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EARTH TIDES AS A TRIGGERING MECHANISM FOR EARTHQUAKES

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ABSTRACT

Since earth tides represent the largest short-period oscillatory strains in the earth, a test has been made to see if any correlation exists between the times of occurrence of earthquakes in Southern California and the tidal potential. Two tests have been made, one of them a cross-correlation. On either basis, a statistically significant sample of earthquake events gives a correlation with the tidal potential that is of the same magnitude as a random sample.

During the twenty-four year period 1934–1957, over 9000 local earthquakes having magnitude 2 or greater were recorded by the Pasadena network. This large body of data has been stored in a manner suitable for further data processing. Such a large number of events, combined with the ease of fast computational procedures, provides us with an opportunity to make statistical studies of the seismicity of small earthquakes on a scale not hitherto possible; the volume of data available reduces the statistical uncertainties by as much as an order of magnitude over earlier computations of correlations with natural phenomena performed by hand.

A large number of searches for diurnal and semi-diurnal or monthly and fortnightly periodicities among earthquake events have been made earlier, but statistically small numbers of events have been used. Some of the reports claim to find positive correlations of earthquake events with solar or lunar periodicities and others do not; it is clear that the statistically small samples used leave the resolution of these correlations in doubt. A listing of some of the early studies is given by Aki (1956).

The largest single periodic strain in the earth is the solid earth-tide. The maximum peak-to-peak strain is about $\frac{1}{2} \times 10^{-7}$. This is the most likely candidate for a possible triggering mechanism; if strain energy were accumulated in the rocks of the outermost parts of the earth from some geologic source, then the tidal strains, superimposed upon this secular term, could pretrigger or posttrigger an earthquake when some critical stress is reached. Therefore there should be a correlation between the times of occurrence of earthquakes and the tide-producing force of sun and moon whether phase lags in the earth tide, compared with the tide-producing force, are present or not.

In principle, a Fourier analysis of the times of occurrence of earthquakes, all considered as events with equal weight, should show periodicities corresponding to the lunar or solar terms. However, as is well known, the tide-producing force has a spectrum which has a population in a large number of lines. Thus, if a weak correlation with earth tides is present then the population in each of the lines may be extremely small; therefore it may be quite difficult to determine whether a positive correlation is present or not. For the time scale used here, the earth tides must be considered as almost periodic rather than as periodic. For this reason a correlation in real-time instead of a harmonic analysis was performed. The two types of correlations performed upon the data are described below.

The list of earthquake events was truncated to give a list having epicenters located between latitudes 32½°N and 36°N and between longitudes 115°W and 120°W. This was done to reduce the possibility of areal bias associated with incomplete coverage by the network, especially in Baja California. This number of events in the truncated list was 8614. No effort was made in these calculations to further reduce the list to avoid local bias; in a later paper (Knopoff, 1964) the list was further truncated to include events of magnitude 3 or greater. No attempt has been made to eliminate aftershocks or swarms from the list used in these calculations; the calculations performed here have been made upon lists variously terminated before the Kern County series. No attempt has been made to classify any further the earthquake sequence as to geologic subprovince or as to occurrence on specific earthquake faults.

The gravitational attraction of sun and moon, the tide-producing acceleration, was calculated on an hourly interval for the entire twenty-four year period using a tabulated formula (Bartels, 1957). The acceleration of gravity was computed for the coordinates of Pasadena and was assumed to apply to the entire area under study. Thus all points within the 5° band of longitude were assumed to have tidal strains in the same phase. In fact, a twenty minute difference occurs in the diurnal term across this band. However, this has been neglected in the present calculation.

In the first type of correlation with tidal accelerations, an interpolation procedure was applied to the hourly list of tidal accelerations in order to compute the times of maxima and minima. The time interval between a maximum and minimum was divided into one hundred parts; the time interval between a minimum and a maximum was similarly divided. Thus a "tidal time" was obtained and the time of occurrence of an earthquake could be described relative to the tidal time. A histogram was constructed for all the events as a function of "tidal time" within the geographic area specified and falling in the interval 1934–1946. Thus the ordinate at the abscissa -0.37 in figure 1 is the number of Southern California earthquakes on the list that occurred between 0.37 and 0.38 of the time interval between a preceding maximum and a succeeding minimum of tide. The histogram is taken over all earthquake events; thus if no earthquake occurred between a given pair of tidal extrema, no entry was made in the summation.

