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Methods for prediction and evaluation of tidal tilt data from borehole and observatory sites near active faults

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Tilt has been measured continuously at tidal sensitivity in borehole and observatory sites in the San Francisco Bay region, California. These sites, within a few kilometres of a major fault and the Pacific Ocean, are part of an extensive network measuring strain and microseismicity. Static response of the Presidio site to ocean loading at the M_2 frequency best fits a finite-element model with lower shear modulus in the San Andreas fault zone than in adjacent material at the same depth. The Presidio tilt data exhibit a secular trend less than 3 μrad/year superimposed on local earthquake and meteorological effects. On two occasions earthquakes ($M_b > 4.3$) occurred within 55 km of a station and were preceded by anomalous tilt accumulating to 1 μrad over several days with an accelerated rate of tilt a few hours before the events. The root-mean-square (r.m.s.) difference for two stations of 25 km apart for 700 h before and after one of these events was 5×10^{-8} and 2×10^{-7}, respectively. A similar r.m.s. difference was observed before and after a larger ($M_b > 5$) but more distant (180 km) earthquake from the same two stations. This latter event did not, however, exhibit the extreme linear slope (10^{-9} rad/h) of the two earlier earthquakes. Although such anomalies can be correlated with meteorological activity over short periods of time, they do not correlate for periods approaching one month. A transfer function derived during a period when there were no local earthquakes can be used for calculating tilt response to surface loading from telemetered meteorological and tilt data. These results can then be input for a prediction beyond the data, and the error in prediction monitored as a final output for instrument performance and potential earthquake hazard.

Introduction

Tilt measurements at tidal sensitivity in borehole and observatory sites in the San Francisco Bay region, California are made to gather data on three types of phenomena: (1) harmonic tilts associated with tidal deformation that may be perturbed by major structures such as the San Andreas fault system; (2) secular tilt that may be associated with tectonic activity, and (3) surface noise of meteorological and oceanic origin. The signals associated with (1) and (2) are quite small compared with the Earth's response to (3). Therefore, in order to investigate (1) and (2) we have developed techniques to separate the responses of the Earth's surface to loading of meteorological and oceanic origin from loading which may be associated with earthquakes and other tectonic processes.

The purpose of this paper is to describe briefly the current analysis scheme for near-real-time processing of tilt data and to discuss a few results from the analysis of these data recorded over the past 3 years. The instruments used in this investigation are described by Wood & Allen (1971) and Allen, Wood & Mortenson (this volume). Locations of the instruments and the earthquakes studied are shown in figure 1.

Monitor M_2 line for anomalous fault strength

Variation in the amplitude and phase of the stable M_2 line has been chosen as a potential indicator of anomalous variations in the strength of the fault. The tidal energy is extracted from the data using a least-squares program that simultaneously fits a prescribed polynomial and the

12 most energetic lines of the tidal spectrum to the raw data. The window of time is arbitrary but is usually the most recent 720 h. A similar analysis is made on the theoretical tidal data with a window of the same length and origin time. The amplitude of each of the extracted lines is normalized by the amplitude of the corresponding line derived from the theoretically generated tides. Routine analysis of such data has shown that the r.m.s. deviation for these normalized lines exceeds 4 % except for the principal lunar semidiurnal and diurnal lines M_2 and O_1, respectively. In general, those lines with greatest r.m.s. deviation reflect a contamination by meteorological phenomena driven at solar frequencies. This is not unusual considering the shallow depths of our sites.

