Spatiotemporal scanning and statistical test of the accelerating moment release (AMR) model using Australian earthquake data

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Abstract

The cumulative Benioff strain release preceding twelve earthquakes was analyzed to test the Critical Point Hypothesis. The earthquakes occurred in Australia during the past 20 years and were larger than 5.0 in magnitude. Twelve earthquakes in the catalog were chosen based on a criterion for the number of nearby events. Of these, seven sequences with numerous events recorded leading up to the main earthquake exhibited accelerating moment release. Two occurred near in time and space to other earthquakes preceded by AMR. The remaining three sequences had very few events in the catalog so the lack of AMR detected in the analysis may be related to catalog incompleteness. Spatiotemporal scanning of AMR parameters shows that 80% of the areas in which AMR occurred experienced large events. In areas of similar background seismicity with no large events, 10 out of 12 cases exhibit no AMR, and two others are false alarms where AMR was observed but no large event followed. The relationship between AMR and Load-Unload Response Ratio (LURR) was studied. Both methods predict similar critical region sizes, but the critical point time using AMR is slightly earlier than the time of the critical point LURR anomaly.

Introduction

Increased intermediate magnitude seismicity (Sykes and Jaumé, 1990; Keilis-Borok et al., 1988, Knopoff et al., 1996) and accelerating seismic moment release (AMR) before large events (Bufe and Varnes, 1993; Bowman, 1998; Jaumé and Sykes, 1999) have been widely observed in recent years, and also have been cited as evidence for the critical state of the crust when a large earthquake is approaching.

The purpose of this study is to test the Critical Point Hypothesis by studying AMR features statistically in a tectonic setting different from the settings previously observed. We use Australian seismicity data (intra-plate rather than inter-plate earthquakes) and retrospectively test its predictive capability. The main questions are: How many large earthquakes are preceded by AMR and how many would be missed by this method? How many regions exhibiting AMR experience a later large event? How many regions where AMR is seen are exhibiting false alarms, with no following large event? We are also interested in the relation between AMR and Load-Unload Response Ratio (LURR) (Yin, 2000). Both AMR and LURR have been proposed as indicators that the crust within a region of study is approaching a critical state. Do these observations correlate with one another? Finally, do AMR and LURR predict a similar time, magnitude and critical region size prior to a large earthquake?

Methods

Using the least-square method, we fit the cumulative Benioff strain according to a time-to-failure formula

$$\Omega(t) = A + B\left(t_f - t\right)^m \tag{1}$$

A curvature parameter *C* (Bowman, 1998) is used to determine the quality of the fitting:

$$C = \frac{\textit{power law fit RMS error}}{\textit{linear law fit RMS error}} \tag{2}$$

The values of A, B and m in (1) that produce a minimum value of C are regarded as the best-fit values. Seismicity data within a circular region around a specified point is used in the fitting. We scan over regions with a range of radii to determine the optimal radius for minimization of C. This optimal radius is termed the critical region size, RC.

Results

AMR curves and optimal radius

Twelve earthquakes fitting a given criterion were chosen from 40 catalogued earthquakes with magnitudes greater than 5.0 occurring in Australia after 1980. Earthquakes met the criterion by having more than 30 events with magnitudes greater than 2.5 and within 200 km of the epicenter of a main earthquake recorded in the catalog. The results show that 7 events are preceded by AMR, and yield very good fits to (1) with high curvature (e.g. C<0.65, m~0.3). Figure 1 shows a plot of the typical cumulative Benioff strain and a plot of the best-fit values for C and m versus radius.

Two earthquakes occurred in nearly the same locations as events of similar magnitudes within very short time intervals (around 4 years). Hence, the sequences preceding these events were too short to be considered independent from the previous large event. There were three other cases in which the best-fit curvature parameter *C* and exponent *m* indicated no AMR. In these cases, re-examination indicated that the sequences had relatively little data (no more than 15 events prior to the main event), so it is possible that data paucity was responsible for the poor fits (e.g. m>0.8,C>0.7).

Relationship between the optimal radius and magnitude

Since our data cover a very limited magnitude range (5.0~5.5), we plotted our results together with the results of other researchers (Figure 2). The plots support the proposal that the critical region size scales with the magnitude of the earthquake (Bowman, 1998; Jaumé et al, 1999). It is also noticeable that our critical sizes are a little larger. A possible explanation is that the fault system is more stretched in intra-plate regions than in inter-plate regions.

