Pure appl. geophys. 161 (2004) 1945–1956
0033 – 4553/04/101945 – 12
DOI 10.1007/s00024-004-2541-z

Pure and Applied Geophysics

Intermittent Criticality and the Gutenberg-Richter Distribution

DAVID D. BOWMAN[1] and CHARLES G. SAMMIS[2]

Abstract—In recent years there has been renewed interest in observations of accelerating moment release before large earthquakes, as well as theoretical descriptions of seismicity in terms of statistical physics. Most aspects of these works are encompassed by a concept called intermittent criticality in which a region alternately approaches and retreats from a critical -point. From this perspective, the evolution of seismicity in a region is described in terms of the growth and destruction of correlation in the stress field over the course of the seismic cycle. In this paper we test the concept of intermittent criticality by investigating the temporal evolution of the Gutenberg-Richter distribution before and after two successive $M \geq 5.0$ earthquakes in western Washington State. The largest event in this distribution, $M_{\max}$, is observed to systematically increase before each event, producing accelerating moment release, and then to subsequently decrease. Associated variations in the b-value are minimal. This is the predicted result if $M_{\max}$ is a measure of the correlation length of the regional stress field.

Key words: Seismicity, earthquake physics, earthquake stress interactions, self-organized criticality, earthquake statistics.

1. 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). Self-organized criticality was originally defined on the basis of simple cellular-automaton models (e.g., BAK and TANG, 1989; SORNETTE and SORNETTE, 1989; OLAMI *et al.*, 1992). In the context of earthquakes, the most important characteristic of self-organized criticality is its inherent ability to produce power-law frequency-size statistics. This relationship, known as the Gutenberg-Richter distribution, has been known for many years to describe the frequency-magnitude statistics of earthquakes (GUTENBERG and RICHTER, 1944). BAK and TANG (1989) recognized that cellular automata models produce similar power-law size statistics, an observation that formed the basis of their claim that seismicity can be described as a self-organized critical system. Another often cited characteristic of self-organized criticality is the

[1] Department of Geological Sciences, California State University, Fullerton, CA 92834-6850.
E-mail: dbowman@fullerton.edu
[2] Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740.
E-mail: sammis@earth.usc.edu

stability of the statistics through time. Because SOC models ideally 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 *b*-value of the Gutenberg-Richter distribution is one of the primary pieces of evidence supporting the model of self-organized criticality (KAGAN,1994; JACKSON, 1996; GELLER *et al.*, 1997).

However, recent works have shown that cellular automata models of self-organized criticality break down if the model includes dissipation or strong heterogeneity. SAMMIS and SMITH (1999) demonstrated that the non-conservative automaton originally formulated by OLAMI *et al.* (1992) naturally leads to seismic cycles. In this model, some energy is removed from the grid during cascades. This energy loss may be interpreted as arising from processes in real earthquakes such as frictional heating, seismic radiation, and breaking new rock. Energy loss introduces memory into the model. 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, self-organized criticality cannot be 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, it is of very little use when trying to understand the space-time distribution of seismicity on a given fault network over a human time scale. An understanding of seismicity on the time scale of individual seismic cycles requires a new paradigm.

2. *Intermittent Criticality*

The work of SAMMIS and SMITH (1999) is representative of a new class of models which display *intermittent* criticality (see also SORNETTE and SAMMIS, 1995; SALEUR *et al.*, 1996; SAMMIS *et al.*, 1996; HEIMPEL, 1997; BOWMAN *et al.*, 1998; HUANG *et al.*, 1998; and GRASSO and SORNETTE 1998). 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 cannot 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 in which the system is always at or near criticality, intermittent criticality implies time-dependent variations in the activity during a seismic cycle.

2.1 Intermittent Criticality and Accelerating Moment Release

It is important to note that the central prediction of intermittent criticality is that large earthquakes only occur when the system is in a critical state. This large earthquake acts as a sort of "critical point" dividing the seismic cycle into a period of growing stress correlations before the great earthquake and a relatively uncorrelated stress field after. Before the large earthquake, the growing correlation length manifests itself as an increase in the frequency of intermediate-magnitude earthquakes. This is commonly referred to as the accelerating moment release model, and has been discussed by a number of authors (SYKES and JAUMÉ, 1990; BUFE and VARNES, 1993; BUFE *et al.*, 1994; SORNETTE and SAMMIS, 1995; BOWMAN *et al.*, 1998; BREHM and BRAILE, 1998; JAUMÉ and SYKES, 1999).