A histogram of this type should show whether more earthquakes tend to occur clustered around specific phases of the earth tides such as extrema in strain or strain gradients. This calculation does not take into account the magnitude of the earthquake nor the magnitude of the tide that produces the strain. Hence no resolution was made with regard to earthquake magnitudes on the list of events.

In this calculation only the times at which the earthquake events take place are compared with the times of tidal extrema.

The rather ragged curve of figure 1 is the result of the calculation. The irregular character may be due to the fact that an extremely fine subdivision of the time interval between extrema was used. Hence a smoothing of the histogram was made in which the histogram was itself Fourier analyzed and the first four terms were preserved; that is, terms to periods of almost six hours were retained. The result is the smooth curve also shown in figure 1. This curve has maxima and minima as might be expected from the Fourier analysis of any irregular function. A question that remains is, does the maximum in this curve indicate any special significance as to the time of occurrence of an earthquake? The answer to this question has been given by considering a set of earthquake events occurring randomly in time and performing a calculation identical to that above. The dotted lines represent one standard deviation for random events. We conclude that there is a statistically significant random component to the actual earthquake events, so that if the times of occurrence of earthquakes show any systematic regularity, then these are masked by a significant random component which shows no correlation to the times of maxima or minima of the tides. Hence, on the basis of this first calculation, no correlation can be distinguished for this statistically significant sample.

As noted above, the first calculation was made without regard to the magnitude of the tidal strain. It may be that earthquakes have a greater tendency to be triggered when the tidal strain differences are large, that is when sun and moon are nearly aligned with the earth, rather than when the strain differences are small. In a second calculation, an attempt was made to take this feature into account. Again the magnitudes of the earthquakes were not used in the calculation, since it is likely that the triggering mechanism should have no influence on the magnitude of the earthquake; the magnitude should depend upon the ability of the rock to store strain energy and principally upon the secular stress gradient near the focus.

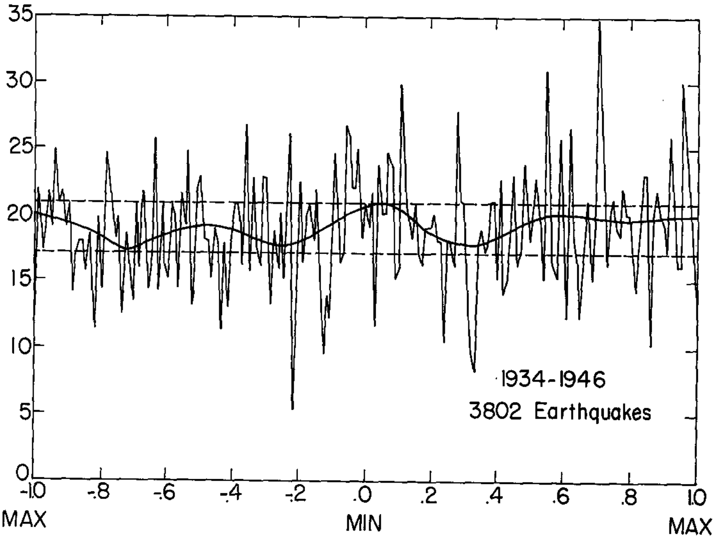

FIG. 1. Histogram of occurrence of Southern California earthquakes in "Tidal Time" relative to tidal maxima and minima.

In the second calculation, the sequence of earthquake events was represented as a comb of delta functions and a cross-correlation was taken with the tidal acceleration using an interpolation formula to derive the values of accelerations at times between the hourly intervals of the original calculation. The cross correlation can be represented by the formula

$$\int_{-\infty}^{\infty} \sum_{n=1}^{N} \delta(t - t_n) g(t - \tau) dt = \sum_{n=1}^{N} g(t_n - \tau)$$

which reduces to a simple sum over the values of gravity at and near the times of occurrence t_n of the earthquakes.

The result of this cross-correlation is shown in figure 2 for lead and lag times using one hour intervals up to twenty-four hours before and after the earthquake, for earthquakes in the interval 1934–1951. The curve marked *EQ* is the result of this calculation. It is not surprising that the curve shows a response which is similar to a tidal curve containing a diurnal and semi-diurnal component. Again, the question of statistical significance becomes important.

To estimate the statistical significance, in this case, a random set of exactly the same number of "earthquakes" has been generated as follows: Combs of delta functions, random in time, have been generated which fit 1) Poisson distributions, 2) Gaussian distributions, and 3) taking the actual times of the real earthquake series and adding to them a random set of times. The results of two examples of a cross-correlation with the tidal accelerations are shown in figure 2: 1) using a Gaussian distribution and 2) adding a random time to the actual time sequence, marked in curves *R* 1 and *R* 2. Other artificially generated numerical combs show similar graphs. In almost all the cases tested, the cross-correlation between the artificially generated random set of events and the tidal strain acceleration showed a peak-to-peak cross-correlation of the same order of magnitude as for the real list of earthquake events. We conclude that the cross-correlation of tidal accelerations with the comb of real earthquake events gives a result which has no larger oscillations than a similar result for a random set of earthquake times.

