Deadline for Nominations: 15 September 1977
AAAS–Newcomb Cleveland Prize: Contest Year Is Nearly Over

The deadline for nominations of papers for the AAAS–Newcomb Cleveland Prize is fast approaching. Readers are invited to nominate papers published in the Reports section of *Science* from 3 September 1976 to 26 August 1977. The prize of $5000 and a bronze medal is now given annually to the author of an outstanding paper that is a first-time publication of the author's own research.

Nominations must be typed and the following information provided: the title of the paper, issue in which it was published, author's name, and a brief statement of justification for nomination. Nominations should be submitted to AAAS–Newcomb Cleveland Prize, AAAS, 1515 Massachusetts Avenue, NW, Washington, D.C. 20005. Final selection will rest with a panel of distinguished scientists appointed by the Board of Directors.

The award will be presented at a session of the annual meeting at which the winner will be invited to present a scientific paper reviewing the field related to the prizewinning research. The review paper will subsequently be published in *Science*. In cases of multiple authorship, the prize will be divided equally between or among the authors; the senior author will be invited to speak at the annual meeting.

Reports

Relation Between Earthquakes, Weather, and Soil Tilt

Abstract. *Two years of local earthquake, temperature, and rainfall data taken near a tiltmeter site were used in a study of the numerical relation between these phenomena and the recorded tilt response. A least-squares shaping and predictive error filter approach was used. The relations were ranked in part according to the root mean square (r.m.s.) error of fit across the entire sample space. The tilt data with an annual range of tilt of approximately 10 microradians were fitted to the combined weather data of temperature and rainfall with a 0.75-microradian r.m.s. error. The best fit of earthquakes to these same tilt data is the subclass of events with magnitude* (M) > 2.5 *within 30 kilometers of the tilt site. The filter that mapped earthquakes to tilt yielded a 1.03-microradian r.m.s. error. The most unusual tilt anomaly over the entire 2-year period has the best fit of rainfall to the data for any single month of the entire data set. This unusual anomaly was the basis of an erroneously predicted earthquake* (M ~ 5). *These data indicate that if there are premonitory earthquake signals, they are buried in local meteorlogical noise. Separating an earthquake anomaly from the response to surface phenomena becomes more difficult as the earthquake anomaly lead time approaches the rise time of the soil to weather and seasonal variations.*

The essential problem of earthquake prediction is to identify and monitor those physical characteristics of the failure process that uniquely foretell the magnitude, location, and the origin time of an earthquake. Identification of these parameters has tended to be heuristic. However, evidence is steadily accumulating toward the support of a sound physical basis for earthquake prediction. Models of the failure process are becoming sufficiently detailed to predict the spatial and temporal character of geophysical results found by measurements conducted in the epicentral region and thus to allow effective testing of these models against observations.

A popular instrumentation strategy for earthquake prediction is to deploy large numbers of relatively inexpensive tiltmeters, strainmeters, creepmeters, and other geophysical instruments (*1*). Most of these instruments are implanted at shallow depths in soil regimes near active faults. In some cases the sites are within the fault zone. Despite careful site selection, site preparation, and instrument emplacement (*2*), instabilities associated with the response of the soil to a variety of meteorological events can overwhelm the response of the site to premonitory earthquake signals of small events [magnitude (M) ≤ 5]. This is a particularly difficult problem if the rise time and duration of a meteorologically induced effect are comparable with the lead time signature for an earthquake.

Of all the meteorological variables, rainfall effects can be the most easily confused with anomalous earthquake precursors of small events because of the episodic nature of both phenomena. In an area of extremely low annual rainfall ($R < 20$ cm per year) a sudden burst of rain ($R \sim 1$ cm) has produced recognizable effects for more than 2 months duration with a lag between the input and response of the order of days (*3*). In areas of moderate to heavy rainfall ($R > 40$ cm per year), such as central California, detailed description of the tilt response to separate bursts of rainfall with separation time less than 2 months is difficult to achieve. The impulse response of the site to a spike of rainfall is different for different times of the year simply because the soil system has different properties at the time of each rainfall (*4*).

Figure 1 illustrates the variability of site response to rainfall at the Presidio site in central California. Clearly the instrument is responding to rainfall, but the incompleteness of the rain-tilt correlation suggests other influences as well. Early seasonal rains occur when the site is still in a state of partial desiccation after the annual 6-month period of no rain.

