OBSERVATIONS AND IMPLICATIONS OF WATER WELL AND CREEPMETER ANOMALIES IN THE MOJAVE SEGMENT OF THE SAN ANDREAS FAULT ZONE

BY YEHUDA BEN-ZION, THOMAS L. HENYEY, PETER C. LEARY, AND STEVE P. LUND

ABSTRACT

Four years of continuous water level data from a 1,900 m deep well near the San Andreas fault in southern California show a 21-month period of unusual rapid fluctuations. The anomalous water level activity ceases with the occurrence of the 8 July 1986, $M_l = 5.6$ North Palm Springs earthquake on the San Andreas fault, approximately 120 km southeast of the well site. The water level data correlate with signals from two San Andreas fault zone strain sensors. The long-term water level variations are similar in shape to those recorded by a borehole dilatometer 30 km from the well site, while the rapid water level fluctuations correlate in time with anomalies in the record of a fault zone creepmeter located 35 km from the water level monitor. The observations are interpreted in terms of strain occurring in a horizontally and vertically heterogeneous crust. Tectonic deformation is concentrated along weak block-bounding fault zones. The blocks are sufficiently rigid to generate correlated displacement phenomena along their weak boundaries. As a consequence, fault zone strain events can be related over large distances as in the case of the North Palm Springs earthquake and the coincident creep and water level anomalies. The observed creep and water level events occur in a weak aseismic shallow (<3 km) material overlying stronger asperities along which the fault is locked and regional strain loading occurs. Local failure of the fault within the weak shallow material has no far-field effects and is not important in the crustal stress budget, but may signal accelerated strain accumulation at depth. In this context, the reported observations demonstrate the possibility of joint detection of fault zone anomalies that relate to, and possibly anticipate, major tectonic strain events on large faults.

INTRODUCTION

This paper focuses attention on the possible existence of tectonic signals that are present primarily at fault zones and their associated near-by fracture zones (i.e., localized compliant regions of the crust). Such signals, which in the framework of simple models may be discarded as noise, can be important to fault mechanics and earthquake prediction studies. The basis of our argument is a series of coincident anomalies in the records of a deep well water level monitor and a fault zone creepmeter.

The two instruments are part of a strain sensor network operated by the University of Southern California (USC). The sensors are situated along the periphery of the Mojave block near the locked section of the southern San Andreas fault. The water level monitor is located in a 1,900 m deep well about 5 km north of the San Andreas fault near Phelan, California. The creepmeter (designated XWR in earlier publications) crosses a trace of the 1857 break of the San Andreas fault near Pearblossom, California, approximately 35 km from the water level site (Fig. 1). Leary and Malin (1984) presented evidence that the XWR creepmeter is responsive to regional tectonic events and that its record contains pre- and co-seismic steps related to the 1979 Homestead Valley earthquake in the south central
Mojave block. Data from the other USC-operated strain sensors are too sparse and/or unstable to be useful in the present study. Data from a Sacks-Everton dilatometer installed at a depth of 200 m at PUBS (Fig. 1), approximately 5 km from the creepmeter site, is used to verify the long-term stability of the Phelan water level measurements. The PUBS dilatometer is a part of a borehole strain network operated by the U.S. Geological Survey (USGS) and the Carnegie Institution of Washington (e.g., Linde and Johnston, 1989).

In the following, we examine correlations between creep and water level anomalies that appear in 31 months of data recorded concurrently by the XWR creepmeter and Phelan water level monitor between March 1984 and October 1986. We find time correlations between six large anomalies in the period October 1984 to July 1986 that we cannot explain by environmental effects. The last of these anomalies occurs around the time of the July 1986 $M_L = 5.6$ North Palm Springs earthquake. The creep-associated water level anomalies occur at roughly 3-month intervals over a period of 21 months before the earthquake, but do not occur in the prior 20 or the following 6 months. In the three most prominent occurrences the onset of the creep anomaly precedes the water level anomaly by 2 to 4 weeks.

