Geophysical Research Abstracts, Vol. 7, 10112, 2005
SRef-ID: 1607-7962/gra/EGU05-A-10112

Precursory Acceleration of Seismicity: From the Theoretical Elegance to the Practical Difficulties

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It has been credibly argued that the earthquake generation process is a critical phenomenon culminating with a large event that corresponds to some critical point. In this view, a great earthquake represents the end of a cycle on its associated fault network and the beginning of a new one. The dynamic organization of the fault network evolves as the cycle progresses and a great earthquake becomes more probable, thereby rendering possible the prediction of the cycle's end by monitoring the approach of the fault network toward a critical state. This process may be described by a power-law time-to-failure scaling of the cumulative Benioff strain, of the form $\varepsilon(t)=K+A(t_f - t)^m$, where t_f is the failure time of the large event and m is of the order 0.2 - 0.4. Observational evidence has confirmed the power-law scaling in many cases and has empirically determined that the critical exponent m is typically of the order 0.3 very close to the theoretical value of m=1/3.

In the present work, we outline a theoretical framework to derive the time-to-failure power-law from basic principles. We use energy conservation in a faulted crustal volume undergoing stress changes and we assume that the fault system obeys a fractal / hierarchical distribution law. Furthermore, we assume that the precursory seismic activation extends over a broad area around the impending failure and rapidly converges to the rupture zone as a function of the time-to-failure. By considering the analytic conditions near the time of failure, we derive the time-to-failure power-law and show that the critical exponent m is a function of the fractal dimension and that the cumulative precursory crustal deformation (A) is a function of the energy supplied to the system and the size of the rupture. The fractallity of the fault system is a necessary

condition for the appearance of power-law acceleration in the seismic release rates.

We note that this approach affords a consistent interpretation of the empirical parameters involved in equation (1). On the basis of these results, it is possible to explain a set of empirical laws derived by other researchers, in terms of a plausible physical framework. Furthermore, by considering the relationship of the instantaneous Benioff strain rate with respect to the mean Benioff strain rate, it is possible to construct approximate analytical expressions to estimate the magnitude and time of failure of the impending earthquake.

More recently, the CP earthquake concept has gained support from the development of regional seismicity models with realistic fault geometry that show accelerating seismicity before large events. Essentially, these models involve stress transfer to the fault network during the cycle such, that the region of accelerating seismicity will scale with the size of the culminating event. It is thus possible to understand the observed characteristics of distributed accelerating seismicity in terms of a simple process of increasing tectonic stress in a region already subjected to stress inhomogeneities at all scale lengths. Then, the region of accelerating seismic release is associated with the region defined by the stress field required to rupture a fault with a specified orientation and rake; it is thus possible to incorporate tectonic information into the analysis.

From a theoretical point of view things appear to be quite illuminated but reality is much more complicated, as will be shown with two examples.

Recent analysis of Greek seismicity shows definite power-law acceleration in two areas along the Hellenic Arc. The first area is in the west Hellenic Arc, (Ionian Sea) and the second one is in the SW Hellenic Arc (Mediterranean Sea). Tectonic modeling of the accelerating sequences showed that they could be interpreted in terms of stress transfer from fault geometries consistent with the regional tectonics and kinematics as well as with fault zones known to have generated large earthquakes in the past. In both cases, there was a region of accelerating seismicity at the areas of positive stress transfer and a region of power-law decelerating seismicity at the areas of negative stress transfer (stress shadows), i.e. the reverse effect which should be observed if energy was extracted from a fault system. In both cases the critical exponent of the accelerating sequence at the positive-stress-transfer regions is very close 0.25, consistent with the view of the fault network as a Self-Organizing Spinodal moving toward a first order phase transition.

The observations were consistent with almost all of the theoretical predictions and expectations made in terms of the critical point / stress transfer model and it appeared as if bona-fide predictions had been achieved. Nevertheless, the “expected” earthquake in the Ionians did not come and recent re-evaluation of seismicity changes in the Ionians shows a spatial redistribution of seismic release with simultaneous broadening of the activated area, which is still accelerating albeit intermittently. Corresponding analysis in the SW Arc shows that the activated area may actually be relaxing, or the crustal material has stiffened and does not release as much seismic energy.

In conclusion, and in spite of the theoretical elegance it is enshrouded with, the real-time predictive capacity of the critical point / stress transfer earthquake model is still to be "critically" tested and our observations can be thought to be a step to this effect. The outcome could be important in assessing the feasibility of using the model to evaluate short and intermediate term seismic hazard in real-time.