Other instruments besides tiltmeters respond to rainfall. Furthermore, responses differ from site to site and instrument to instrument. Figure 2 is a collection of geophysical data from a set of instruments sited along the central section of the San Andreas fault. They all exhibit anomalous behavior over the time bracketed by the dashed lines; this time was the only period of rainfall within a month (5). All these data appear to show a response during this storm on many but not all instruments over a distance of some 200 km from Fremont to Cholame Valley. These data suggest that the response was due to widespread rain, not to widespread favorable conditions for local quakes.

Detailed case-by-case correlation of episodic rainfall, earthquakes, and all of the geophysical anomalies shown in Fig. 2 is not yet practical owing to the lack of the necessary data for all the variables at each site. In this report we must therefore consider a more restricted and preliminary approach to the relation of three phenomena at one site: weather (rainfall and temperature), earthquakes, and tilt. We explore correlations in a least-squares sense over the entire time span of the data rather than speculating on the cause-effect relation between any two of the phenomena over a very narrow range of time.

The tilt and earthquake data used are from a previous publication (6) on tilt precursors before earthquakes on the San Andreas fault. That report includes earthquakes, temperature, rainfall, and tilt data for three sites selected from 14 sites with tiltmeters operating at 0.1 μrad sensitivity. Because the cited report found no obvious dependence of tilt on rainfall, pressure, or temperature, we decided to test more sensitively the degree of dependence of tilt on these parameters for one of those three sites. The tilt data used in the cited report were smoothed to weekly means; our investigation used daily means for all inputs. Since weather was not recorded on site, closest rainfall and temperature stations were approximately 5 and 20 km, respectively, from the Libby tilt site (6). These data, although less than ideal, are the best available for that time period, and the data contain two tilt anomalies originally considered (6) premonitory to a local earthquake.

To test the relation between earthquakes, weather, and tilt as classes of phenomena, we employed the well-established least-squares shaping and predictive error filtering techniques from communications theory (7). We solved the Wiener-Hopf equations in discrete time with the use of Levinson's recursive method (8). Although we have used this technique extensively for prediction and interpolation of tidal tilt data (9), the application in this report is restricted to the special case of zero length prediction, that is, fitting. Simply stated, the procedure consists of finding a filter that will map one phenomenon into the other

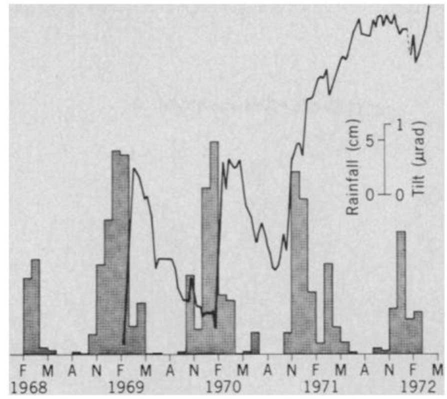

Fig. 1. Histogram of monthly rainfall (San Francisco) superimposed on tilt data. Tilt data were continuously recorded at a resolution of 10^{-8} radian and decimated to hourly samples, and earth tides were removed. Tiltmeter is a mercury tube–single component instrument sited in a bunker at the Presidio of San Francisco (4).

with root mean square (r.m.s.) error of the fit minimized across the entire sample space. The efficacy of the fitting process depends upon the correlatability of the phenomena. Although a high degree of correlation does not prove a cause-and-effect relationship between the two phenomena, in the absence of other information it is inferrred.

The r.m.s. error was tested as an overall criterion of significance. Clearly, fit should be perfect (r.m.s. error = 0) for two identical phenomena used as input and output, and this result was obtained.

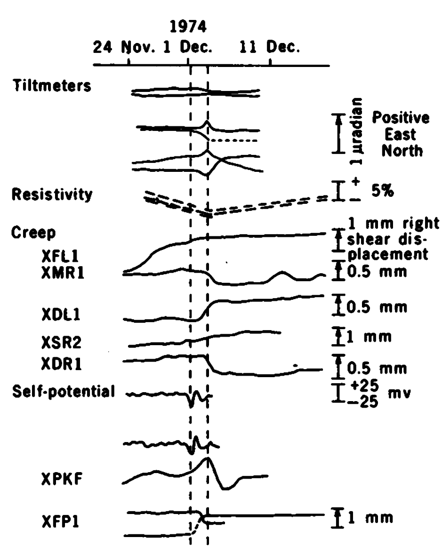

Fig. 2. These data are from a variety of geophysical instruments implanted in the soil near to or within the central California section of the San Andreas fault system. Maximum separation of sensors is approximately 275 km. The time bracketed by the dashed lines is the only period of rainfall for the time of the record shown (5). The abbreviations *XFL1*, *XMR1*, and so forth designate site names.