From the observations, we attempt to draw implications for fault zone structure and block tectonics in southern California. Although our study is phenomenological in nature, the data suggest that these near fault instruments record regional disturbances that are related to tectonic sources. We suggest that the temporal

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**Fig. 1.** The Mojave crustal block in southern California, bounded by the San Andreas fault to the south and the Garlock fault to the west and north. XWR, Phelan, and PUBS are the creepmeter, water level, and borehole dilatometer sites, respectively. Cajon Pass marks the location of a deep drill scientific site. PFO marks the Pinon Flat strain observatory. Asterisks locate the sites of the 1979 Homestead Valley and 1986 North Palm Springs earthquakes.
association of the creep and water level anomalies with the 1986 North Palm Springs earthquake, with epicenter approximately 120 km to the southeast, is evidence for regional spatial coherence of strain along major faults in southern California. This is a direct manifestation of the block-like structure of the southern California crust. We suppose that fault zones are vertically heterogeneous, consisting of weak shallow material on top of stronger asperities along which the fault is locked and where earthquakes nucleate. The weak shallow crust may fail during block-wide strain episodes, while the underlying earthquake nucleation zone absorbs the increased load. The block-wide strain episodes signaled by the failure of the weak uppermost fault zone material may, however, indicate an increase in the likelihood of an impending earthquake on the bounding fault system. We thus suggest that an improved array of fault zone and near-field instruments operating at high sensitivity could provide important data for fault mechanics and earthquake prediction studies.

**ANALYSIS**

The amount and quality of the available data renders a quantitative study impractical. We therefore restrict our analysis to the identification of local anomalies in the creep and water level records. While quantitative modeling of the anomalies' source(s) is obviously desirable, the precise nature of the source(s) is unimportant to our general conclusions. Some may argue that unless the creep and/or water level anomalies can be explained by some “plausible” tectonic source(s) they are probably due to instrumental or environmental “noise.” However, in our opinion, the range of plausible sources is large, given the actual complexity of the San Andreas fault zone and its environs, and thus attempts at modeling the rather limited data presented here seems unwarranted.

The Phelan water level monitor is situated in an abandoned 1,900 m deep dry wildcat well. The well is cased to 1,800 m, open in the bottom 100 m and is perforated at various intervals between 350 and 1,800 m. The site is instrumented with a piezoresistive pressure gauge (Foxboro Model 1800) sensitive to 2 mm changes in water head. The gauge remained stable at 5 to 6 mm level against appreciable drift over a few years. The long-term stability of the sensor was verified using a standard wireline water level detector lowered into the well at 6-week site maintenance intervals. Repeated checks of the water level agree to 3 mm. Temperature effects on the sensor are negligible in the nearly isothermal environment of the water table in the well. The tidal signal in the water level record has an amplitude of about 10 cm, implying that the water column is in contact with a large compliant fracture zone (Heney and Lund, 1983).

The Phelan water level record shows a series of large rapid water level drops and associated recoveries between November 1984 and July 1986 (Fig. 2). The magnitude of the largest excursion approaches 110 cm. The onset of the last water level anomaly on July 8, 1986 is coincident with the \( M_L \approx 5.6 \) North Palm Springs earthquake. The down direction of all the large water level anomalies suggests that they are associated with new void space in the surrounding rocks, resulting, perhaps, from prefailure rock dilatancy and/or the creation and extension of fractures during local failure episodes. The period of anomalous water level activity contrasts sharply (Fig. 2) with the quiet background of the bounding previous 20 and following 6 months. Fortunately, the XWR creepmeter was operating during the time interval of the anomalous water level activity.

The XWR creepmeter is a standard USGS 22 m Invar wire device installed in a 2 m deep trench at an angle of 45° across the surface trace of the San Andreas fault...
Arrows indicate the times of the May 2, 1983 (M = 6.5) Coalinga and July 8, 1986 (M = 5.6) North Palm Springs earthquakes.

(Schulz and Burford, 1977). Creepmeter piers are deeply driven into the soil. A weight on a rocker arm provides tension on the Invar wire stretched between the piers, and displacement of the weighted end of the wire is measured by an LVDT. Normally, USGS creepmeters run at a least count sensitivity of many tens of microns, but because the present site is on a locked segment of the San Andreas fault we have raised the least count sensitivity to about 1 micron. At this sensitivity, soil temperature variations are routinely recorded by the creepmeter. The thermoelastic strain is an important but tractable component of its record.

