Temporally Unstable Recurrence of Earthquakes Due to Breaks in Fractal Scaling

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Observed sequences of large earthquakes are not consistent in either recurrence time or energy release; long-term prediction has been impossible even in areas, such as Parkfield, with well-defined recurrence intervals. The seismic gap hypothesis, which predicts characteristic earthquakes in areas of the circum-Pacific belt that have not produced recent great earthquakes, has also failed to predict the observed clustering of high-energy events. Models in which fractal scaling is broken at high magnitude predict that characteristic events and recurrence behavior will be unstable in time. The central predictions of these models are supported by recent observations at Landers and Big Bear in California.

There is some debate as to the usefulness of the concept of a characteristic event in earthquake seismology. The characteristic event hypothesis (CEH) suggests that spatially limited sections of seismically active faults fail periodically in response to uniform increases in strain that are a consequence of long-term uniformity in the translation velocities of lithospheric plates. A result of constant strain rate and periodic recurrence on a fault is that these regular events tend to give rise to earthquakes of predictable magnitude; the amount of energy released from these earthquakes depends on the amount of accumulated strain. These are characteristic earthquakes.

The CEH seems to be most applicable in relatively simple tectonic environments such as along strike-slip transform faults like the San Andreas fault in California. Although there is much evidence that restricted sections of such transform faults do exhibit sequences of large events with remarkably uniform features (*1–3*), it is clear that these patterns are neither universal nor consistent even in these relatively simple environments. The activity on even the simplest system is not confined to large earthquakes; there are many more small-magnitude events on any fault plane. These small-magnitude earthquakes, though contributing only a fraction of the total slip, undoubtedly complicate the dynamics of the system. Here we examine the consequences of these small events on the temporal distribution of characteristic events in an earthquake model that has been shown to reproduce many features of earthquake catalogs.

The global cumulative frequency-magnitude distribution for seismicity follows a power law. Fault systems also show a power law relation between trace length and cumulative number (*4*) and trace length and displacement (*5*). A fractal distribution of faults, each with a characteristic event size, would reproduce the Gutenberg-Richter relation (GRR) up to the magnitude corresponding to the largest fault. However, it is clear that seismicity on a given fault cannot be fully described by a single magnitude value.

Developments in the understanding of the organization of complex systems show that some systems evolve naturally to a so-called self-organized critical state (*6*), which is characterized by the absence of spatial or temporal correlations and which exhibits fractal statistics. Cellular automata, designed to model the behavior of a single fault plane (*7, 8*), have been shown to evolve to such a state, and these models produce seismicity that agrees well with the GRR. Such models have much in their favor; they belong to the same universality class (*9*) as natural seismicity without the need for tuning by an external parameter, and they appear to exhibit precursory phenomena (*10*) that are similar in many respects to those in real earthquakes (*11*). The concept of self-organized criticality, then, appears to offer the possibility of a general theory for earthquake generation.

In these models, however, the linked concepts of characteristic events and recurrence intervals have no important meaning. There is (probably) a maximum event size for a given model, and in general, large events that approach this magnitude appear to be more common than would be expected by extrapolation from smaller magnitudes (*12*), particularly in rectangular models with high aspect ratios (*10*). However, it has been argued that this apparent change in universality class is an artifact of the undersampling of the less frequent high-magnitude events, an argument that is supported by the observation (*13*) that the frequency-magnitude distribution for global seismicity smooths out high-magnitude deviations in universality class that are evident in some local catalogs. The implication here is that, viewed over a sufficiently long time window, the physics of stress dissipation on a fault plane is dynamically identical to that of other systems (such as phase transitions or avalanches in sand piles) that are known to exhibit self-organized criticality.

But a vital ingredient is missing from this perspective. Whereas the condensation of a gas at the critical point, the magnetization of iron at the Curie point, or the collapse of sand piles at the angle of repose are features of statistically homogeneous systems, fault planes (particularly extended fault planes) are by their nature macroscopically heterogeneous. Furthermore, many causes of this heterogeneity [such as lithology, rheology, or the finite width of the seismogenic layer (*14, 15*)] are not fractally distributed in space but divide the fault trace into large dynamical units. It would appear, from the observations we have discussed (*1–3*), that the activity on the fault mirrors this heterogeneity, at least over the short time window of observations. The heterogeneity of an extended fault appears to impose on the seismicity a greater degree of spatial and temporal order than would be expected from an extended, uniform dynamical system at a critical point. In this view, characteristic events, recurrence intervals, coupling between neighboring segments across seismic gaps (*16*), and changes in universality class are the predictable consequences of interactions within and between these dynamical units; the GRR for seismicity in local catalogs is interpreted as being the result of self-organized critical organization of the internal dynamics of a given fault segment.