AMR fitting in the region where there are no earthquakes with magnitude above 5.0

We randomly chose 12 points with enough data for the analysis but no large events during a curtain period, and determined the fit to (1). The results show that 10 out of 12 regions have no acceleration of Benioff release, and C and m values are larger than 0.6, mostly exceeding 0.7. The remaining two cases have good fits, which means false alarms would have been triggered using the AMR method.

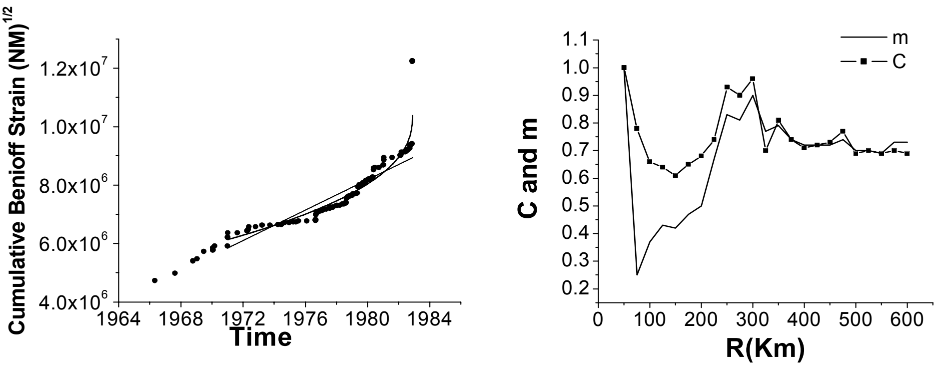

Figure 1 Typical cumulative Benioff strain and AMR fit (left), and best fit *C* and *m* versus radius (right) for the event on 21 Nov. 1982. The latitude and longitude are –37.2 and 146.9.

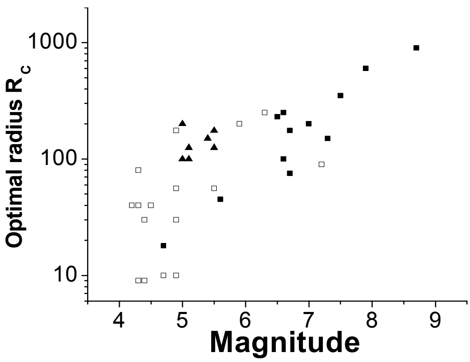

Figure 2 Relation between magnitude and optimal radius. Solid squares are results from Bowman (1998), open squares are from Brehm and Braile (1998), and solid triangles are our data. Note that the Bowman data is for California.

Spatiotemporal scanning of AMR parameters

In order to investigate how many AMR anomalies large earthquakes follow, we performed a spatiotemporal scan of AMR in Australia since 1980. The spatial range covered longitudes from 110 to 155 and latitudes from -45 to -11. A spatial interval of 0.2 degrees was used in the scanning, a time interval of 3 months was used for tf , and a radius of R = 125 km was used when selecting data from the earthquake catalog for analysis at each point. Since single large earthquakes can cause an apparent AMR anomaly, we neglect such anomalies in the following summary. In total, 24 AMR regions are detected and earthquakes above magnitude 4.5 follow in 20 of these regions. The remaining four cases are false alarms. It is possible that the false alarms are partly due to the uniform parameters for all points in the scanning (such as the fixed radius of 125 km) and the circular regions used to select the events. Further work would be required in order to test this possibility.

Relation between AMR and LURR

For each of the 7 earthquakes, we calculated AMR and LURR as well as the optimal radius. We found that the optimal radius for LURR (corresponding to maximum LURR value) is almost the same as the optimal radius for AMR (corresponding to minimum C and m).

By comparing LURR versus time plots with plots of C and m versus time (Figure 3), we found that earthquakes occur 1.2 to 3.2 years (average 1.9) after the LURR value begins to rise, and 0.3- 2 years (average 1) after the LURR value reaches its maximum. In contrast, for m and C values, earthquakes mostly occur 1.7 –12 years after C and m values begin to decrease (the average is 3.5 years excluding the largest value of 12), and 1 to 9 years (the average is 1.3 years excluding the largest value of 9) after C and m values reach a minimum. Hence, AMR predictions for tf appear to occur a little earlier than LURR peaks, or equivalently, the LURR method appears to provide a shorter-term prediction than the AMR method.