Many works have shown that accelerating moment release before large earthquakes typically occurs over a distance much larger than the size of the mainshock rupture (e.g, BOWMAN *et al.*, 1998; BREHM and BRAILE, 1998; JAUMÉ and SYKES, 1999; ROBINSON, 2000; PAPAZACHOS and PAPAZACHOS, 2001) . KING and BOWMAN (2003) developed a simple model that relates the large region of increased activity prior to a large event to the region that is stressed by tectonic loading of the fault. In their model, the process of stress accumulation and release on the main fault perturbs the constant uniform driving stress assumed by models of self-organized criticality. This forces the system out of equilibrium and into the strongly fluctuating regime described by SMITH and SAMMIS [1999]. While KING and BOWMAN (2003) show that the size of the region experiencing accelerating moment release should scale as the size of the mainshock, there are many processes that may cause the absolute size of the regions to vary between different tectonic regimes (e.g., differences in the distribution of strength heterogeneities in the region). Also, the level of background seismicity may affect the size of the active region in the same way it affects the time duration of an aftershock sequence (see, e.g., DIETERICH, 1994).

2.2 Intermittent Criticality and Frequency-Magnitude Statistics

Intermittent criticality also makes predictions relating to the evolution of the Gutenberg-Richter distribution during the course of the earthquake cycle. The central feature of intermittent criticality is that the correlation length of the stress field controls the size of the largest event in a region ($M_{\max}$). As the correlation length grows prior to a large earthquake, the size of the maximum expected earthquake also increases. For all magnitudes smaller than this maximum cutoff, the region is effectively at a critical state. As with self-organized criticality, this leads to power-law scaling of the frequency-magnitude distribution at the lower magnitudes. The important difference between SOC and intermittent criticality is the evolution of the correlation length. In self-organized criticality, 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 of seismicity.

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. This extends the Gutenberg-Richter scaling to higher magnitudes, but does not alter the underlying scaling relation. The b-value for the region will remain constant, with a small change in the a-value. Thus, traditional measurements of temporal variations in the b-value in a region will be insufficient to differentiate between self-organized criticality and intermittent criticality. A more complete description of the frequency-size statistics must also include the evolution of a and $M_{\max}$. We will illustrate the relative importance of these parameters by analyzing seismicity before and after a series of M $\geq$ 5 earthquakes in the Puget Sound region of the state of Washington, USA.

3. Seismicity of the Pacific Northwest

The data in this study were recorded by the Pacific Northwest Seismograph Network (PNSN). The PNSN, headquartered at the University of Washington, began operation in 1970, however consistent catalogs for events $M \leq 3.5$ were not available until 1980. Therefore this study will be limited to seismicity from 1980 to 2000. The dense short-period seismograph network that comprises the bulk of the PNSN covers western Washington and Oregon states from roughly 42° to 49°N latitude and from 119° to 125°W longitude.

Interpretation of seismicity in this area is complicated by the fact that the region sits astride the Cascadia subduction zone. However, as Fig. 1 shows, the vast majority of seismicity in the region occurs in the upper plate of the subduction zone. The largest earthquakes within this region are lower plate events, which can be as large as magnitude 7. In contrast, the largest instrumentally recorded events in the upper plate have been in the magnitude 5–6 range, although there is paleoseismic evidence for a large tsunamigenic crustal earthquake about 1100 years ago (BUCKNAM *et al.*, 1992). Focal mechanisms of shallow earthquakes in the Puget Sound region indicate a consistent pattern of north-south compression in the upper plate (ZOBACK and ZOBACK, 1991). In contrast, the focal mechanisms of events in the subducting slab indicate down-dip tension (LUDWIN *et al.*, 1991; MA and LUDWIN, 1987). This significant difference in tectonic stress orientation indicates that the plates are not mechanically coupled. Therefore, in this work we assume that the upper and lower plates are decoupled, and will only consider upper plate seismicity.

Since 1982 there have been 3 $M \geq 5$ earthquakes within 170 km of each other in the area surrounding Puget Sound. The maximum magnitude of historical upperplate seismicity in this region is in the $M \approx 5$ range. Figure 2 is a map of all seismicity $M \geq 2.5$ since 1985 in the region we shall consider, with stars denoting the epicenters of $M \geq 5.0$ events. The circles in Figure 2 delineate the critical regions before the