In response to these ideas we have developed a model for seismicity on a short section of a transform fault which comprises more than one active segment (*17*) (Fig. 1). This model is a hybrid of two end-member types; dynamically low-dimensional models (*18, 19*) designed to represent entire segments and dynamically high-dimensional models (*7, 8, 10*) based on the self-organized critical interactions between asymptotically small increments of a fault face. The frequency-magnitude distribution for the model seismicity (Fig. 2A) shows a distinct break in slope that is the result of the magnitude-sensitive dynamics of the model. Moreover, this behavior is very similar to the break in slope observed for natural seismicity recorded on a short section of the San Andreas fault that also contains two active segments, Parkfield and Stone Canyon, separated by a largely aseismic creeping segment (Fig. 2B). Because high-magnitude events in this simulation are controlled by a low-dimensional, chaotic mechanism and are entirely deterministic,

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they are inherently predictable over short periods of time (*20*).

The time evolution of the system can be examined by using the method of Huang and Turcotte (*19*, *20*), by plotting a trajectory in the Y_1-Y_2 phase plane (*21*) (Fig. 3). Characteristic events in this system are triggered when the trajectory touches the failure envelope; the size of the resulting earthquake is a function of the displacement of the failing block. These block failures do represent characteristic events for the model (Fig. 3); consecutive large events on each block are similar in magnitude.

The temporal relation between these events is, however, not so clear. The characteristic event origin time is largely influenced by the deterministic stress accumulation from the constant velocity driver and the total force that can be supported by friction at the base of the block. In this respect the model behaves in much the same way as traditional slider block models that exhibit simple time- and slip-predictable behavior. Here the situation is complicated by both the nonlinear boundary conditions and the stochastic stress dissipation that results from the self-organized critical interactions on the base of the block. Therefore, the precise time of failure is absolutely unpredictable.

However, there does appear to be some regularity to the trajectory, at least in the short time window (Fig. 3). Noisy stress accumulation on lines subparallel to phase plane diagonals seems to end in block failure at predictable places on the failure envelope, giving the characteristic events a fairly well-defined recurrence interval.

So that temporal variations in the recurrence time could be examined, the data were first normalized to allow comparisons between recurrence intervals for events of different magnitude. Consider the origin times t_n $(n = 1, 2, \ldots N)$ of a series of events whose magnitudes exceed a given threshold. The nth recurrence time in this series, T_n, is defined by $T_n = t_{n+1} - t_n$. The mean recurrence time for the entire series, $\overline{T}$, is given by

$$\overline{T} = \frac{1}{N-1}\sum_{i=1}^{N-1} T_i$$

and the normalized recurrence time $\langle T_n \rangle$ is defined as

$$\langle T_n \rangle = \frac{T_n}{\overline{T}}$$

Plots of this normalized recurrence time versus event number will show a horizontal line for perfectly defined recurrence behavior. Model events above a low threshold magnitude (Fig. 4A) do not conform to any regular recurrence pattern but represent genuinely critically organized generating dynamics; no temporal correlations are evident. The situation for high threshold magnitude, particularly on the stiff block (see Fig. 1), is different. Here there is a distinct tendency for characteristic earthquakes to occur a fixed time after the previous large event. In Fig. 4B, for example, over long periods of time the recurrence interval is approximately constant at $\sim 1.4\overline{T}$. This recurrence interval is not stable over time but decays into noisy cycles with alternating long and short repeat times. However, the interval $1.4\overline{T}$ is fundamental to the dynamics of the system (for these parameter values), and the series soon returns to this value for an unspecified amount of time.