Ben-Zion and Leary (1986) showed that strain and sensitive creep data recorded near the southern San Andreas fault contain large environmental signals. The largest of these effects results from thermoelastic strain due to spatial variations in ground temperature and the response of the rocks. The thermoelastic strain at a given point is a contribution of two terms: (1) strain resulting directly from temperature variations at that point, and (2) thermally induced strains transmitted from shallower depths that are elastically coupled to the point under consideration (Berger, 1975; Ben-Zion and Leary, 1986). A simple but realistic model of the response of a buried strainmeter assumes the crust to consist of a weak (unconsolidated) layer overlying, and decoupled from, an elastic half-space. In this framework, the waveform of the thermoelastic strain at a point in the unconsolidated material is the same as the waveform of the temperature variation at that point, while the waveform of the thermoelastic strain in the underlying half-space is, to first order, determined by the waveform of the temperature variation at the base of the unconsolidated layer. The XWR creepmeter is covered by 2 m of soil and is therefore assumed to be located in unconsolidated material. We expect the thermoelastic strain in the XWR record to be proportional to the temperature variation at the depth of the creepmeter.

Figure 3 shows 31 months of data recorded concurrently by the XWR creepmeter and Phelan water level monitor between March 1984 and October 1986. Also shown are subsurface soil temperature at the creepmeter site and rainfall at Palmdale, California. The period of Figure 3 spans the entire time interval in which USC
Fig. 3. XWR creepmeter (top, thick line), subsurface temperature (top, thin line), Phelan water level (middle), and regional rainfall (bottom) records for the period March 1984 through October 1986.

maintained the XWR facility, and the creepmeter was recording with high sensitivity. The creep data (thick line) and temperature variation at the 2 m depth of the creepmeter (thin line) are plotted at the top panel of Figure 3. The temperature variation is an ever-present strain source and, in the absence of other sources, the creep record would be due entirely to thermoelastic strain. On the other hand, large deviations of the creep record from the thermoelastic strain indicate that additional sources are operating during these time windows. Comparing the slopes of the creep and subsurface temperature curves, it is seen that for most of the 31 months of data shown, the slope of the creep data tracks the driving slope of the temperature variation.

There are six zones (shaded in Fig. 3) where the creep and temperature slopes are in the opposite sense. We consider these zones anomalous since the data indicate that sources other than temperature variations are acting during these time intervals. The onsets of these anomalies are easy to determine; however, the times where the anomalies end are complicated by the nonlinear mechanisms of soil response.
and source relaxation, and are harder to assess. Thus, while we have confidence in the times marking the beginning of each anomaly, their terminations as indicated in Figure 3 should be regarded as upper limits. The creep events range in magnitude from 100 to 400 microns (0.1 to 0.4 mm). The largest of these events would be only marginally detectable on typical fault zone creepmeters not operated at high sensitivity.

The lower curve in Figure 3 shows the Phelan water level variation for the corresponding time interval. It is seen that the six largest water level anomalies during this period fall within the zones marked by the creep anomalies. At the bottom of Figure 3 we show rainfall recorded at Palmdale, California, for the studied time interval. It appears that there is no clear correlation between the creep/water level anomalies and rainfall, although it is possible that the second anomalous zone is affected by the heavy precipitation in the preceding few weeks. We note, however, that the rainfall in early 1986 did not produce similar anomalies in the creep and water level records.

In addition to the large correlated creep/water level anomalies, the data contain numerous smaller creep anomalies that do not have corresponding water level excursions, and vice versa. These may be attributed to site, instrument, and/or local environmental effects.

As noted previously, we do not offer an explanation for the particular source(s) of the anomalies. The nonthermal deviations in the creepmeter record do not form a monotonic sequence as is sometimes observed in records of standard creepmeters (e.g., Schulz et al., 1987). We do not expect, however, a standard creepmeter signal in a locked section of the San Andreas fault. We expect instead low-level events resulting, perhaps, from shifts in the creepmeter environment. Examples are non-linear thermal responses, long-term ground water migration, and hill side slumping. Such low-level shifts may be of strictly local origin or they may be manifestations of broad deformation associated with the San Andreas fault. A distinction between local and regional (tectonic) sources may be obtained by assembling a statistically convincing set of correlations in time and space. In Figure 3, we attempt to isolate such a set of correlations. Admittedly, the sample is small and therefore the statistics are poor. It would be of course desirable to have longer water level and creep records, as well as additional instruments (on and off the fault). These, however, are not available at present.

