Intermittent Criticality and the Seismic Cycle

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Introduction

In recent years, there have been many attempts to describe the physics of distributed regional seismicity using the framework of self-organized criticality (SOC) as originally defined on the basis of simple cellular-automaton models [e.g. 1, 14, 17]. In the context of earthquakes, the most important characteristic of SOC is its inherent ability to produce the power-law frequency-size statistics known as the Gutenberg-Richter distribution. On this basis, Bak and Tang [1] claimed that seismicity reflects a self-organized critical system. Because SOC models contain no tuning parameters, a system that has achieved self-organized criticality will remain in that state with constant power-law frequency-size statistics for as long as the external driving force remains constant. The apparent stationarity of the Gutenberg-Richter thus supports the model of self-organized criticality [7, 10, 12].

However, cellular automata models of self-organized criticality break down if the model includes dissipation or strong heterogeneity. Sammis and Smith [15] demonstrated that the non-conservative automaton originally formulated by Olami et al. [14] produces seismic cycles. Energy loss introduces memory. Since the total energy on the grid is drastically reduced after a large event, the system must recover before it can produce another large avalanche. In this model, SOC is not reached on the time-scale of the seismic cycle. However, when averaged over many earthquake cycles the model reproduces a stationary power-law distribution, similar to SOC. Thus the question of determining whether or not a system is in a state of self-organized criticality depends very strongly on taking a large enough space-time window to average out fluctuations in the stress field associated with large events. Therefore, while SOC may be an important concept for understanding seismicity averaged over very long space-time domains, an understanding of seismicity on the time scale of individual seismic cycles requires a new paradigm.

Intermittent criticality

The work of Sammis and Smith [15] is representative of a new class of models which display intermittent criticality [see also 2, 8, 9, 16]. This viewpoint is based on the hypothesis that a large regional earthquake is the end result of a process in which the stress field becomes correlated over increasingly long scale-lengths, which set the size of the largest earthquake that can be expected at any given time. The largest event possible on the fault network can not occur until regional criticality has been achieved and stress is consequently correlated at all length scales up to the size of the region. This large event then destroys criticality on its associated network, creating a period of relative quiescence after which the process repeats by rebuilding correlation lengths towards criticality and the next large event. In contrast to self-organized criticality where the system is always at or near criticality, intermittent criticality implies time-dependant variations in the activity during a seismic cycle.

Intermittent Criticality and Accelerating Moment Release

The central prediction of intermittent criticality is that the ultimate largest earthquake only occurs when the system is in a critical state. This largest earthquake divides the seismic cycle into a period of growing stress correlations before and uncorrelated seismicity after. Before a large earthquake, the growth of correlation will manifest itself as an increase in the frequency of intermediate-magnitude earthquakes, a phenomenon frequently referred to as the accelerating moment release model [2, 3, 4, 5, 11, 16].

Intermittent Criticality and Frequency-Magnitude Statistics

Intermittent criticality also makes predictions about the evolution of the Gutenberg-Richter distribution during the course of the earthquake cycle. In SOC, the correlation length of the stress field is by definition constant and infinite. Thus, there should be no systematic temporal fluctuations in any parameters of the Gutenberg-Richter distribution, including the maximum magnitude. However, in intermittent criticality the correlation length of the stress field varies in time. As the correlation length grows before a great earthquake, M_{max} increases and the Gutenberg-Richter scaling extends to higher magnitudes. However, the b-value remains constant, with a small change in the a-value to accommodate the larger events. Thus, traditional measurements of the a and b-values are not be sufficient to differentiate between SOC and intermittent criticality. A determination of M_{max} is also required.

Intermittent Criticality and the Seismic Cycle

Intermittent criticality also provides an explanation for phenomenological descriptions of the seismic cycle [e.g. 6]. In this viewpoint, the interseismic period (whose duration may vary from cycle to cycle) represents a period when the correlation length is short, so that small events are less likely to cascade into larger ones. The period of increasing seismicity is a result of the growth of the correlation length of the stress field as the region emerges from the stress shadow created by the last great earthquake. Strongly heterogeneous dynamic and static stress redistribution after this large event reduces the correlation length, causing a systematic decrease in Mmax. Thus while earthquakes in the interseismic and preseismic portions of the seismic cycle are progressively increasing the correlation length of the regional stress field, aftershocks can be viewed as the mirror image of this process whereby the regional stress field becomes increasingly decorrelated. By using themaximum magnitude of seismicity as a proxy for the correlation length, it may be possible to determine where any given region sits in the seismic cycle.