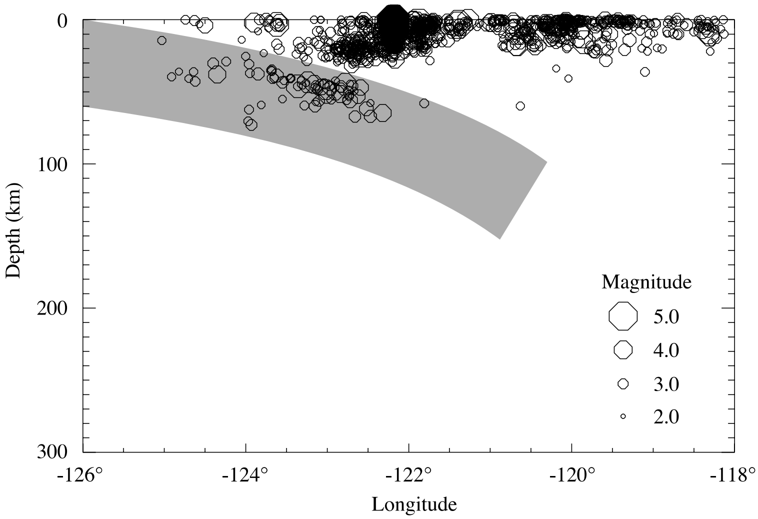

Figure 1
Crosssection of seismicity in the Pacific Northwest. Gray region is the inferred Wadati-Benioff zone. 2:1 vertical exaggeration.

1996 $M_b = 5.4$ Duvall and the 1990 $M_b = 5.0$ Deming earthquakes. These regions were found using the algorithm described by BOWMAN *et al.* (1998). Figure 3 shows the cumulative Benioff strain (square root of the seismic energy) release for both of these events. The reasons for using Benioff strain are described by a number of works (e.g., BUFE and VARNES, 1993; SORNETTE and SAMMIS, 1995; SALEUR *et al.*, 1996).

Note that the star in Figure 3d is the 1995 $M = 5.0$ Robinson's Point earthquake. While this event is large enough to be considered a "mainshock", it is significantly smaller than the 1996 Duvall event. Thus, in the context of intermittent criticality, the Robinson's Point earthquake is a large precursor to the nearby $M_b = 5.4$ Duvall event.

5. Observed Evolution of the Gutenberg-Richter Distribution

Ideally, a complete description of the evolution of the Gutenberg-Richter distribution through the seismic cycle would include two or more repeated events on the same fault. However, few existing seismicity catalogs are of sufficient quality for a long enough time period to measure reliable frequency-magnitude statistics (including M_{max}) over more than one earthquake cycle. In this study, we are not attempting to describe a seismic cycle in the commonly accepted sense of the term (ELLSWORTH *et al.*, 1981). Rather, we are describing regional variations in frequency-magnitude statistics due to the loading cycle on neighboring fault systems.

Figure 4 shows the frequency-magnitude statistics for all events $M \geq 2.5$ within the black circle in Figure 2 in a two-year moving window from 1981–1997. In this figure, a

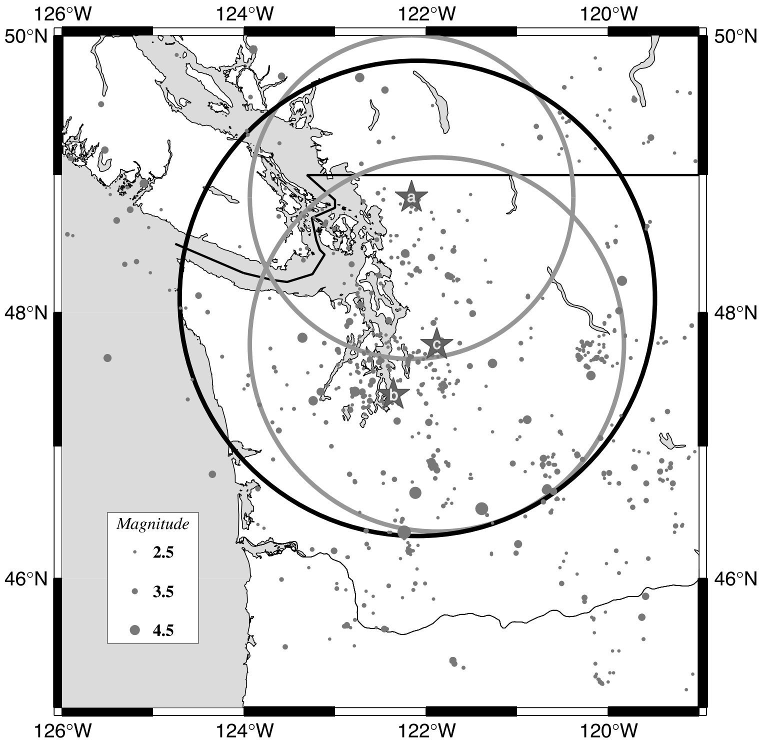

Figure 2
Seismicity of the Pacific Northwest from January 1, 1985 to November 1, 1998, $M \geq 2.5$. Stars indicate events $M \geq 5.0$. a) 1990 $m_b = 5.0$ Deming earthquake, b) 1995 $m_b = 5.0$ Robinson's Point earthquake, c) 1996 $m_b = 5.4$ Duvall earthquake. Light circles show the critical regions 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.

