.5	2.1
Huntington Beach	88J3250539	33.5096	−118.0715	4.5	R3	0.015	0.01
Pasadena	88J3381138	34.1392	−118.1338	4.9	R3	11.7	8.6
Uplands	88J1781504	34.1362	−117.7095	4.5	R3	0.7	0.5

In Units of nanostrain.
*R1, *Pacheco and Nabelek* [1988]; R2, *Hauksson and Jones* [this issue]; R3, L.M. Jones (personal communication, 1988).

and competent. The general characteristics of the data from the site are good; the site is quiet at high frequencies, and the tidal signals are very clean.

Perhaps most important in this context is the fact that for a number of other earthquakes, PUBS records coseismic offsets which agree remarkably well with values calculated from seismic models including that for the largest Whittier aftershock on October 4, 1987 (see Table 3). It is true that this observed offset at PUBS is larger than any of the others; perhaps there is some unknown threshold effect which results in a distorted offset. We know that the instrument itself behaves linearly under much more extreme conditions [*Sacks et al.*, 1971; *McGarr et al.*, 1982].

Our modeling assumes that the Earth is a homogeneous half-space, and clearly this assumption introduces errors into our analysis. There have been some attempts to perform similar calculations for media with elastic variations [e.g., *Rybicki and Kasahara*, 1977; *McHugh and Johnston*, 1977]. Such variations could result in local strain changes being different from those calculated on the basis of simple models, but it is unlikely that a change in sign could result. Another possibility is that aquifer perturbations produce local strains which mask the direct coseismic effect. We find this improbable since aquifer effects at PUBS do not seem to affect its behavior for other earthquakes and aquifers in general have relatively long time constants. Also the postseismic changes at PUBS in the hours following the earthquake are quite small relative to the coseismic change.

The most likely possibility appears to be that the Whittier Narrows earthquake triggered sympathetic slip on one or more faults close to PUBS, for example, the San Andreas fault, the Punchbowl fault, or any of the many other subparallel faults in the Devil's Punchbowl near PUBS, which pass within a few kilometers of PUBS. Such effects have been reported, for example, for the Imperial Valley earthquake of 1979 [*Fuis*, 1982; *Sieh*, 1982]. The mechanism of the Whittier Narrows earthquake was such as to reduce the normal stress across the complex fault system near PUBS so that we expect an increased probability of slip on those faults. One centimeter of slip at a depth of 3 km (or shallower), on a 1 km by 1 km patch of the Punchbowl fault could produce 30 nstrain at PUBS while not significantly affecting the data at BBSS.

SUMMARY

1. Coseismic static strain offsets with amplitudes exceeding 10 nstrain were recorded on two borehole dilatometers at distances of 46.7 and 65.5 km from the October 1, 1987 Whittier Narrows earthquake. Smaller offsets were recorded on similar instruments at distances up to 315 km from the earthquake and on laser extensometers at a distance of 157 km.

2. These static offsets are, by themselves, insufficient to allow independent determination of the source mechanism, but by augmenting the strain offsets with elevation change data for the epicentral area we are able to invert for source parameters consistent with all the available deformation data. The resulting models have slip extending to depths of about 30 km, much deeper than the seismogenic zone. This requirement for slow slip derives from the offset at PUBS, but high-frequency data from the same site exclude any significant slow component of moment release. We cannot determine the cause of the spurious strain offset at PUBS, a station which otherwise has exhibited excellent behavior, but speculate that it may be due to sympathetic slip on a nearby fault.

3. The preferred model of the Whittier Narrows earthquake, obtained by inverting all available deformation data but ignoring the data from PUBS, indicates slip of 25 cm on a fault patch about 6 km long and 15 km wide that extends to a depth of 16 km. The fault strikes N56°W, dips 42° down to the north, and has a rake of 114°. The moment release was 0.7×10^{18} N m.

4. Neither intermediate- nor short-term precursory strains before the event are apparent on the closest instruments at levels above 10 and 0.5 nstrain, respectively. In contrast, the dynamic straingram exceeded 1000 nstrain.

5. The nearest two borehole strainmeters showed a definite change in strain rate at the time of the earthquake; in both cases the change in rate was in the opposite sense to that of the coseismic offset.

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