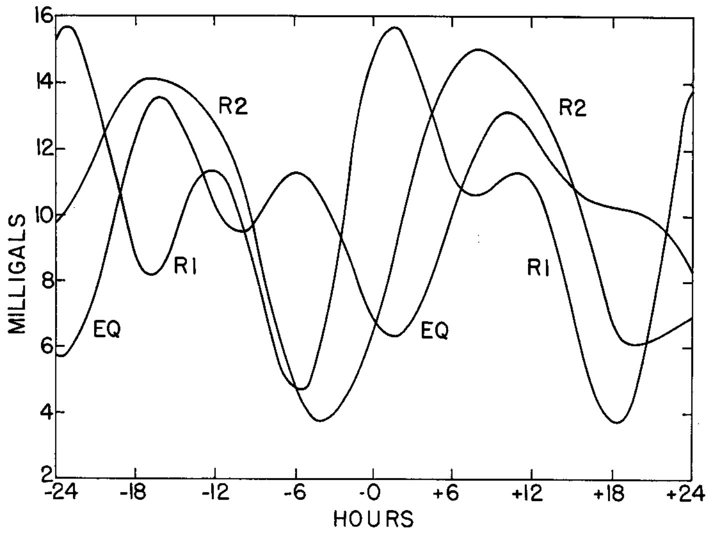

FIG. 2. Cross-correlation of Southern California earthquakes (*EQ*) and cross-correlation of random events (*R* 1, *R* 2) with tidal accelerations.

An order of magnitude calculation leads to a similar result. If one assumes that we have a random distribution in time of the earthquake events, then the product of the peak-to-peak daily gravitational variation, of the order of 300 microgals, by the square root of the number of earthquake events, gives a peak-to-peak value which is of the same order as curve *EQ* in figure 2. Thus, again, we conclude that a random set of events gives a similar cross-correlation to the real set.

The conclusion from these calculations is that the largest possible triggering mechanism in the earth, namely that of oscillatory tidal strains, has no detectable influence upon the times of occurrence of small earthquakes in Southern California.

One can seek a physical explanation for the negative result obtained in these calculations. From Bridgman (1952) we may infer a curve of the type shown in figure 3, illustrating schematically the time necessary for rupture of matter after stress in excess of the critical is applied. For stresses exactly equal to the critical stress, an infinite time is required for rupture; for very small overstresses, a large time is required; in a short time following the application of very large overstresses, rupture will take place. It must be emphasized that this description is qualitative and inexact; precise considerations of the nature of flow and fracture in solids and the environmental conditions surrounding these phenomena are obviously outside the scope of this presentation. Let us assume that some of the outermost parts of the earth are substantially in a state ready for rupture, the critical state having been achieved or almost achieved from tectonic sources. If tidal strains are very large compared to the critical strain, then rupture will take place in a short time. However, the tidal stress gradients are clearly very small, being of the order of 10^{-10} bars per cm peak-to-peak, whereas the critical stress gradients are a number of orders of magnitude larger than this. Accordingly, for these very small supercritical stresses, a very long time will be required for rupture, undoubtedly a time much longer than the period of the tidal strain itself. Thus trivially small tidal overstresses will cause rupture in the order of many days, perhaps months or years; since this time is long compared to the tidal strain, no synchronization with the tidal periods is to be expected.

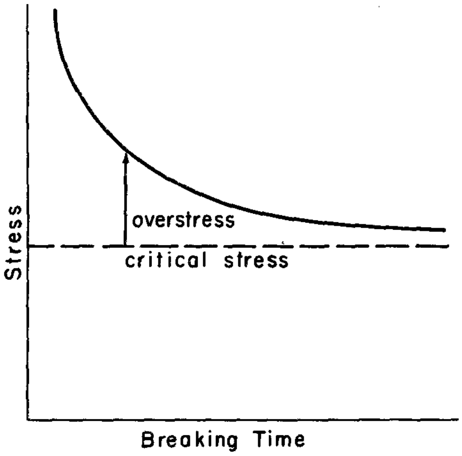

Fig. 3. Schematic diagram of rupture time vs. overstress.

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