Seismicity Patterns and the Stress State in Subduction-Type Seismogenic Zones

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Research during October, 1990 through April, 1991 was directed to the following efforts: (1) further development of the analysis of the effect of stress redistribution by moderate earthquakes on the spatial distribution of smaller earthquakes in the neighborhood; and (2) investigation of an alternative to the modified Omori relation for modeling aftershock sequence decay.

Seismicity-based Stress Model

The seismicity based stress model is a model of the changes in stress expected in the neighborhood of magnitude 4 and greater earthquakes in the central Aleutians. These changes in stress are compared with changes in the spatial distributions of smaller earthquakes nearby. Significant similarities between the changes in stress and the changes in seismicity have been found, especially when the surrounding earthquakes occur within 15 km of the hypocenters of the large earthquakes. The first attempt at a seismicity stress model was reviewed and several improvements made.

The stress field is computed with reference to a coordinate system centered on the large earthquake, with the z direction taken normal to the plane of slip, and x parallel to the slip vector. Four components of the stress tensor have been compared with changes in seismicity. τ_{zz} shows the strongest relationship with the seismicity, with decreases in the compression across the fault plane corresponding to increases in seismicity. τ_{xz} also shows a relationship to the seismicity, with increases in the shear stress in the same sense of the fault slip being associated with increases in seismicity. τ_{yz} and τ_{xx} show no relationship to the seismicity. This result suggests that the smaller surrounding earthquakes have a mechanism similar to that of the large earthquake. If conjugate planes were active, τ_{xx} would be expected to correlate to changes in seismicity.

The method of assessing the significance of a change in seismicity as related to a change in stress has undergone considerable evolution since the early stages of the model formulation. The stress change from the large earthquake calculated at the hypocenters of small earthquakes comprises a set of numbers. When the small earthquakes are divided into those that occurred before and after the large earthquake, there are two sets of numbers. A comparison between these sets can be made with a t test,

$$t = \frac{\bar{\tau_1} - \bar{\tau_2}}{\sqrt{(\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2})}}$$

where τ_1 and τ_2 represents the two sets of stresses, with $\bar{\tau}$ being an average, n the number of points in the data set, and σ a standard deviation. Assessment of the significance of t was made on the basis that σ_1 and σ_2 were not necessarily equal, but there is a problem with doing this sort of statistics on earthquakes, because they may not be independent of one another in space or time. The use of t represented an improvement over earlier formulations, but absolute assessment of its significance is still a subject of inquiry.

Investigations of the temporal behaviour of the relationship between modeled stress and seismicity were undertaken during this period. These produced some preliminary results suggesting that the rheology of the crust is not purely elastic. When data before and after all the larger earthquakes were pooled, there were enough smaller earthquakes to break them up into a larger number of time slices. When the normal component of the traction on the slip plane τ_{zz} was averaged in each bin, the plot in Figure 1 resulted.

This figure shows that the similarity between stress and seismicity gradually increasing from the time of the occurrence of the mainshock. The time axis is replaced by the event number, counting all events in the catalog, to smooth out fluctuations in seismicity rate. 1000 events roughly correspond to 15 months. The error bars on the plot are the standard deviations of the means of the stresses in each bin. The gradual increase in similarity between the stress model and the seismicity could be due to a time-dependent friction type of rheology.

An important area of work for the seismicity based stress model is improvement of the source model. The current model is based on an assumed uniform source orientation. To improve it, independent determination of focal mechanisms for about 100 magnitude 4 events in the central Aleutians is needed. Teleseismic data for these events have been read off of CD-ROMs and are being processed. Focal depths from the CASN network are used to determine take off angles, and the resulting angles and azimuths can be used to find first motion focal mechanisms.