To further investigate the correlation between creep and water level shown in Figure 3, we have broken down the creep curve into a simple thermoelastic component and a hypothetical “tectonic” curve (Fig. 4, top panel). The thermoelastic strain in the soil (corresponding to the unconsolidated layer of Ben-Zion and Leary, 1986) is expected to be proportional to the local temperature variations. We thus approximate the thermoelastic component by simply multiplying the subsurface temperature curve with a scaling constant \( \alpha \) (coefficient of thermal expansion) given by \( \alpha = (\Delta L/L)/\Delta T \), where \( \Delta L, \Delta T \) are, respectively, creep and temperature variations in some nonanomalous time interval (i.e., outside the shaded bands in Figure 3), and \( L \) is the creepmeter length. A mean scaling constant of \( 8 \times 10^{-6} \) per °C is calculated. This value is consistent with published coefficients of thermal expansion for soils and similar materials (CRC Handbook of Chemistry and Physics, 1962). A soil layer on top of a realistic contoured and heterogeneous crust is expected to sustain horizontal thermal expansion as suggested by the obtained value of \( \alpha \). Ben-Zion and Leary (1986) modeled this effect by assuming lateral variations in the source temperature signal and/or the response of the rock, with a scale length
that is controlled by the local topography. The XWR creepmeter lies in a gentle topographic swell with a radius of curvature $R \sim 100$ m. In such an environment, the horizontal thermal deformation of the upper soil is expected to be proportional to the induced vertical expansion. That is, if the creepmeter subtends an angle $\theta = L/R$, a thermally induced vertical change $\Delta R$ creates a horizontal expansion $\Delta L = (L/R)\Delta R$.

The hypothetical tectonic creep curve is constructed with the constraint that it is composed of the fewest number of events and the fewest number of straight line segments per event, and still produces a credible fit to the observed creep when added to the thermoelastic component. Any attempt to model the creep anomalies with more complex shapes (e.g., exponentials representing damped responses to
impulses) is probably not justified given their uncertain origin. Six assumed creep anomalies are needed to provide a good fit to the observed creepmeter record, consistent with the correlations identified in Figure 3.

The hypothetical tectonic creep curve is plotted again in the bottom panel of Figure 4 together with the Phelan water level curve (inverted from Fig. 3). The onsets of the assumed creep anomalies tend to occur at or before the times of the major water level excursions, varying from well in advance of the corresponding water level excursion for the first and last events to near coincidence for the middle four events. We conclude that the creep events lead the water level excursions by weeks to days, and that there is a statistically significant time correlation between the assumed series of creep events and the water level excursions.

On the basis of our data, it is impossible to assess the probability that the water level and creepmeter records both have six or so major fluctuations in a 31 month period. However, if it is accepted from inspection of Figures 2 to 4 that six distinct anomalies occur in each of the creepmeter and water level records during the covered period, the probability of coincidence between two independent anomaly sequences is simple to compute using a familiar analogy. Suppose there exist $N$ identical bins and $M < N$ bins are occupied. We calculate the probability that placing a second set of $M$ items in the $N$ bins will result in a final state of all originally occupied bins having two and only two items. Since each item placement is independent of all other placements, the cumulative probability is the product of all individual probabilities, giving

$$P = \frac{M}{N} \cdot \frac{M - 1}{N} \cdot \ldots \cdot \frac{1}{N} = \frac{M!}{N M^M}.$$  

$P$ is a strong function of $M$ and $N$. In our case $M = 6$, standing for the 6 anomalies in each time series. The value of $N$ is given by the total time span of the recorded data divided by the duration of a deformational event. Suppose first that the duration of a deformational event is 3 months and that water level and creepmeter anomalies are coincident if they occur in the same 3-month interval. In 30 months, there are $N = 10$ such intervals or bins. The probability that six water level and six unrelated creepmeter anomalies occur in the same 3-month intervals is $(6/10) \cdot (5/10) \cdot (4/10) \cdot (3/10) \cdot (2/10) \cdot (1/10) \sim 7 \cdot 10^{-4}$. Alternatively, suppose the first and last creepmeter anomalies are considered as not coinciding with the nearest water level anomalies and that the remaining four creepmeter deviations occur within the same 1-month intervals (bins) as the nearest water level events. Then $M = 4$, $N = 30$, and the probability for this case occurring strictly by chance is $(6/30) \cdot (5/30) \cdot (4/30) \cdot (3/30) \sim 4 \cdot 10^{-4}$. In either case, even in the absence of any probabilistic weight that the two event series have something in common, the chance of random overlap of the two sequences is very small.