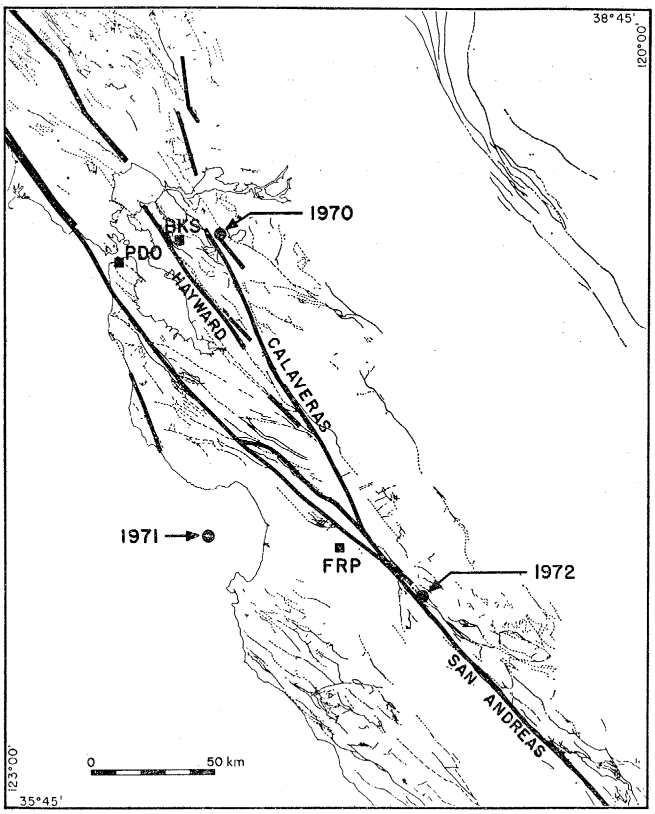

Figure 1. Map of central California showing major active faults (heavy lines), minor or inactive faults, tiltmeter sites (■), and epicentres (●) of principal earthquakes of 1970, 1971 and 1972 studied in this report.

The San Andreas fault is within a few kilometres of the Pacific Ocean throughout most of central and northern California. A detailed study of the effects of ocean tidal loading on the surface measurements of earth tides and tilts in the San Francisco Bay region indicates that the San Andreas fault may have perturbed the response of the tilt site to ocean loading (Wood 1969). The Boussinesq model used in that investigation was unable to account for either the known contrast in rigidity values occurring across the San Andreas fault or the character of the fault zone. The San Andreas fault neatly divides San Francisco Bay from the continental shelf, and most of the tidal loading occurs in these two areas (84 % of the load is within the first 150 km of the station assuming a correction radius of 1000 km). The Presidio station is east of and approximately 10 km from the San Andreas fault zone.

Because the residual tilt vector derived from the earlier 'faultless' Boussinesq model had a large component orthogonal to the strike of the fault, but with a phase suggesting that the effect of bay loading was more pronounced than the Pacific Ocean load, we decided to use a plane-strain finite-element modelling technique that would allow variations in the stiffness of the fault. Figure 2 is a cross-section of the crust and mantle along a line through the Presidio station and orthogonal to the strike of the fault trace. The Lame constants prescribed for each cell were derived from studies of the seismic velocity models of Stewart (1968) and the work he referenced. The Poisson ratio was set at 0.25 and density derived using the Nafe–Drake curves. The surface load corresponds to the amplitude of the M_2 ocean and bay tide with phase adjusted to the zero hour of the PDO station. The width of the fault zone was arbitrarily set at 3 km. We chose this width because Mayer–Rosa (1972), considering the measured seismic delay times (about 0.4 s) across some segments of the fault system, also characterized by a systematic shift of earthquake epicentres off the fault, concluded that the fault must be connected to a vertical low-velocity zone at least several kilometres wide, extending into the lower crust.