vertical section perpendicular to the time axis is the frequency-magnitude distribution for a two-year period centered at time T. The figure resembles a mountainside with prominent "valleys" at the years 1987 and 1993, and "ridges" at 1981, 1990 and 1996. Note that the *b*-value in this figure (the "slope of the mountainside") is relatively constant throughout the time considered here, as predicted above. 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 of seismicity in the region increased prior to the two large events in 1990 and 1996, producing the pronounced ridges in the plot. The valleys are a result of the reduction in $M_{\max}$ due to the decorrelated stress field after the 1990 Deming and 1996 Duvall events. The quality of the earthquake catalogs prior to 1981 restrain us from analyzing data in this time period, however the time period from 1980–1981 saw heightened activity in the southern section of the region discussed here, including both an $M = 5.2$ event north of Elk Lake, Washington and the May 1980 eruption of Mount St. Helens.

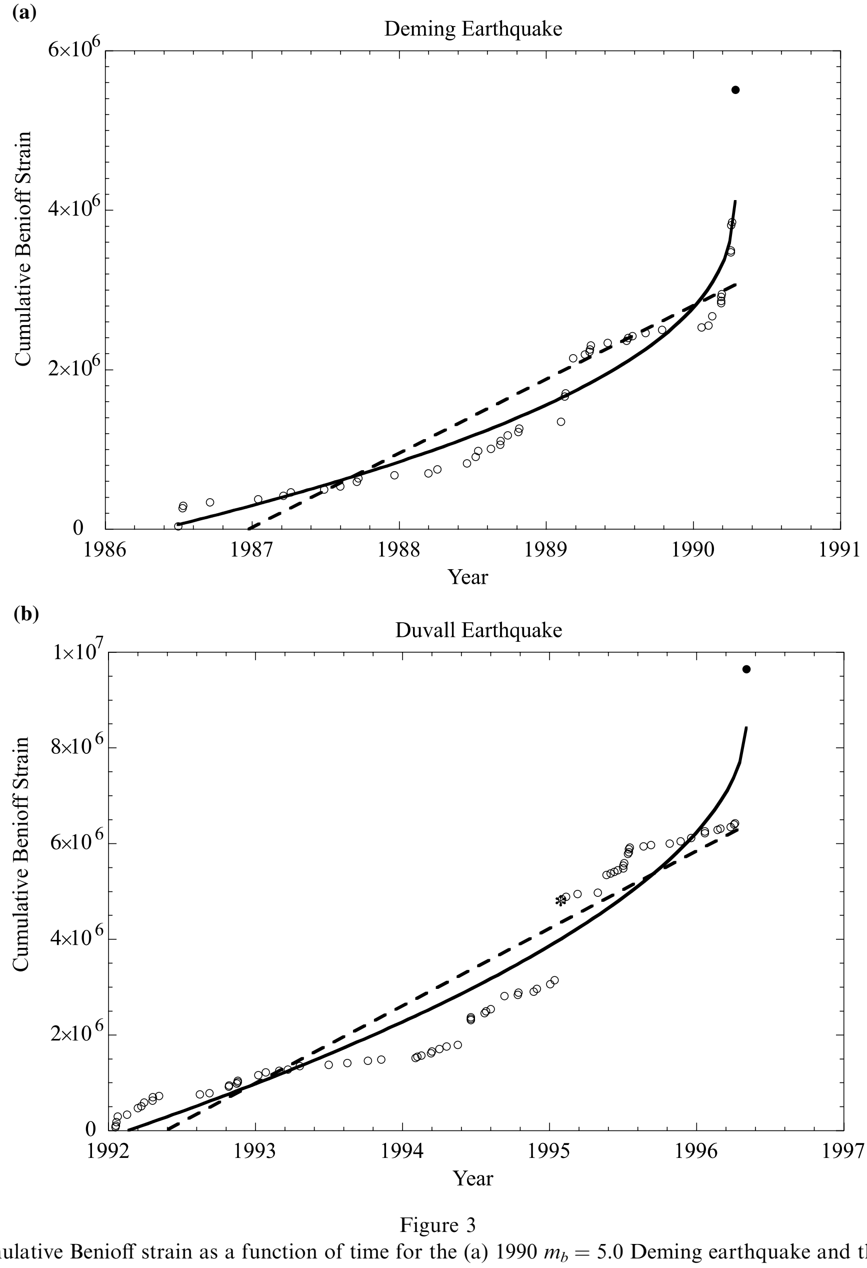

Figure 3
Cumulative Benioff strain as a function of time for the (a) 1990 $m_b = 5.0$ Deming earthquake and the (b) 1996 $m_b = 5.4$ Duvall earthquake. In both plots, the final event is denoted by a filled circle. The star in (b) is the 1995 $m_b = 5.0$ Robinson's Point earthquake. See text for details.