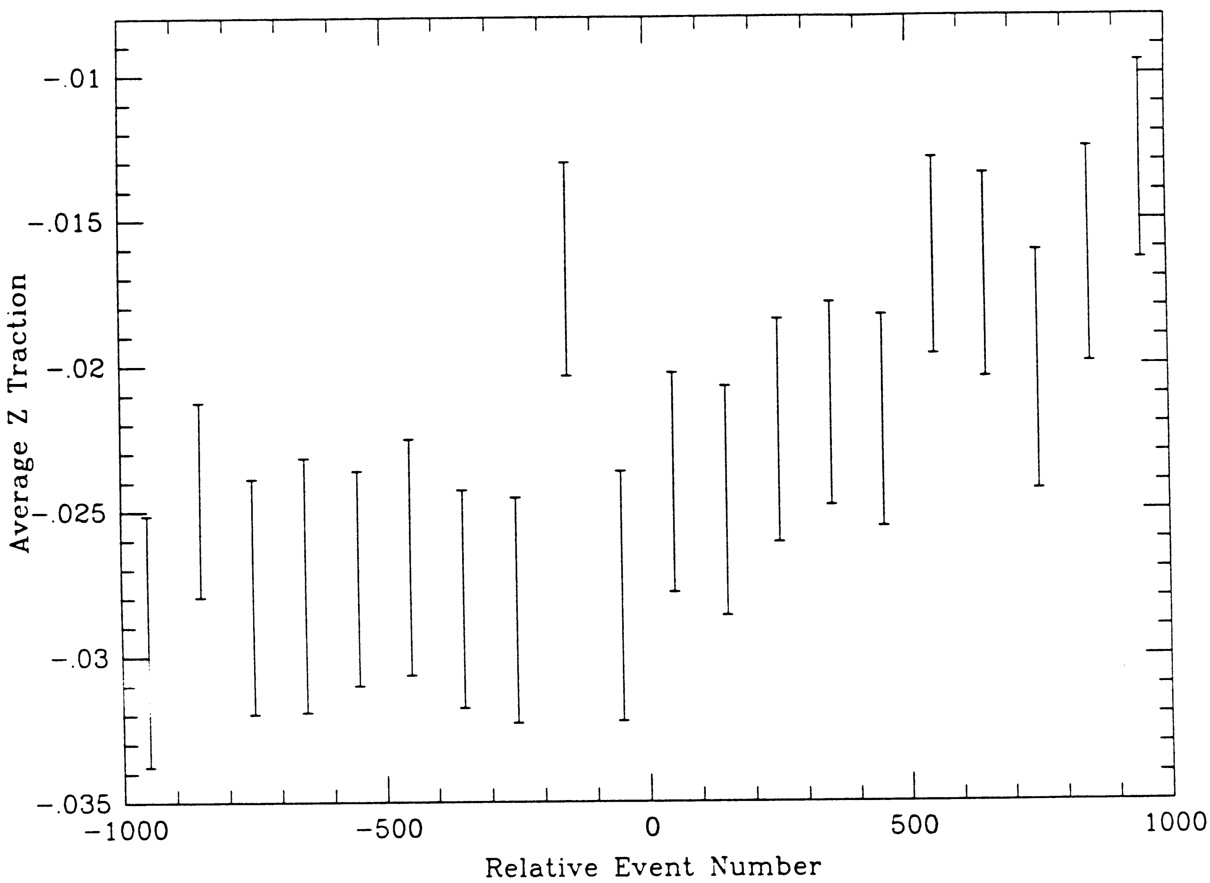

Figure 1: Average modeled normal stress evaluated at the hypocenters of small nearby earthquakes as a function of relative event number, where 1000 events roughly correspond to 15 months. The error bars are standard deviations of the mean.

A simple numerical model of scattering in the crust which may explain the different relationships between earthquake coda durations and source distance observed in the central Aleutians and California has been developed. Codas of local earthquakes in California are nearly independent of distance to the source when measured from the origin time of the earthquake. In the central Aleutians, coda durations are most independent of source distance when measured from the shear wave arrival time. The California coda decay pattern matches that for a crust which has inhomogeneities distributed evenly throughout it. The Aleutian decay pattern can be modeled by a crust with scatterers concentrated near the receiver.