In another test, a time series consisting of random numbers was first multiplied by a factor that progressed, in several separate runs, from 0.01 to 1.0, and then was added pointwise to the tilt data. This procedure increased with each run the random appearance of the data set so treated. A filter function was derived to map rainfall as input into this "polluted" tilt output. The r.m.s. prediction error was found to increase linearly with the noise factor. Other tests were made in order to demonstrate that the method used to map rainfall onto tilt would not yield similar results with any two randomly chosen time series such as, for example, stock market data and tilt data.

The annual range of the Libby tilt data is approximately 10 μrad. We mapped subsets of the earthquake population into tilt and, for the sake of completeness, into rainfall in order to show that r.m.s. prediction error does indeed depend on the correlation between the phenomena used. Earthquakes were filtered according to magnitude ($M \geq 3.5$, $M \geq 3.0$, $M \geq 2.5$) in three separate runs, and according to distance from the tilt site (≤ 30 km) in another run. The r.m.s. errors obtained were 2.27, 2.36, 1.81, and 1.03 μrad, respectively. Earthquakes were mapped into rainfall with a r.m.s. error of 0.318 cm of rainfall output. It is, of course, impossible to compare previous tests directly with this one, since the units of measurements are different. The important point, however, is that the results are dependent on the degree of correlation between the time series used. However, detailed inspection of the earthquake-rainfall test leads us to conclude that in this case earthquakes did not trigger rainfall.

Correlating rainfall and temperature serially with tilt, we obtained a r.m.s. error of 0.81 μrad. Figure 3 is a summary of these data. Overall r.m.s. error was further reduced by about 7.4 percent by doubling the length of the data set from 1 to 2 years. When the rainfall or temperature alone was fitted to tilt over the 2-year period, the r.m.s. errors were 1.56 and 1.44 μrad, respectively. A lumped weather effect was obtained by mapping rainfall onto tilt, calculating the error of fit pointwise, and mapping temperature into this residual. Reversing the order of this operation changes minor details, but the overall r.m.s. error of fit remains unchanged. This lumped weather fit to the data produces the lowest r.m.s. error of 0.75 μrad over the 2-year period.

The tilt "bump" of April 1975, which is the most unusual anomaly over the entire 2-year period, was considered by Raleigh (10) to have been premonitory to