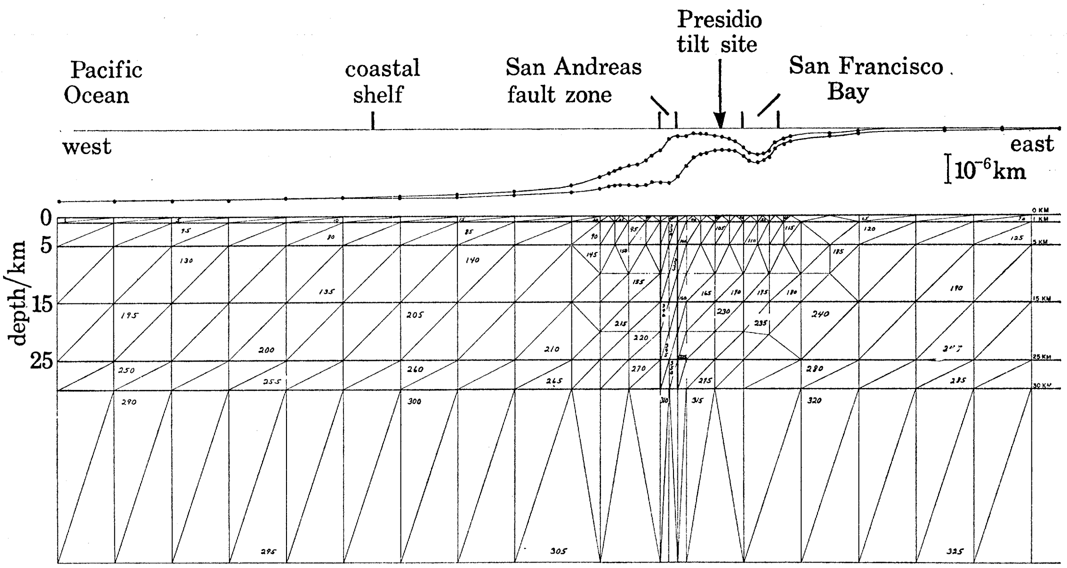

FIGURE 2. Two-dimensional finite-element profile striking N45°E through the Presidio station. The two response curves are the vertical nodal displacements (scale 10^{-6} km) at the surface due to the static ocean and bay load derived at the M_2 tidal frequency. The San Andreas fault is represented as a narrow vertical-line-mesh zone less than 10 km west of the Presidio site. The lower response curve assumes each fault element to be identical in elastic properties to adjacent elements outside the zone. The upper curve results from a one order of magnitude drop in the shear modulus of the fault zone.

The two curves in figure 2 are the static vertical response of the surface nodal points to the M_2 load. The lower curve is based on the assumption that no gouge zone exists and the elements in it are therefore identical with those adjacent to the zone at the same depth. The upper curve results when the fault zone shear modulus is one order of magnitude less than the shear modulus of adjacent elements at the same depth. The amplitude and phase of the upper curve more closely account for the anomalous M_2 residual tilt vector at the Presidio site. This two-dimensional model is still considered insufficient to adequately describe the response of the surface due to water loading on such a complex three-dimensional site as the Presidio. But these data and this model do suggest that differential monitoring of the M_2 line for several close pairs of instruments across the San Andreas fault zone holds promise for continuous monitoring of variations of fault strength along the fault for periods ranging from transient to secular. If we are cursed with such a fault, then we are blessed with the Pacific Ocean as a large and 'constant', if imperfectly understood, forcing function on one side of the fault.

DERIVATION AND ANALYSIS OF RESIDUAL TIME SERIES

A harmonic time series is derived by reconstructing in the time domain the wave form derived from the amplitude and phase of the best fitting tidal lines. The residual time series is obtained by differencing the harmonic series from the raw time series. This residual time series 'drift' is the convolution of effects due to the (*a*) long-term mechanical and electrical drift of the instrument, (*b*) response to local and regional tectonic activity, and (*c*) the influence of seasonal and transient meteorological changes on the local site.

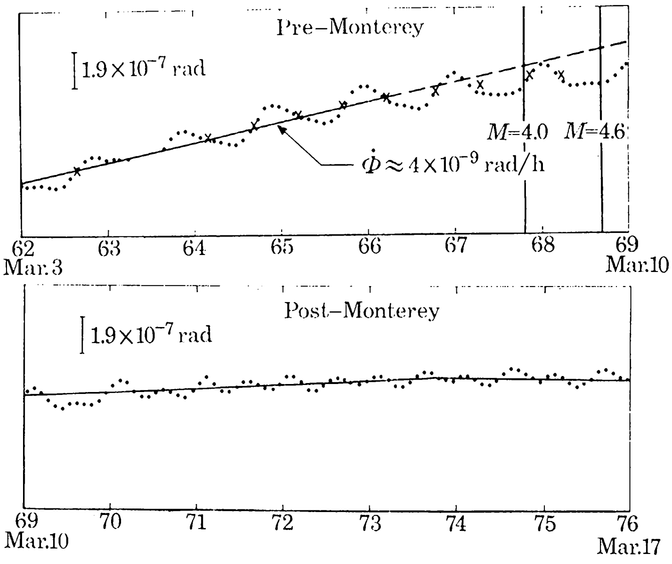

FIGURE 3. Digital plot (hourly) of raw tilt data from Fremont Peak site (FRP) before and after the Monterey Bay quakes.

Limits can be set on the magnitude of problem (*a*). Previous papers (Wood & Allen 1971; Allen *et al.*, this volume) have discussed the details of the calibration procedures employed for the mercury-tube tiltmeters. The r.m.s. deviation of this calibration has not exceeded 3 % for the 5 m along instruments for the past 3 years' operation. Currently no corresponding *in situ* calibration procedure exists for the borehole instruments, so this problem cannot be isolated from other elements of drift. The remainder of this paper discusses the separation of (*b*) in the 'drift' using data exclusively from long-base mercury-tube instruments.