The evolution of the frequency-magnitude statistics over this time period can also be seen in Figure 5. From top to bottom, this figure shows the evolution of the total number of events, maximum magnitude of seismicity, and the b-value for the same

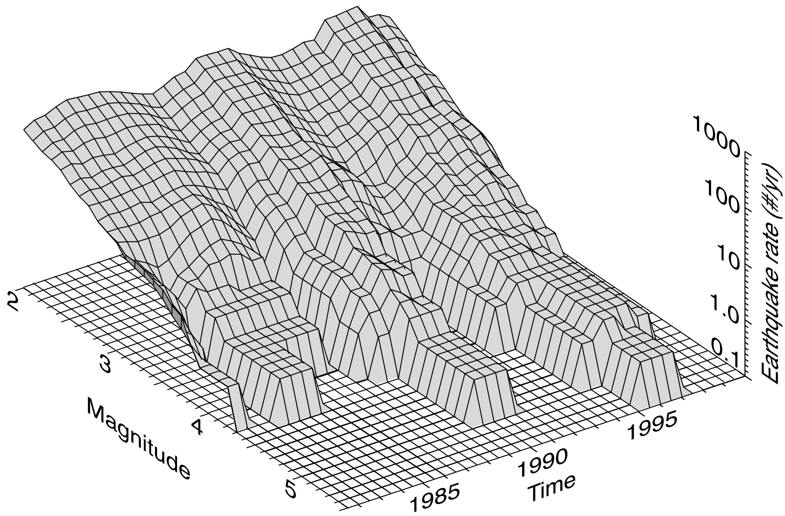

Figure 4
Frequency-magnitude statistics from 1981–2000 for the region shown in figure 3. The statistics were calculated in a two-year moving window. Note that $M_{\max}$ in the distribution slowly increases prior to 1990 and 1996. Also note that the slope (b-value) of the distribution remains relatively constant throughout the period, with fluctuations in the height (a-value) of the distribution.

two year moving window in Figure 4. Both the Deming and Robinson's Point earthquakes show a strong increase in both the maximum magnitude of seismicity and the overall level of seismicity in the five years prior to the events. The increase in the number of $M \geq 2.5$ earthquakes shows a strong correlation with the increase in $M_{\max.}$. This can be easily understood in terms of a systematic variation in the a-value in the region. The increase of a before a large earthquake creates a higher probability for intermediate-magnitude events. In a two-year moving window, this will manifest as an increase in $M_{\max}$, while in a plot of the cumulative Benioff strain as a function of time this will be see as accelerating moment release. Following the large event, the a-value decreases, lowering $M_{\max}$.

Note that, to first order, b is constant over the entire time period, having a mean $\{b\} = 1.13$ and a standard deviation $\sigma = \pm\ 0.19$. There are slight fluctuations in the b-value which are anti-correlated with $M_{\max}$ (low b-value corresponding to large $M_{\max}$). This anti-correlation is quantified in Figure 6 which shows that the cross correlation between b and $M_{\max}$ has a strong negative peak at a time shift of 0 and weaker positive correlations at shifts of $+4$ years and –3 years. This asymmetry in the correlation function reflects the variable duration of the seismic cycle. However, note that most of the b-value data points in Figure 5 lie within one σ of the mean, so that the observed fluctuations in b-value are not statistically significant.