Direct observation of the stages of the seismic cycle

The data in this study were recorded by the Pacific Northwest Seismograph Network (PNSN). Since a consistent catalog for events M ≤3.5 was not available until 1980, this study will be limited to 1980-2000. High density PNSN coverage extends from roughly 42° to 49° N latitude and from 119° to 125° W longitude.

Although this area sits astride the Cascadia subduction zone, the vast majority of seismicity occurs in the upper plate. While lower plate events can be as large as M=7, the largest instrumentally recorded events in the upper plate are in the 5-6 range. Focal mechanisms of the shallow earthquakes indicate north-south compression in the upper plate [19]. Focal mechanisms of events in the subducting slab indicate down-dip tension [13]. We therefore assume that the upper and lower plates are decoupled, and only consider upper plate seismicity.

Figure 1 is a map of all seismicity M ≥2.5 since 1985 in the region we shall consider, with 3 stars denoting the epicenters of the only M ≥5 earthquakes. Circles, found using the algorithm described in [2], show the critical regions before the 1996 Mb=5.4 Duvall and 1990 Mb=5.0 Deming earthquakes. Note the close correspondence between the two circles.

The black circle defines a larger system, which includes the critical areas from both the 1996 Duvall and 1990 Deming events. Figure 2 shows the cumulative Benioff strain from 1981 to 1997 for the earthquakes in this circle. The evolution of seismicity agrees with the stages of the seismic cycle described by Ellsworth et al [6]. The periods of accelerating moment release (stage II) before both the 1990 and 1996 events are clearly visible in this plot. Immediately following the earthquakes and their aftershocks (stage III) is an interseismic period (stage I) characterized by a nearly linear cumulative Benioff strain with time.

The linear increase in seismicity in stage I is a symptom of the disorganized nature of the stress field after a large earthquake. In this state, there is no correlation between events and any measurement of seismicity will be essentially constant in time.