Anomalous tilts that bracket the occurrence time of local earthquakes are observed to exist for periods up to 1000 h in the drift part of the data for the three largest earthquakes in the region from 1970 through September 1972.

A remarkably linear drift in the residual time series for periods to 1 month preceded the largest earthquakes in the San Francisco Bay region in 1970 and 1971. On 8 and 9 March 1971, earthquakes of magnitude 4.0 and 4.6 occurred in the Monterey Bay area nearly in line with the long-base mercury-tube tiltmeter installed at Fremont Peak some 50 km east of the epicentres. A digitized record from the Fremont Peak tilt site was plotted for approximately 140 h before and after these two events (figure 3). The X marks on the straight line of the pre-Monterey record represent the mean of the diurnal tidal range and show the remarkably linear slope of the drift curve. It can be recognized that the tidal residue starts to deviate from this linear trend about 15 h before the first event, and after the second event the linear trend approaches zero slope.

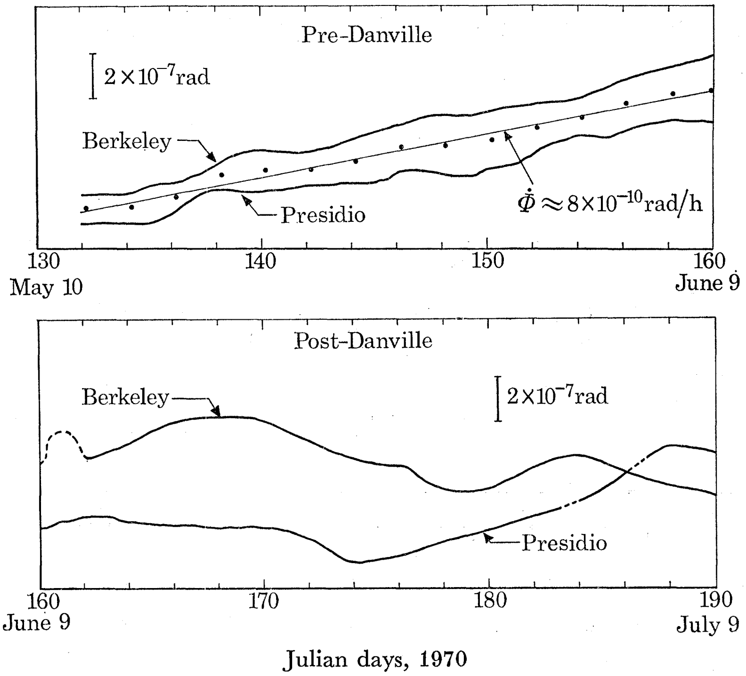

FIGURE 4. Plot of residual tilt data (tides removed) from Berkeley and Presidio tilt sites before and after the principal Danville events of 12 June 1970 (after Wood & Allen 1971).

The premonitory character of the pre-Monterey record is marginal, but the gross change in slope is probably related to the earthquake and not to any ageing process associated with emplacement of the meter. On two separate occasions the instrument was deliberately perturbed with a 30 μm displacement of the calibration jack, and at no time did this procedure obviously perturb the secular drift of the instrument.

The Danville earthquake(s) of 1970 was preceded by an anomaly quite similar to the Monterey event, but two instruments were operating within 50 km of the epicentre. In a plot of the output of these two stations (tides have been removed), the average of the difference of the two stations suggests again a constant rate of change of tilt of approximately the same value as that determined for the Monterey sequence (figure 4). The postquake plots show a somewhat reduced average slope value, although the post-Danville record is much noisier than the post-Monterey record. This sequence has been discussed elsewhere in more detail (Wood & Allen 1971), and it suggests that the magnitude of the constants in the polynomial fit of the data be monitored as indicators of anomalous tilt preceding the earthquake. Checking for anomalous tilt would amount to checking for extreme linear drift for prolonged periods climaxing with an accelerated microtilting not correlatable with any other measurable parameter.

Preliminary coherence test

The two types of anomaly discussed were sought in the largest event of early 1972 (Bear Valley, 24 February), i.e. constant rate of change of tilt and accelerated tilt shortly before the event. Neither of these phenomena was found on the records bracketing the earthquake from the same sites (Berkeley and Presidio), possibly owing to the great distance from the epicentre, which was about 180 km south of the stations but on the same fault. The closest tiltmeter (Fremont Peak) was 35 km northwest of the epicentre, but it was not operating properly at the time of the event.