The general behavior of the model may help to explain the failure of the seismic gap hypothesis (*22*, *23*) to predict the apparent clustering of large events on segments of the circum-Pacific belt neighboring quiescent

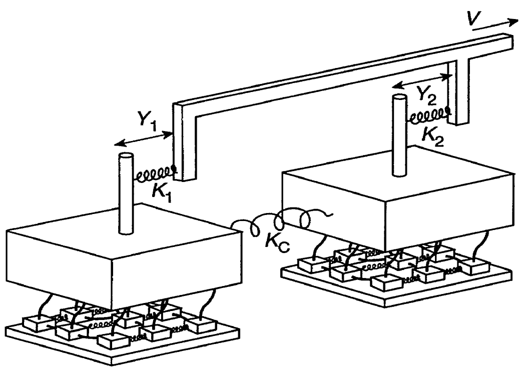

Fig. 1. A schematic of the hierarchical model that incorporates two dynamically distinct mechanisms. Frequent, low-magnitude seismicity is controlled by the dynamically high-dimensional cellular automata [see for example (*7*, *8*, *10*)]. This seismicity, which conforms to the Gutenberg-Richter relation, is inherently unpredictable. When an entire fault face fails, the dimensionality of the underlying dynamics is reduced to that of a simple spring-block system, which is, given sufficient data, both time- and slip-predictable [compare with (*17*)]. As in (*18*) and (*19*), friction on these blocks is asymmetric, ensuring that the double-block system is entirely aperiodic.

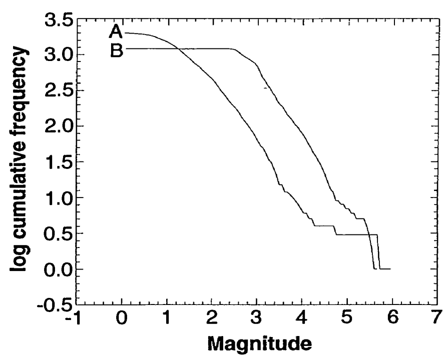

Fig. 2. Frequency-magnitude distribution for model seismicity (plot A) (see Fig. 3 for model parameter values) exhibits the same general features as the same distribution calculated for natural seismicity on a short section of the San Andreas fault (between about 35.5° and 37.5°N) (plot B). This section comprises two active segments (Parkfield and Stone Canyon). The break in slope in plot A is a direct consequence of a change in universality class due to the discontinuous nature of the underlying dynamics. This type of discontinuity has been reported frequently [see for example (*13–15*)].

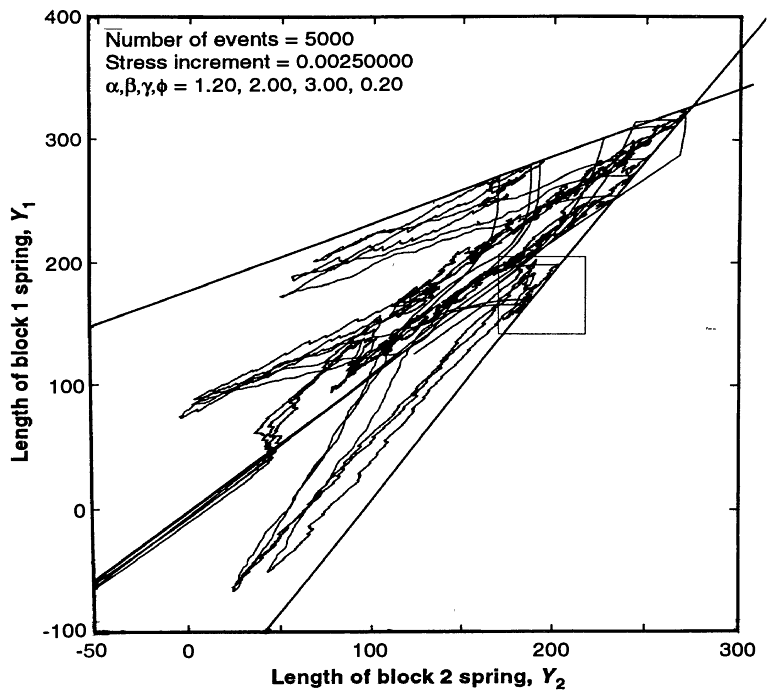

Fig. 3. Evolution of a trajectory in Y_1-Y_2 space for the parameter values given. The parameters α, β, γ, and ϕ govern the strength of coupling between the blocks, the amount of frictional asymmetry, the extent of velocity weakening during block failure, and the amount of energy dissipated seismically during any failure, respectively. The values used here have been shown to be consistent with the geology of the Parkfield and Stone Canyon segments of the San Andreas Fault (*19*). The box in the diagram indicates a section of the trajectory on which the recurrence time for large events is significantly affected by the high-dimensional self-organized critical seismicity; a small failure on one block in this region can trigger a characteristic event on the other. This effect, coupled with the sensitivity of the double-block model to changes in its initial conditions, makes the prediction of large events in this model extremely difficult.

areas. Over large times the total slip on neighboring segments is necessarily equal, although in models such as this, significant short-term disequilibrium allows repeated rupture on a single segment; frictional asymmetry promotes this behavior.