Figure 5 compares the Phelan water level data of Figure 3 (top) with the PUBS borehole strain record (bottom) for the same time interval. The anomalous zones of Figure 3 are superimposed on the water level and dilatational data. The water level anomalies are clipped for better vertical resolution of the signal in the nonanomalous time intervals. We observe that excluding the rapid water level anomalies there is a clear similarity between the trends and long-term variations of the Phelan water level and PUBS dilatational records. The correlation implies that the Phelan water level monitor and PUBS dilatometer are stable instruments that faithfully record the regional long-term strain variations.
In addition to the long-term variations, the Phelan well experiences episodes of rapid strain events that are also sensed by the XWR creepmeter. Strain in such episodes can be absorbed by the compliant material sampled by the Phelan well and XWR creepmeter, therefore passing undetected by the PUBS dilatometer. We note that as a policy dilatometers are installed in locally stiff or competent rock. The PUBS record, however, shows its own correlation with the sequence of short-term events seen in the water level and creepmeter records. An examination of the PUBS signal shows that it may be roughly approximated by a sequence of straight line segments. It appears that the changes in the slopes of such discontinuous segments correlate with the anomalous zones of Figure 3 which mark deviations between the slopes of the creepmeter data and the subsurface temperature.

The correlations over tens of kilometers between the Phelan water level and PUBS dilatational data add credibility to the assumed correlations (over a similar distance) between the anomalies in the Phelan water level and XWR creep records. We, thus, suggest that both the Phelan water level monitor and PUBS dilatometer record the regional long-term variations, both the XWR creepmeter and Phelan water level monitor respond to regional rapid strain events, and that the anomalous
zones sensed by the XWR creepmeter are averaged out in the data of the PUBS dilatometer.

From Figures 3 and 4, it is seen that for anomalies 1, 5, and 6 the onset of the creep events preceded the respective water level excursions by 2 to 4 weeks. In particular, the sharp change in the slope of the creep record that leads the last water level excursion may be considered a preseismic signal to the July 8, 1986 North Palm Springs earthquake. Although there is nothing obvious in the creep and/or water level records to indicate that an earthquake would occur during this particular creep/water level episode, nor is there any indication of which fault bounding the Mojave block would sustain an earthquake, the May 1986 creep/water level event appears to be a partial precursor to a significant earthquake along a fault which did indeed affect the Mojave block.

DISCUSSION

The characteristics of the coincident creep and water level anomalies at XWR and Phelan can be used to develop a conceptual model of fault zone structure and block tectonics of southern California. The data are from two sites, 35 km apart, in the near-field of the locked Mojave segment of the southern San Andreas fault (Fig. 1). The last anomaly corresponds in time with the $M_L = 5.6$ North Palm Springs earthquake of July 1986 on the San Andreas fault, 120 km to the southeast. Leary and Malin (1984) reported similar pre- and co-seismic signals in the data from the same creep site in association with the 1979 Homestead Valley earthquake, which was within the Mojave block. Their anomalies also registered as water level excursions at points along the Los Angeles and Colorado River aqueducts located in the near field of faults bounding the Mojave block. In all cases, there is no clear environmental source for the reported anomalies. Local site or instrumental effects can be excluded since the anomalies are recorded by physically different and widely separated instruments. Noteworthy is the fact that none of these anomalies were recorded at the Pinon flat strain observatory (King et al., 1988; Agnew, personal communication). Also, the rapid anomalies reported in the present paper were not recorded by the PUBS dilatometer.