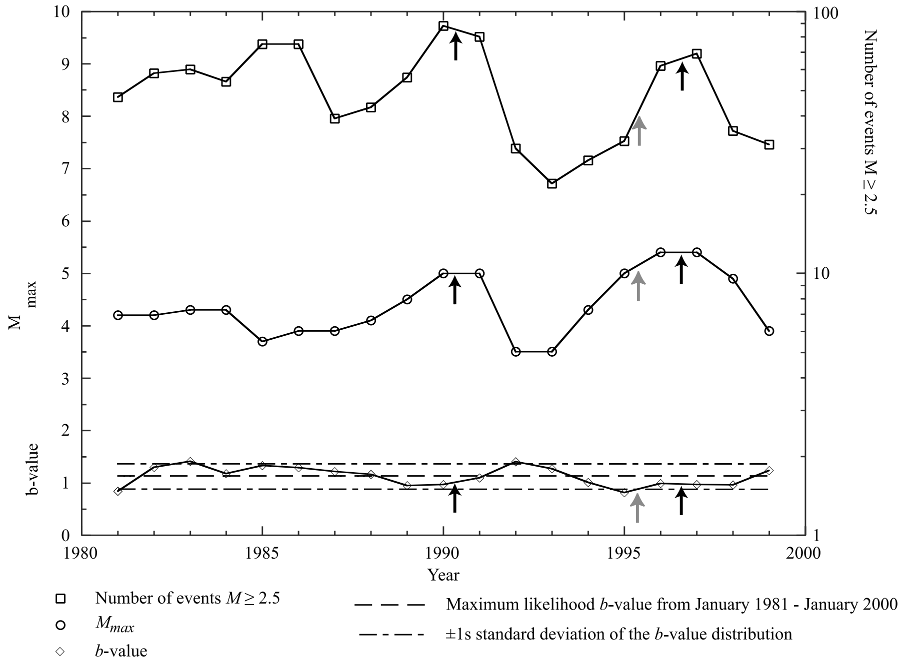

Figure 5
Variations in seismicity during the seismic cycle. The data points are from the same two-year moving windows used in Figure 6. The upper curve (square symbols) is the total number of events $M \geq 2.5$ in the region at each time step. The middle curve (round symbols) is $M_{\max}$ at each time step. The lower curve (diamond symbols) is the *b*-value at each time step calculated by the maximum-likelihood technique. The dashed line shows the average *b*-value over all time steps, and the dot-dash line shows the 1-s standard deviation of the observed *b*-values. The black arrows indicate the time of the 1990 Deming and 1996 Duvall earthquakes. The gray arrow is the time of the 1995 Robinson's Point event.

6. Discussion

Although the fluctuations in $M_{\max}$ found above are incompatible with the concept of self-organized criticality, they are consistent with the predictions of intermittent criticality. Of particular note are the following observations:

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

2) The *b*-value during the study period remains roughly constant. There is minor variability in the *b*-value which is anti-correlated with $M_{\max}$.

3) $M_{\max}$ 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 $M_{\max}$, 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

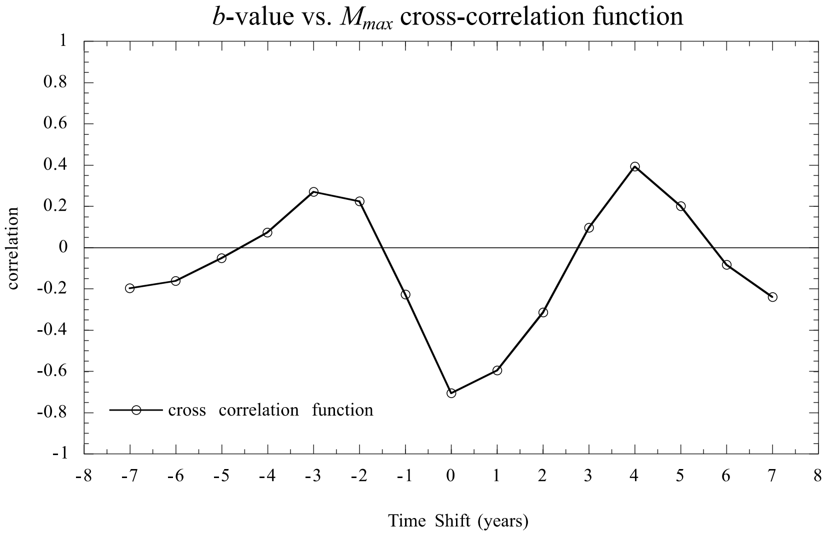

Figure 6
Correlation of cyclic variations in the temporal evolution of b-value and $M_{\max}$ in the Pacific Northwest. The strongly negative correlation at a time shift of 0 years indicates a strong anti-correlation in the cycles. The fact that a strong positive correlation cannot be found by time shifting the data is a result of the irregularity in the period of the cycles.

such clustering would display the systematic behavior noted here. However, this observation supports a basic prediction of the concept of intermittent criticality as described above.

It should be noted that the stationarity of the b-value that we describe here is contradicted by JAUMÉ and SYKES (1999). Their work asserts that accelerating moment release before large earthquakes is a direct result of a systematic decrease in the b-value. However, the changes in b-value observed by JAUMÉ and SYKES (1999) occur in the high-magnitude tail of the distribution (generally at $M > 5$). It is certainly true that an increase in $M_{\max}$ could be viewed as a change in the b-value for the largest events. However, b-value is generally thought to reflect the scaling of faults or other heterogeneities in the system (e.g., MOGI, 1962; KING, 1983). Thus, the variations of b-value in the high magnitude tail of the distribution described by JAUMÉ and SYKES (1999) can be viewed as an artifact of the more physically meaningful fluctuations in $M_{\max}$. This is supported by the observation that a maximum-likelihood calculation of the b-value is largely insensitive to fluctuations at higher magnitudes, as shown in figure 5.