The observed temporal instability of recurrence times in hierarchical seismicity may also be significant in our interpretation of the failure of predictions based on more idealized recurrence behavior. Our hierarchical model predicts that periodic recurrence behavior, though being a fundamental property of some fault segments, is temporally unstable; high-dimensional self-organized critical interactions that are inherently unpredictable apply random local fluctuations on the deterministic far field stress (*24*). Recent sequences of seismicity in California appear to support the hypothesis that such local fluctuations can significantly alter recurrence predictions based on deterministic strain accumulation. For example, King and others (*25*) show that the occurrence of the Landers earthquake (magnitude $M = 7.4$) may have been advanced by as much as one to three centuries by small changes in Coulomb stress ($\approx$1 bar) as a result of preceding moderate magnitude events at Galway Lake, Homestead Valley, North Palm Springs, and Joshua Tree. They further argue that the Landers earthquake increased the Coulomb stress at Big Bear by 2 to 3 bars, triggering the $M = 6.5$ Big Bear event.

It appears that natural seismicity may exhibit sensitivity to small stress changes which is similar to this model. If these observations are generally reflected in real seismicity, then it will not be possible to use recurrence intervals, no matter how well-defined, in the long-term prediction of earthquakes.

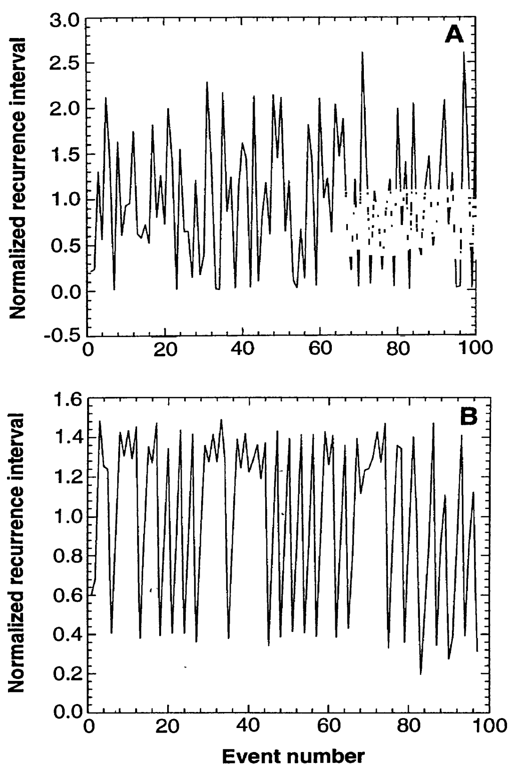

Fig. 4. Temporal variation in normalized recurrence interval for events on the stiffer block. (**A**) Events above model magnitude 4. (**B**) Characteristic events above model magnitude 6. In each case data are normalized to the mean recurrence time of the weak block. Although the low-magnitude events show absolutely no tendency toward uniform recurrence time, high-magnitude events tend to recur at about 1.4T. However, this recurrence interval is unstable over time, showing windows of time-unpredictable behavior.

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Paleomagnetic Record of a Geomagnetic Field Reversal from Late Miocene Mafic Intrusions, Southern Nevada

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Late Miocene (about 8.65 million years ago) mafic intrusions and lava flows along with remagnetized host rocks from Paiute Ridge, southern Nevada, provide a high-quality paleomagnetic record of a geomagnetic field reversal. These rocks yield thermoremanent magnetizations with declinations of 227° to 310° and inclinations of −7° to 49°, defining a reasonably continuous virtual geomagnetic pole path over west-central Pacific longitudes. Conductive cooling estimates for the intrusions suggest that this field transition, and mafic magmatism, lasted only a few hundred years. Because this record comes principally from intrusive rocks, rather than sediments or lavas, it is important in demonstrating the longitudinal confinement of the geomagnetic field during a reversal.

The record of marine magnetic anomalies and terrestrial magnetostratigraphy demonstrates that geomagnetic field reversals have occurred frequently throughout geologic time. Detailed paleomagnetic records are needed to determine the behavior of the transitional field during reversals in order to evaluate whether dipolar or strong low-order nondipolar fields define transitions and thus the processes responsible for polarity reversals (*1–4*). However, because field reversals are short-lived phenomena (*5*), they are by no means always well-recorded. Several high-quality, partial to essentially com-

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