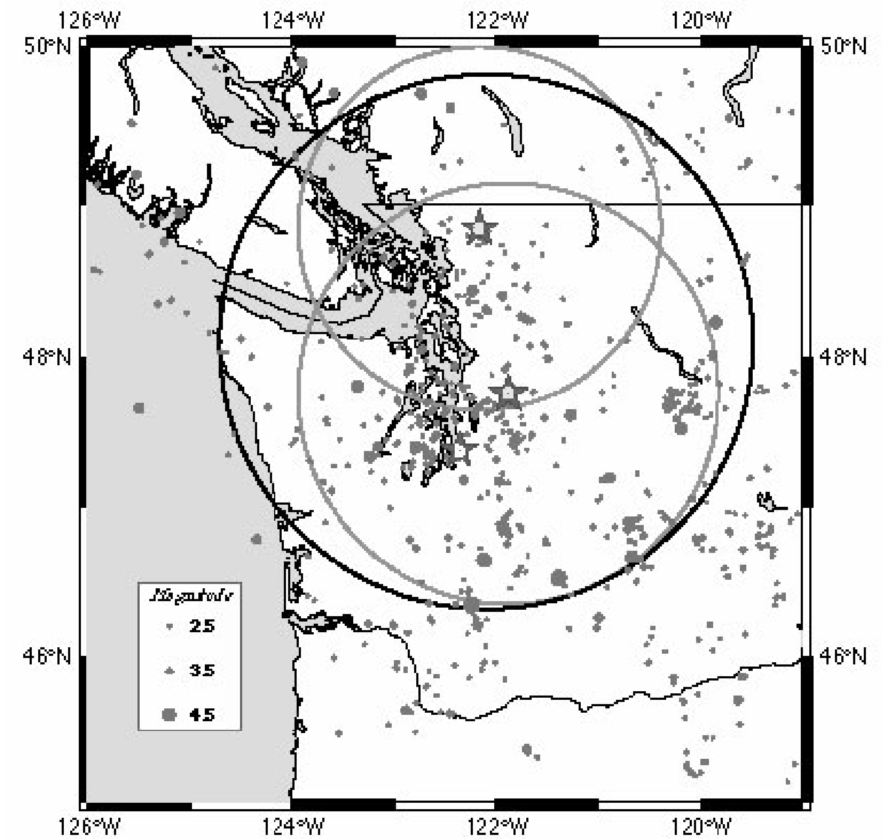

Figure 1: Seismicity of the Pacific Northwest from January 1, 1985-November 1, 1998, M ≥2.5. Stars indicate events M ≥5.0. a) 1990 mb=5.0 Deming earthquake b) 1995 mb=5.0 Robinson's point earthquake c) 1996 mb=5.4 Duvall earthquake. Light circles show the critical regions for the Deming and Duvall events. The dark circle encloses the larger region used to study the evolution of frequency-magnitude statistics in the time interval between these two events.

Stage II represents a period of accelerating moment release associated with the approach to a critical point. Stage III is the period of time immediately before and after the earthquake, and includes classical foreshocks and aftershocks. Classical foreshocks during the first half of stage III (immediately prior to the earthquake) are most likely the result of some direct mechanical triggering process, and are not treated from a the standpoint of a statistical model like intermittent criticality. However, seismicity during latter half of stage III is dominated by classical aftershocks, which from the standpoint of intermittent criticality reflect the disorganization of the stress field after the large earthquake. It is true that aftershocks, like foreshocks, likely reflect some sort of direct mechanical link to their associated mainshock through various mechanisms (e.g. static/dynamic stress changes, fluid flow, etc). However, even though individual aftershocks redistribute very little stress, taken in aggregate they play a large role in the evolution of the stress field.

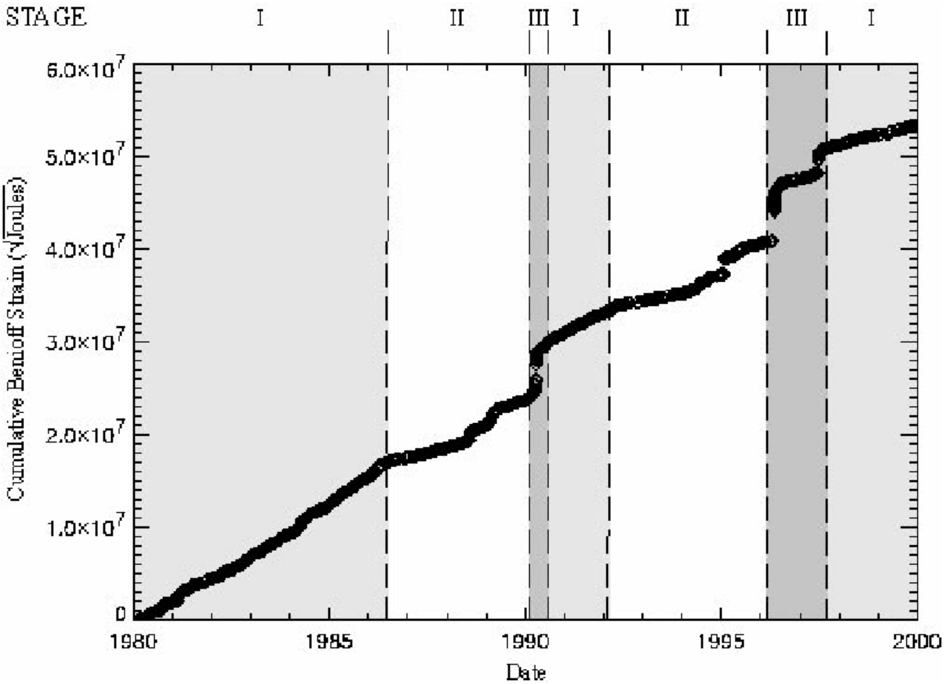

Figure 2: Cumulative Benioff strain in the Pacific Northwest from 1982-1997, all earthquakes mb ≥2.5. The shaded regions correspond to the postulated stages of the seismic cycle described by Ellsworth et al. [1981] (see figure 1.1). Stage I (light shading), the "interseismic" period, is characterized by a linear trend in the cumulative Benioff strain release, which intermittent criticality associates with a decorrelated regional stress field. Stage II (no shading) is the period of accelerating moment release described by the critical point model, and is associated with the growing correlation length of the stress field. The cycle culminates in stage III, which includes both the mainshock and its associated foreshocks and aftershocks.