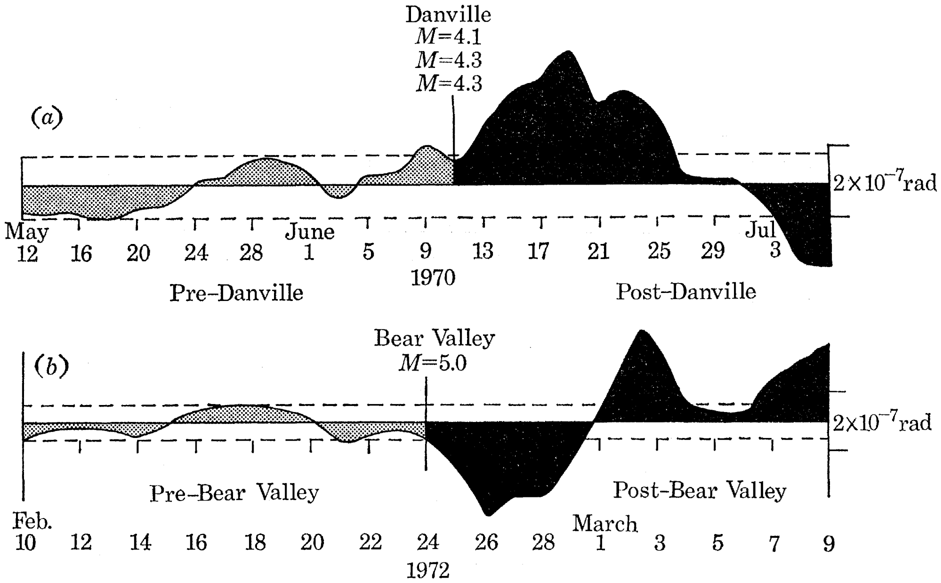

Figure 5. (*a*) Coherence plot of tilt difference, Presidio minus Berkeley. Time line brackets occurrence of Bear Valley earthquake, 1972

(*b*) Coherence plot of residual tilt difference, Presidio minus Berkeley. Time line brackets occurrence of Danville sequence of 1970.

Unusual coherence in the tilt differences (less than 2×10^{-7} rad) was observed for the two distant stations approximately 1 month before the event and a lack of coherence much greater than one Earth tide was found for a period of at least 1 month after the event. The preliminary coherence test is performed simply by taking the algebraic difference of the residuals between two stations. The coherence curves from the Presidio and Berkeley stations that include the Bear Valley and Danville events are presented in figures 5*a* and *b* respectively.

It is important to note that coherence between these two sites is unusual for periods exceeding 5 days. However, passage of local weather fronts through the area can impress comparable coherencies on these sites for shorter periods of time. The emphasis in these preliminary data is on the *contrast in coherency* for equal periods of time before and after each of the major events of 1970, 1971, 1972. The width of the time window for each premonitory anomaly has been maximized to that point concident with the onset of coherence. Incoherence is the rule, coherence the exception. A more detailed paper will examine the statistical significance of these observations.

Prediction of tilt due to rainfall

Of all the surface-loading phenomena, the effect of rainfall on tilt measurements is the most extreme and most difficult response to extract from the raw data. While the anomalous tilts we have observed that are related to ocean loading and earthquake activity are of the order of the mean daily range (10^{-7} rad) of the theoretical earth tide predicted for this lattitude, the tilt that appears to be related to rainfall has a seasonal range of 2×10^{-6} rad.

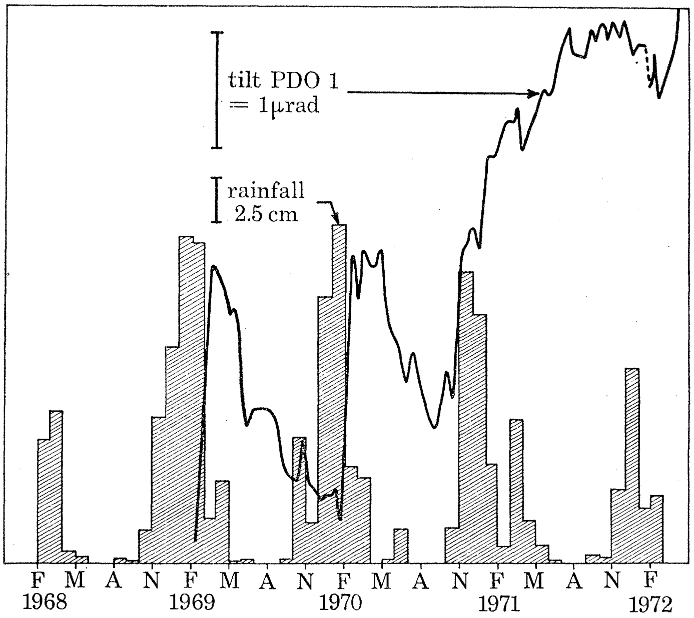

Figure 6. Histogram of monthly rainfall superimposed on residual tilt from PDO 1 instrument in Presidio vault.