A qualitative model of crustal structure, which is consistent with the broad deformational data set containing both our observations and those from Pinon flat and the PUBS dilatometer, is shown in Figure 6. The model, modified from King (1986), consists of strong crustal blocks separated by a weak, vertically heterogeneous, fault zone. At seismogenic depths the fault zone contains relatively strong asperities along which the blocks are locked and strain accumulates. These asperities control the regional strain pattern. Failures at the asperities (i.e., earthquakes) change the regional strain pattern and are expected to be recorded by all strain-sensitive instruments within the range of the linear elastic displacement field. Overlying the seismogenic region, the fault zone consists of a shallow weak compliant material in which instruments such as the XWR creepmeter and Phelan water level monitor are located. Since this upper zone is weaker than the deeper seismogenic zone, it is expected to fail (perhaps with nearly spatial and temporal randomness) during regional strain build-up or release before seismic rupture at depth occurs. However, failure in the shallow weak material (e.g., creep) has negligible effect on the regional strain budget, and thus such occurrences are expected to be observed only by monitors located directly in weak compliant regions of the fault zone.
There is considerable evidence suggesting that the San Andreas fault is a weak crustal feature (Henyey, 1968; Brune et al., 1969; Henyey and Wasserburg, 1971; Lachenbruch and Sass, 1988; Li et al., 1988; Shamir et al., 1988) and that the upper crust is weak, at least in the vicinity of fault zones. A common feature of California seismicity outside geothermal areas is the absence of seismicity in the upper 3 to 5 km of the crust. Presumably, the outer crust is too weak to store seismic levels of elastic stress to the extent possible by the underlying seismogenic zone. In addition, Marone and Scholz (1988) concluded from laboratory experiments that shallow fault zones would favor stable sliding over catastrophic earthquake failure. Their conclusion is based on the lack of observed velocity weakening in granular materials characteristic of shallow fault zones. Finally, most evidence for southern California suggests that crustal deformation anomalies, when observed, tend to occur on major faults (Allen et al., 1972; Alewine and Heaton, 1973; Leary and Malin, 1984; Bilham and Williams, 1985).

Other evidence points to a weak uppermost crust. Seismicity studies along the Mojave sector of the San Andreas fault (Sauber et al., 1983; Jones, 1988) show a diffuse distribution of epicenters and a mixture of faulting mechanisms. In particular, thrust mechanisms are common, indicating that nonvertical slip planes exist locally in the crust. Detailed seismic reflection data from the Cajon Pass deep drill site reveal abundant horizontal to subhorizontal reflectors to depths of 3 to 5 km (Leary et al., 1988). To the depths these reflectors were drilled (3.5 km) petrologic,
core, and geophysical logs indicate that the seismic reflectors are rich in fractures. Thin-section analysis of core from Cajon Pass has shown a pervasive fabric of microfractures (Wang and Sun, 1990; Blenkinsop, 1990). Grains shattered by shearing show little sense of rotation among the fragments (Blenkinsop, personal communication) suggesting that extensive shearing has occurred over time, but that slip has been a slow process (creep) rather than a rapid one (seismic slip).

Figure 7 shows a compilation from Heaton (1990) of slip distribution during six earthquakes, obtained by forward modeling and inversion of the seismic data. In all cases, it is clear that the amount of seismic slip diminishes toward the earth’s surface. Moreover, it is well known that in most earthquakes the rupture front does not reach the surface of the earth. King (1986) noted that usually only $M > 6$ earthquakes, with more than 1 m of slip at depth, form surface breaks. Since in the long term the amount of surface slip should equal the slip at depth, it follows that slip in the form of creep must take place in the weak shallow material during intraseismic intervals.

Model computations showing failure in near-surface zone overlying a locked, shear loaded, vertical fault have been given by Tse (1985) and Tse and Rice (1986). The computations assume depth variation in (rate and state dependent) frictional sliding constitutive law rather than a pervasively weak upper crust. An example of calculated slip distribution as a function of depth is illustrated in Figure 8. The example shows a 0.5 m of near-surface creep that precedes the catastrophic failure at depth. This is similar to what we observe along the periphery of the Mojave block. The relatively strong, deep seismogenic zone is capable of transmitting strain fields originating from elastic dislocations in the crust, over relatively long distances, as required by the Pinon Flat observations of co-seismic strain from the Homestead

![Figure 7](image_url)

**Fig. 7.** Slip distribution on earthquake rupture surfaces modified from: Coyote Lake, California (Liu and Helmberger, 1983); Imperial Valley, California (Hartzell and Heaton, 1983); Morgan Hill, California (Hartzell and Heaton, 1986); Borah Peak, Idaho (Mendoza and Hartzell, 1988); Michoacan, Mexico (Mendoza and Hartzell, 1989); North Palm Springs, California (Hartzell, 1989).
Valley earthquake (Wyatt, 1988; King et al., 1988), while low stress shallow fault zone slip (possibly precursory) is also permitted.