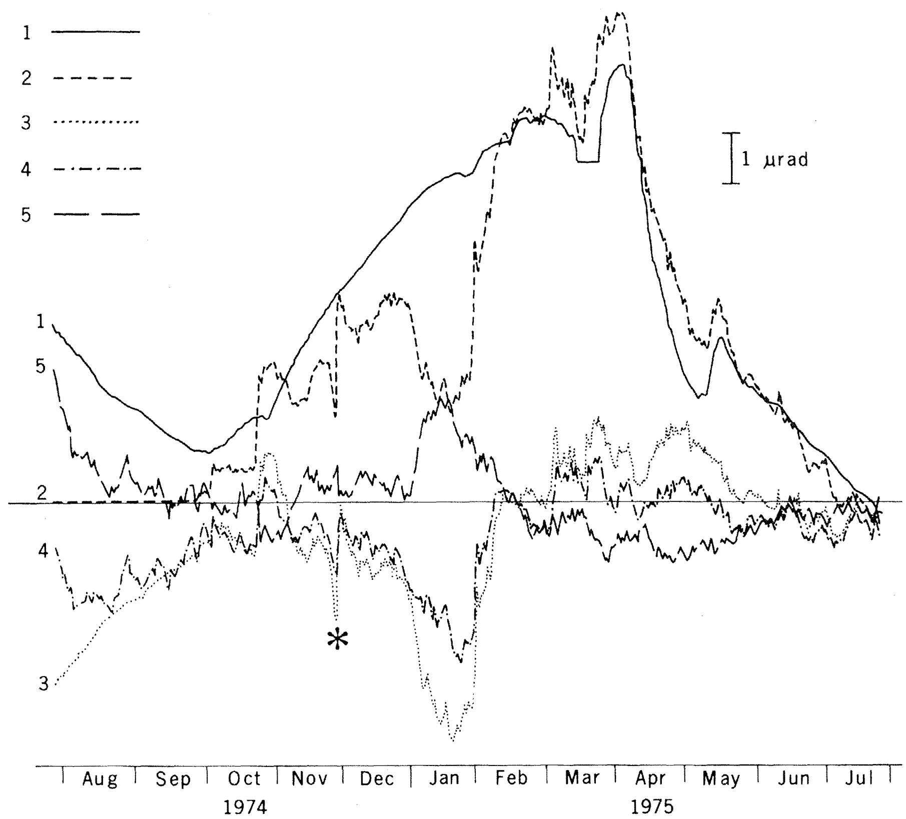

Fig. 3. Multiple time series starting with (curve 1) observed daily tilt from Libby-N, (curve 2) tilt predicted from rainfall, (curve 3) residual (difference) between curves 2 and 1, (curve 4) residual predicted from temperature, and (curve 5) final residual, that is, curve 4 minus curve 3. Occurrence time of largest earthquake ($M = 5.2$) on 28 November 1974 is denoted by *.

an earthquake ($M \sim 5$) that failed to occur. The best fit of rainfall to the tilt data for any single month of the entire data set occurs over the duration of this anomaly. The heaviest rainfall of the 2-year period preceded this anomaly. On the basis of this analysis we consider this anomaly to be the combined effect of weather (rainfall and temperature) on the local soil environment. Moreover, the existence of this tilt anomaly is not supported by data from two precise (10^{-6} radian) level line surveys bracketing the time and within the local space of this tilt record (*11*). The simplest physical explanation for resolving a possible conflict between the level line data and the goodness of fit of the weather to the tilt data is that the tilt response is a local effect, whereas the long-based level data average out the local effects. This possible conflict could also be an apparent response to a change in the thermal regime of the sensor. The thermal gradient sensitivity of the tilt sensor is 106 μrad per degree Celsius of the temperature gradient, and the instrument scale factor is first-order sensitive by about 1 percent per degree Celsius (*12*). If the tilt is only apparent, it could be thermally related. Yet it is rainfall that produces the best fit to the anomaly. Therefore, the most plausible way to produce an apparent tilt is to consider rainfall percolation to the sensor as a means of altering the thermal regime of the sensor without producing a physical tilt within the resolution of the level line data. The external housing of the tiltmeter sensor was found, on removal from the soil, to be corroded (*13*). While detailed effects of corrosion on the sensor are not known, it is irrelevant to this argument whether or not the corrosion ultimately penetrated the sensor. The corrosion is used only as evidence that alteration of the local thermal regime can be caused by percolation of moisture to the sensor.

The poorest fit of weather to the raw tilt data is over the 2-month period following the largest local earthquake ($M = 5.2$) of 1974–1975. The poor fit could be due in part to the impulse response of the region to the earthquake. It could also be due in part to a very local response of the tilt site to the mechanical shaking of the soil, which may have triggered micro creep or altered in some manner the thermal regime of the sensor. The total tilt change for the 2 months preceding this earthquake is approximately 3 μrad. Removal of rainfall and temperature response reduces this range to a value less than 1 μrad. It is difficult to locate the time of the earthquake solely on the basis of the tilt signature in the residue. Anomalous tilt preceding the earthquake is discussed elsewhere (*14*).

In summary, this particular data set indicates that a tiltmeter site with an annual range of tilt of approximately 10 μrad can be fitted to the combined weather data of temperature and rainfall with a 0.75-μrad r.m.s. error. This same tilt data can be fitted to the subclass of earthquakes $M \geq 2.5$ within 30 km of the site to a r.m.s. error of 1.03 μrad. If the tiltmeter is responding significantly to local earthquakes, it is responding even more significantly to weather. The poorest fit of weather to the raw tilt data follows the largest local earthquake of the 2-year period. The best fit of weather to the data is to the tilt "bump" of April 1975.

Because we have restricted our investigation to one type of instrument at one site, our conclusions should be similarly restricted. It appears, therefore, that in this case premonitory earthquake signals are buried in noise that is probably a local response to meterological inputs. For large earthquakes with anomaly lead times that approach the rise time of the soil to weather and seasonal variations, input identification and separation of such phenomena is imperative—however difficult it may be.

M. D. Wood
N. E. King

U.S. Geological Survey,
Menlo Park, California 94025

References and Notes

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