The most remarkable aspect of Fig. 2 is that these stages are visible before and after two large events in succession. The quality of data in this region combined with the frequency of “large” earthquakes permits a detailed examination of this process. We now take the analysis one step further to test the evolution of the frequency-magnitude statistics predicted by intermittent criticality using the same space-time window as in Figs. 1 and 2.

Observed evolution of the Gutenberg-Richter distribution

Figure 3 shows the Gutenberg-Richter statistics for all events M ≥2.5 within the black circle in Figure 1 in a two-year moving window from 1981-1997. A vertical section perpendicular to the time axis is the frequency-magnitude distribution for a two-year period centered at time T. Note that the b-value in this figure is relatively constant throughout the time considered here. The “ridge and valley” structure of the plot is a direct result of the growth and destruction of the correlation length of the regional stress field. The maximum magnitude increased prior to the two large events in 1990 and 1996, producing the pronounced ridges. The valleys reflect a reduction in Mmax following the 1990 Deming and the 1996 Duvall events.

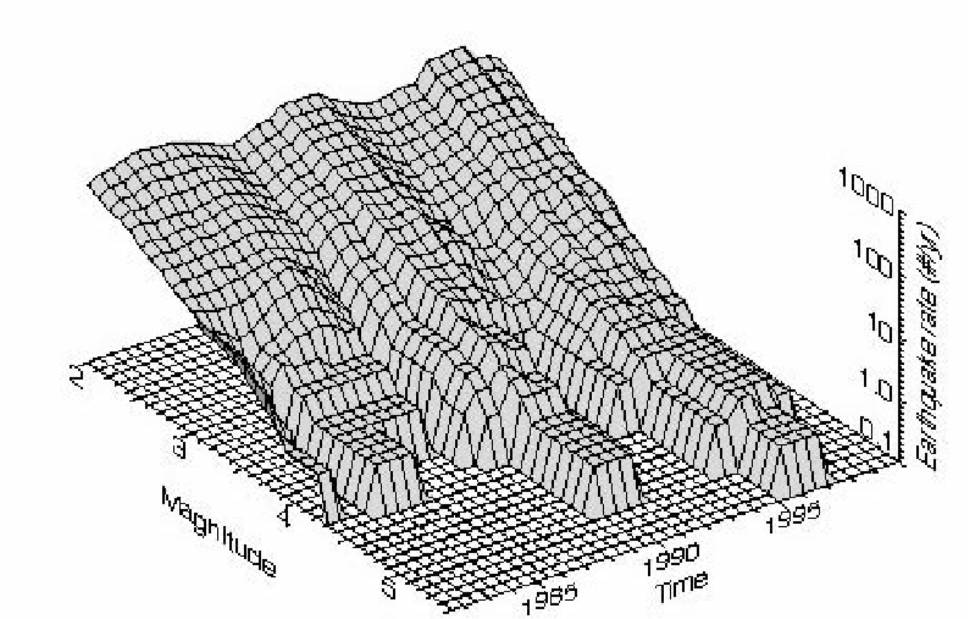

Figure 3: Frequency-Magnitude statistics from 1981-2000 for the region shown in figure 1. The statistics were calculated in a two-year moving window. Note that Mmax in the distribution slowly increases prior to 1990 and 1996. Also note that the slope (b-value) of the distribution remains relatively constant throughout the period, with fluctuations in the height (a-value) of the distribution.

Discussion

Our observations of upper plate seismicity in the Puget Sound region can be summarized as follows:

1) There are systematic trends in both the frequency-magnitude distribution and the cumulative Benioff strain over the course of two earthquake cycles.

2) The b-value during the study period remains roughly constant.

3) Mmax grows prior to a large earthquake, and decreases following it.

4) There is an apparent variation in the a-value over the course of the seismic cycle. This variation coincides with variations in Mmax, and may be causally related.

While it is likely that SOC systems may produce clustering of events that would produce fluctuations in the frequency-magnitude statistics, it is highly unlikely that such clustering would display the systematic behavior noted here. However, these observations support the concept of intermittent criticality. At present, this is the only known case where systematic variations in the frequency-magnitude statistics have been observed over more than one continuous earthquake cycle.

Acknowledgments

This research was funded by National Science Foundation grant EAR-0105405 and through Cooperative Agreements EAR-0106924 and USGS-02HQAG0008 to the Southern California Earthquake Center

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