Many previous works (BUFE and VARNES, 1993; BUFE *et al.*, 1994; SORNETTE and SAMMIS, 1995; SAMMIS *et al.*, 1996; BOWMAN *et al.*, 1998; BREHM and BRAILE, 1998; JAUMÉ and SYKES, 1999) have characterized accelerating seismicity before large earthquakes by fitting a power-law time to failure equation to some measure of cumulative seismic energy release (usually measured in Benioff strain) to the observed earthquake catalog. This approach is motivated by analogy to a critical point (SORNETTE and SAMMIS, 1995). However, the relatively small number of intermediate size events comprising this precursory acceleration makes the statistical significance of such analytical curve fits questionable (BOWMAN *et al.*, 1998). In this paper we have taken the alternative approach of attempting to indirectly measure the implied correlation length by simply tracking the maximum magnitude of seismicity in a region before and after a pair of large earthquakes. This approach, which is also motivated by analogy to the behavior of a system approaching a critical point, monitors the increase of correlation length approaching the ''critical event'' and the corresponding decrease in the correlation length following it. As earthquake catalogs improve in quality, observable fluctuations in either the a-value or $M_{\max}$ may provide a useful tool for seismic hazard assessment.

Acknowledgements

The authors acknowledge helpful discussions with Geoffrey King and James Dolan, as well as two anonymous reviewers. This research was funded by National Science Foundation grants EAR-0105405 (CGS) and EAR-0107129 (DDB) and through Cooperative Agreements EAR-0106924 and USGS-02HQAG0008 to the Southern California Earthquake Center. This is SCEC contribution number 602.

REFERENCES

BAK, P. and TANG, C. (1989), *Earthquakes as a Self-organized Critical Phenomenon*, J. Geophys. Res. *94*, 15,635–14,637.

BOWMAN, D. D., OUILLON, G., SAMMIS, C., G SORNETTE, A., and SORNETTE, D. (1998), *An Observational Test of the Critical Earthquake Concept*, J. Geophys. Res. *103*, 24,359–24,372, 1998.

BREHM, D. J. and BRAILE, L. W. (1998), *Intermediate-term Earthquake Prediction Using Precursory Events in the New Madrid Seismic Zone*, Bull. Seismol. Soc. Am. *88*, 564–580.

BUCKNAM, R. C., HEMPHIL-HALEY, E., and LEOPOLD, E. B. (1992), *Abrupt uplift within the past 1700 years at southern Puget Sound, Washington*, Science, *258*, 1611–1614.

BUFE, C. G. and VARNES, D. J. (1993), *Predictive Modelling of the Seismic Cycle of the Greater San Francisco Bay Region*, J. Geophys. Res. *98*, 9871–9883.

BUFE, C. G., NISHENKO, S. P., and VARNES, D. J. (1994), *Seismicity Trends and potential for large earthquakes in the Alaska-Aleutian Region*, Pure Appl. Geophys. *142,* 83–99.

DIETERICH, J., (1994),, *A constitutive Law for Rate of Earthquake Production and its Application to Earthquake Clustering*, J. Geophys. *Res. 99*, 2601–2618.

ELLSWORTH, W. L., LINDH, A. G., PRESCOTT, W. H., and HERD, D. J. The 1906 San Francisco Earthquake and the seismic cycle. In *Earthquake Prediction: An Internation. Review, Maurice Ewing Ser*., vol. 4, (D.W. Simpson and P.G. Richards, eds.) (AGU, Washington, D.C., 1981) pp. 126–140.

GELLER, R. J., JACKSON, D. D., KAGAN, Y. Y., and MULARGIA, F. (1997), *Earthquakes Cannot be Predicted*, Science, *275*, 1616–1617.

GRASSO, J. R. and SORNETTE, D. (1998), *Testing Self-organized Criticality by Induced Seismicity*, J. Geophys.Res., *103*, 29,965–29987.

GUTENBERG, B. and RICHTER, C. F. (1994), *Frequency of earthquakes in California*, Bull. Seismol. Soc. Am. *34*, 185–188.

HEIMPEL, M. (1997), Critical Behavior and the Evolution of Fault Strength during Earthquake Cycles, Nature, *388*, 865–868.