The Stretched Exponential Function (Williams-Watt Relaxation) as a Model of Aftershock Decay

Because relaxation processes occur in a wide variety of physical systems, a large literature discussing mechanisms by which relaxation occurs and alternate forms of the relaxation time function exists. Little of this work has been examined for applicability to the aftershock problem. In this study, an alternative to the conventional relaxation function is being investigated.

The conventional way of modeling aftershock decay is by the the modified Omori (MOM) relation, $n(t) = K/(t+c)^{-p}$, where $n(t)$ is the rate of occurrence of aftershocks at time, t. In recent work, the differences in p-values among sequences have been examined in an attempt to relate the rate of decay of aftershocks to ambient physical or geological conditions (Kisslinger and Jones, 1991, Kisslinger and Hasegawa, 1991).

Of the forms for the relaxation function that have been analyzed and tested against data, the stretched exponential function, $N(t) = N(0)exp[(-t/t_o)^q], 0 < q \leq 1$ emerges as "a universal function that slow relaxation obeys" (quoted in Scher, et al. Physics Today, Jan. 1991). Here, $N(t)$ is the number of "events" (relaxation of a molecule polarized in an electric field that is cut off or of an oriented magnetic domain, or occurrence of an aftershock, etc.) that have not yet occurred, starting with N(0) initially. This form was first proposed in 1847, and demonstrated as a good model of relaxation in dielectrics by Williams and Watt in 1970. Because this form has been found to describe relaxation in a wide variety of physical systems, it seems worthwhile to investigate it for applicability to aftershocks.

For the stretched exponential,

$$N(t) = N(0)e^{-(t/t_o)^q}, \qquad 0 < q \leq 1 \qquad (1)$$

$$N_S(t) = N(0)[1 - e^{(t/t_o)^q}] \qquad (2)$$

$$n(t) \;=\; qN(0)t^{q-1}t_o^{-q}e^{-(t/t_o)^q}. \tag{3}$$

where $N(t)$ is the number of events that have not yet occurred, starting with $N(0)$ at $t = 0$, N_S is the cumulative number that have occurred to time t, $n(t)$ is the rate of occurrence at t.

This may be put in a form similar to the MOM relation by letting $K = qN(0)t_o^{-q}$ and $p = 1 - q : n(t) = Kt^{-p}e^{-(t/t_o)^{1-p}}$. Here p is always less than 1. For those sequences for which the modified Omori p is greater than 1, the exponential factor, with a small value of t_o, produces the rapid decay rate. For $q = 1, p = 0$, this becomes the straight exponential decay (Debye relaxation).

One more empirical model for aftershock decay would be of limited interest, but the stretched exponential relaxation has been related to a well-defined physical model by others and so the values of parameters resulting from the fit of this function to aftershock data may give additional insight into the physics of the aftershock generating process. Also, a problem with the MOM relation that apparently has not been noted previously is that if $p < 1$, the cumulative number of aftershocks diverges. Values of $p < 1$ are frequently found when the MOM relation is fit to real data, though values greater than 1 may be more common. A divergent aftershock series contradicts the postulate that a finite number of sites are loaded at the instant of the mainshock and that these fail at a decreasing rate to produce a sequence with a finite number of aftershocks, toward which the sequence converges more or less slowly. There is no problem for $p > 1$, as N_S converges to $N(0)$ at very long times.

A program for calculating the maximum likelihood estimates of the parameters in the stretched exponential function from aftershock time series has been written and tested for a number of the southern California sequences previously studied. The fits of the modified Omori relation and the stretched exponential function have been compared by use of the Akaike Information Criterion. The quality of fit by this criterion is very similar, with the MOM slightly better in many cases, the stretched exponential distinctly better in a few. Because the stretched exponential function avoids the problem of divergence for slowly decaying sequences modelled by a power law, and the parameter t_o has a clear physical meaning and obvious dependence on ambient physical conditions, especially temperature, further investigation of this model is warranted.

Publications

Kisslinger, C. and L. M. Jones, Properties of aftershock sequences in Southern California, accepted for publication in *J. Geophys. Research*, **96**, 1991.

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