The close temporal correlations between the six creep and water level anomalies over a period of nearly 2 yr at sites located 35 km apart near the San Andreas fault zone suggest that these events are related to common tectonic activity to which the fault zone is responding. The culmination of the anomalous creepmeter and water level activity with the magnitude 5.6 North Palm Springs earthquake further suggests that the response to the common tectonic activity extends at least as far south along the fault as the North Palm Springs epicenter. Long distance interaction (of several hundred kilometers) between earthquake epicenter region and water level activity is commonly observed (Roeloffs, 1988). A sequence of anomalous near-surface displacements at the XWR creep site and elsewhere on the San Andreas and Garlock faults preceding the Homestead Valley earthquake of 1979 (Leary and Malin, 1984) provides a close parallel to the present sequence of deformation anomalies. Also, episodes of aseismic surface slip triggered by, or coeval with major southern California earthquakes, including the 1986 North Palm Springs event, have been reported on the southernmost San Andreas fault by Sieh (1982), Louie et al. (1985), and Williams et al. (1988). Louie et al. attributed these episodes of creep to regional (block-wide) strain processes similar to that advanced by our hypothesis.

King et al. (1988) have objected to the association by Leary and Malin (1984) of the 1979 creep activity at the XWR site with the 1979 Homestead Valley earthquakes. Their objection follows from an assumption that the only failure associated
with an earthquake must be on the fault patch that is about to rupture. They argue that, if the 1979 XWR precursory creep steps are regarded as strains in an elastic half-space that originate as preseismic displacements at the site of the Homestead Valley rupture, they should have been seen at the Pinon Flat strain observatory (Fig. 1). Since the co-seismic strain step was seen at Pinon Flat, but not the precursory strain reported by Leary and Malin at XWR, King et al. concluded that the XWR creep steps are unrelated to the Homestead Valley earthquake.

According to our model, the reported anomalies are not due to elastic strains originating at distant hypocenters. With a regional stress field acting across the cluster of blocks in southern California, the blocks seek accommodation at their weak boundary faults. In 1979 the Mojave block failed at an internal zone of shear weakness. In 1986, the block failed again, this time at its southern boundary. In both cases, seismic failure was accompanied by precursory regional tectonic accommodations which, in turn, initiated small surficial strain events at the loci of greatest crustal weakness—the near-surface of major faults. We suggest that the block accommodations develop too slowly to be detected by strain instruments above the environmental noise and the long-term instrumental drift (Agnew, 1987). The near-surface creep and water level events, however, are local weak crust failure phenomena which, being concentrated in time and space, are relatively easy to detect.

**CONCLUSIONS**

We suggest that an appropriate short-term tectonic model for southern California is that of strong (nondeforming) crustal blocks shifting at weak (easily deformed) fault zones. A multiple block model for southern California is supported by numerous geodetic and geologic studies (e.g., Garfunkel, 1974; Bilham and Beavan, 1979; Hill, 1982; Bird and Rosenstock, 1984; Hornafius et al., 1986; Nur and Ron, 1987) and could serve as a plausible means of relating deformatonal events that are separated by large distances. It appears that quantitative studies aiming at modeling earthquake precursory phenomena should at the very least include the model elements of Figure 6. Lateral heterogeneity is necessary to constrain the earthquake deformation zone while vertical heterogeneity is needed to connect deep source phenomena and shallow observations in the outer crust.

Our study suggests that compliant regions of fault zones experience correlated rapid strain episodes. Such events may be the result of minute adjustments along block boundaries, perhaps during time of accelerated strain build-up. Comparison between data measured by different instruments located along the fault zone can be used to separate such signals of tectonic origin from environmental, instrumental, or local site effects. Such measurements should improve our understanding of fault mechanics and are expected to contribute to earthquake prediction studies.

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**University of Southern California**
**Department of Geological Sciences**
**Los Angeles, California 90089-0740**

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