Discussion and Conclusions

The results of this study provide support for use of the AMR model for earthquake forecasting and for the Critical Point Hypothesis. Our results show that seven of the events with magnitudes greater than 5.0 and sufficient data (defined here as more than 15 events within the optimal radius) are preceded by accelerating Benioff strain release. The results also suggest that if two events of similar magnitude occur in the same region within a short time interval, the AMR model will fail to predict the second event, possibly due to interference with the first event.

The optimal region size for AMR scales with the magnitude, in agreement with previous results, but the critical size in Australia is slightly larger than that in California. This may be related to the difference between intraplate fault systems and interplate fault systems. The fitting time period also roughly scales with the magnitude, but it should be constrained by the recurrence time of similar magnitude events in that area.

In regions of similar seismicity without large earthquakes but with enough data for the analysis, most cases (10 out of 12) do not exhibit AMR and an optimal region size cannot be determined. Two false alarms were found where AMR was not followed by a large event. In a spatiotemporal scanning study, earthquakes follow 83% of AMR anomalies and 17% of the AMR anomalies are false alarms.

LURR and AMR predict a similar critical region size, but the critical time predicted by AMR is observed to be a little earlier than the time of LURR peaks. The mechanisms for AMR and LURR need to be better understood to comprehend the significance of this observation.

Although AMR has some predictive capability, further research is required in order to apply AMR to the practice of earthquake prediction. The present study raises several questions. The first is: Do the these earthquakes which can not be fit well really have no AMR beforehand or is it a symptom of incomplete catalogs due to too few seismograph stations nearby? If there is no AMR beforehand, then AMR and critical point theory may fail in a certain percentage of cases. If it is a catalog problem, then improved monitoring may decrease the failure rate of AMR.

Another interesting question is: In what circumstances does AMR appear prior to the large events? According to Jaumé (1999), three possible necessary conditions for AMR are: a certain degree of heterogeneity in the fault system, the density of faults or asperities, and the presence of a sufficiently large earthquake. Another potential factor may be the loading rate of tectonic stress. It is suggested by Vidale et al. (1998) that preseismic stress rates in fault zones are much higher than long-term tectonic stress rates. Does this high stress rate within the fault zone contribute to AMR? In other words, is AMR mainly caused by relatively high stress rates or stress evolution under constant or low loading rates? What kind of parameters control C and m in Equation (1), and what controls the optimal size Rc?

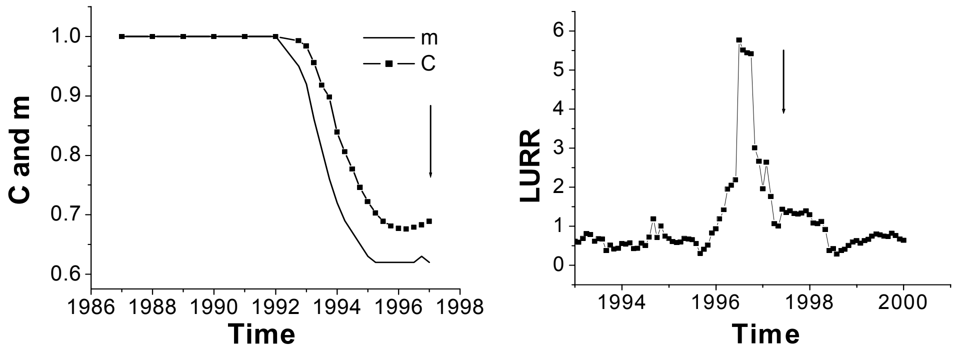

Figure 3. Plot of LURR values versus time before earthquakes (left) and plots of *C* and *m* values versus time (right) before the earthquake on 5 May, 1997 at (–33.82, 138.97). The arrow indicates when the above magnitude 5 earthquake occurred.

The relationship between LURR and AMR deserves further study. For example, what percentage of large earthquakes is preceded by both phenomena? How many earthquakes does only one or none of these phenomena precede? While they are both observed just prior to a large earthquake, one could ask, is high LURR generally cause by increased seismicity in loading cycles, or by decreased seismicity in unloading cycles, or increased seismicity in both cycles, but at a much faster rate in loading cycles? What is the mechanism responsible for this? Is there a common physical basis behind AMR and LURR as suggested by the common critical scaling region (Yin et al, 2002)? These questions could be studied further using good quality earthquake data or using numerical simulations.

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