Our best information on this problem is summarized in figure 8, which relates tidal tilt data (tides have been removed) from the Presidio (PDO 1), which has the longest continuous record of all our instruments, to rainfall, suggesting a strong correlation between rainfall and tilt before February 1971. A straight-line approximation of the drift indicates a value less than 3 μrad/year. The overall response seems to be sufficiently cyclic that given the rainfall, tilt response can be derived by a transfer function approach. The function so derived is novel to the instrument and site but if it remains time invariant, and if we know the current rainfall, we can predict the response several days into the future. This function must, of course, be derived during earthquake-free periods; for this reason the transfer function for PDO 1 was derived from data before February 1971. The anomalous tilt steps recorded during February 1971 (the month of the San Fernando earthquake) remains as yet unexplained.

Conclusions

Transient signals that exist in the harmonic and secular drift parts of tilt data measured in shallow sites near active faults of central California may be related to transient changes in the tectonic régime of the region.

The magnitude and duration of some of these signals lie within the Earth tide spectrum. Because the tidal forcing function is the most predictable input to which the earth and its fluid envelope respond, and because an extensive segment of the San Andreas fault system is near the Pacific Ocean, two valuable experiments can be performed, both of which have important bearing on earthquake prediction in California. The first experiment is to study the influence of the San Andreas fault zone in perturbing the response of a tilt site to ocean loading at a particular frequency. In order to fit the observed data, two-dimensional finite-element computer models of the tilt response to the ocean load input require a fault zone that is weaker in shear modulus than material adjacent to it. The results from these modelling studies are still considered preliminary but sufficiently valid to suggest the second experiment: monitoring the difference in the output of instruments on opposite sides of the fault at the previously studied frequency as a means of monitoring in real-time the dynamic behaviour of the fault zone. The differential response of the fault zone to ocean loading may vary significantly from the long-term secular value for the short periods of time bracketing a moderate-sized local earthquake.

Anomalous tilts that bracket the occurrence time of local earthquakes are shown to exist for periods up to 1000 h in the drift part of the data. The Danville (1970), Monterey (1971), and Bear Valley (1972) anomalies bracket the occurrence times of the largest earthquakes that occurred within the N.C.E.R. northern California microseismic network over the past 3 years. These two principal types of anomalies can be associated with meteorological phenomena. Unusual coherence between instruments 25 km apart can be induced over short periods of time (1 to 2 days, typically) by passage of local weather fronts through the area. However, the duration of the coherency (up to 1 month) preceding the Danville and Bear Valley earthquakes and the abrupt loss of coherency immediately following these events mitigates even further the very poor correlation with meteological activity. The second type of anomaly, accelerated microtilting preceding the event, has also been produced by local rainfall effects. Of all the surface-loading phenomena, the effect of rainfall on tilt is the most extreme and difficult response to extract from the raw data. The overall response, however, seems to be sufficiently cyclic that given the rainfall, the tilt response can be derived by a transfer function. If this function remains time invariant, then prediction beyond the data can be made with a least-squares predictive error filter after the predicted response to rainfall has been removed. The difference between predicted and observed residual data may be a measure of what cannot be predicted from any known input – namely response of the site (region) to changing tectonic conditions that may or may not lead to an earthquake.

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REFERENCES (Wood *et al.*)

Mayer-Rosa, D. 1972 *Abstracts with Programs, Geol. Soc. Am.* **4**, 195.

Stewart, S. W. 1968 In *Proceedings of Conference on Geologic Problems of San Andreas Fault System*, **11**, 218–230. Stanford University Publications in the Geological Sciences.

Wood, M. D. 1969 Ph.D. thesis, Stanford University, California.

Wood, M. D. & Allen, R. V. 1971 *Bull. seism. Soc. Am.* **61**, 1801–1809.