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ACCELERATING MOMENT RELEASE IN AREAS OF HIGH STRESS?

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Accelerating Moment Release in Areas of High Stress? Preliminary Results

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Abstract

Several retrospective analyses have proposed that significant increases in moment release occurred prior to many large California earthquakes of recent time. However, the finding of accelerating moment release (AMR) strongly depends on the choice of several parameters (magnitude range, area being considered surrounding the events, time period prior to large earthquake) and the AMR analysis may appear as a data-fitting exercise with no new predictive power. As AMR may relate to a state of high stress around the eventual next epicenter, it is interesting to compare the AMR results to models of stress accumulation in California. Instead of assuming a complete stress drop on all surrounding fault segments implied by the back-slip stress lobe method of *Bowman and King* [1992], we consider that stress evolves dynamically, punctuated by the occurrence of earthquakes and governed by the elastic and viscous properties of the lithosphere [e.g., *Freed et al*., 2007]. We study the seismicity of California obtained from the ANSS catalog between 32N and 40N since 1911 and extract events for AMR calculations following the systematic approach employed in previous studies. To quantify the AMR, we examine the ratio (c-value) between the root mean square of a power-law time-to-failure function versus a linear fit to the cumulative energy of events. Using Nutcracker, a stress and seismicity analysis software, we generate several sensitivity tests of the method, as well as a first grid-search analysis for a few large events in Southern California (Kern County, Landers and Loma Prieta). With the same optimized AMR parameters as Bowman, the grid search results show that the regions surrounding the earthquakes have the smallest c-value. That may be interpreted as a positive result for the AMR analysis. However the AMR parameters are first chosen in order to get the smallest c-value at the epicenter of each particular event and they are different for each earthquake. We also present here a more general AMR analysis from 1955 to today with a fixed magnitude range, radius of area and period of time. We compare these results to the occurrence of large events in time and to maps of Coulomb stress changes due to all M>7.0 earthquakes since 1812, subsequent postseismic relaxation and interseismic strain accumulation. The goal of this comparison is to evaluate if areas inferred to be highly stressed also exhibit significant evidence of accelerating seismicity.

Significance and Objectives

It has been proposed that significant increases in moment release occurred prior to many large California earthquakes of recent times [*Bowman and King*, 2001; *Bowman, et al*., 1998; *Bufe and Varnes*, 1993; *Ellsworth, et al*., 1981; *Jaumé and Sykes*, 1999; *Sammis, et al*., 2004]. Precursory accelerating seismicity has also been suggested in other regions of the world [*Lindh*, 1990; *Mignan, et al*., 2006; *Robinson*, 2000]. Most of these analyses were retrospective forecasts or "postdictions" [*Sammis, et al*., 2004], and the evidence for accelerating moment release (AMR) depends on the choice of the area being considered surrounding such events. Some prospective forecasts have been undertaken and some success been reported [*Bowman, et al*., 2003; *Bufe, et al*., 1994]. Related methods, such as the Pattern Informatics approach by Rundle and colleagues [*Rundle, et al*., 2002; *Rundle, et al*., 2003] identify correlated regions of seismicity in catalog data that are thought to precede a main shock by months and years. A large number of models have been proposed to explain the mechanical source of AMR-type behavior including intermittent criticality, damage mechanics, critical stress accumulation, and Coulomb stress interaction [*Bufe and Varnes*, 1993; *King and Bowman*, 2003; *Rundle, et al*., 2002].

A key challenge in using AMR analysis to improve the precision of earthquake forecasts is to determine the area over which seismicity is being evaluated and where stress is thought to be close to critical levels. Earlier studies considered circular regions of varying radii (e.g., Figure 1b). *Bowman et al*. [1998] suggest that the size of the critical region of significant AMR in past events scales with the magnitude of the concluding earthquake and thus needs to be scaled appropriately for each event. A critical analysis of the AMR approach employing circular regions by *Michael et al*. [2006] suggests that the evidence for AMR may be biased by optimizing the time period, area, and sometimes magnitude range analyzed before each mainshock. Following the approach of *Bowman et al*. [1998], *Michael et al*. [2006] conduct an analysis of both real and synthetic catalogs of southern California seismicity to ultimately "suggest that the AMR observed using this method is actually the result of data-fitting and does not represent a real, precursory process".

As AMR may relate to the level of stress loading the impending rupture, *Bowman and King* [2001; *King and Bowman*, 2003] propose that the critical region of high stress and likely moment-release acceleration is one that is better represented by high-stress areas determined with a back-slip dislocation model of the final rupture. In retrospective studies "recovering" Coulomb stress lobes are modeled using the reverse of the earthquake-rupture slip model, in prospective studies various potential scenario earthquakes need to be considered. With this stress recovery method a specific pattern of stress is being considered which is equivalent to that being produced by aseismic and/or seismic slip of the fault plane adjoining and below the future rupture (*Bowman and King*, 2001, Figure 1a). Similar to the optimization procedure in finding the critical region in circular areas, an optimal Coulomb stress contour is determined (Figure 1b), within which AMR is inferred to occur. This model is clearly a first-order representation of the pre-rupture stress, as it assumes complete relief of stress on all but the impending rupture plane. Use of this technique for earthquake forecasting or prediction is complicated by the required knowledge of the fault or fault segments that will rupture in future events [*Bowman and King*, 2001]. Nonetheless, systematic evaluation of a large number of rupture segment scenarios can be undertaken (e.g., [*Mignan, et al*., 2006]).