HUANG, SALEUR, Y., H. SAMMIS, C. G. and SORNETTE, D. (1998), *Precursors, Aftershocks, Criticality and self-organized criticality*, Europhys. Lett., *41*, 43–48.

JACKSON, D. D. (1996), *The Case for Huge Earthquakes*, Seismol. Res. Lett. *67*, 3–5.

JAUMÉ, S. C. and SYKES, L. R. (1999) *Evolving towards a Critical Point: A Review of Accelerating Moment/energy Release prior to Large and Great Earthquakes,* Pure Appl. Geophys. *155*, 279–306.

KAGAN, Y. Y. (1994), *Observational Evidence for Earthquakes as a Nonlinear Dynamic Process,* Physica D *77*, 160–192.

KING, G. (1983), *The Accommodation of Large Strains in the Upper Lithosphere of the Earth and other Solids by Self-similar Fault Systems: The Geometrical Origin of b-value*, Pure Appl. Geophys. *121*, 761–814.

KING and BOWMAN (2003), *The evolution of regional seismicity between large earthquakes,* J. Geophys. Res. *108*, 2096, doi: 10.1029/2001JB000783.

LUDWIN, R. S., WEAVER, C. S., and CROSSON, R. S., *Seismicity of Washington and Oregon* In *Neotectonics of North America,* (D. B. Slemmons, E. R. Engdahl, M. D., eds.) 1991.

ZOBACK, and BLACKWELL, D. D. *Decade of North American Geology Map Volume 1*, pp. 77–98, Geological Society of America, Boulder, 1991.

MA, L., and LUDWIN. R. S. (1987), *Can Focal Mechanisms be Used to Separate Subduction Zone from Intraplate Earthquakes in Western Washington*?, *EOS, Trans. Am. Geophys. Un. 68*, 46.

MOGI, K. (1962), *Study of Elastic Shocks Caused by the Fracture of Heterogeneous Materials and their Relation to Earthquake Phenomena*, *Bull. Earthquake Res. Inst. Univ. Tokyo, 40*, 125–73.

OLAMI, Z., FEDER, H. J. S., and CHRISTENSEN, K. (1992), *Self-organized Criticality in a Continuous, Nonconservative Cellular Automaton Modeling Earthquakes*, Phys. Rev. Lett. *68*, 1244–1247.

PAPAZACHOS, C. and PAPAZACHOS, B. (2001), *Precursory Accelerated Benioff Strain in the Aegean area*, Annali di Geofisica *44*, 461–474.

ROBINSON, R. (2000), *A Test of the Precursory Accelerating Moment Release Model on Some Recent New Zealand Earthquakes*, Geophys. J. Int. *140*, 568–576.

REASENBERG, P. A. and JONES, L. M. (1989), *Earthquake Hazard after a Mainshock in California*, Science *243*, 1173–1176.

SALEUR, H., SAMMIS, C. G., and SORNETTE, D. (1996) *Discrete Scale Invariance, Complex Fractal Dimensions, and Log-periodic Fluctuations in Seismicity*, J. Geophys. Res. *101*, 17,661–17,677.

SAMMIS, C. G., SORNETTE, D., and SALEUR, H. *Complexity and earthquake forecasting*. In *Reduction and Predictability of Natural Disasters, SFI Studies in the Sciences of Complexity*, vol. XXV, (J.B. Rundle, W. Klein, and D.L. Turcotte, eds.) , (Addison-Wesley, Reading, Mass., 1996) pp. 143–156.

SAMMIS, C. G. and SMITH, S. (1999), *Seismic Cycles and the Evolution of Stress Correlation in Cellular Automaton Models of Finite Fault Networks*, Pure Appl. Geophys. *155*, 307– 334.

SORNETTE D. and SAMMIS, C. G. (1995)*, Complex Critical Exponents from Renormalization Group Theory of Earthquakes : Implications for Earthquake Predictions*, J.I. Phys *5*, 607–619.

SORNETTE, A. and SORNETTE, D. (1989), *Self-organized Criticality and Earthquakes*, Europhys Lett. *9,* 197.

SYKES L. R. and JAUMÉ, S. (1990), *Seismic Activity on Neighboring Faults as a Long-term Precursor to Large Earthquakes in the San Francisco Bay Area*, Nature *348*, 595–599.

ZOBACK, M. D. and ZOBACK, M. L. *Tectonic stress field of North America and relative plate motions*. In *Neotectonics of North America* (D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell eds,) *Decade of North American Geology Map Volume 1*, (Geological Society of America, Boulder, 1991) pp. 339–366.

(Received September 27, 2002, revised April 25, 2003, accepted May 5, 2003)