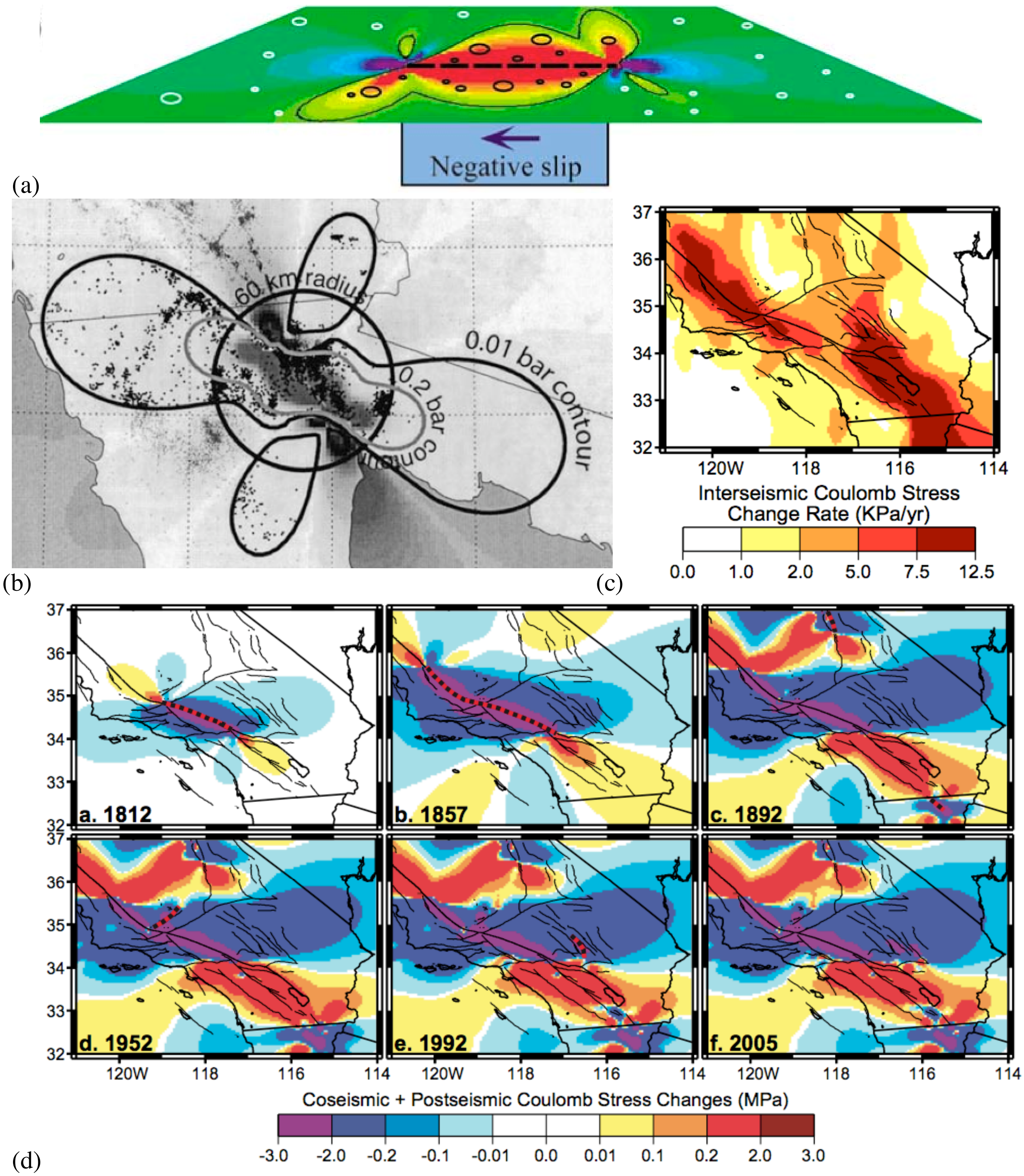

Figure 1. (a) Illustration of back-slip approach to identify areas of high stress prior to a large earthquake rupture based on the assumption that slip has occurred either by creep or seismic rupture on the adjoining fault plane (modified from Bowman and King, 2001). (b) Example of circular and back-slip stress-lobe areas evaluated for AMR prior to events in Baja California (modified from Sammis et al., 2004). (c) Interseismic stressing rate (Coulomb stress on N40°W fault planes assuming $\mu' = 0.4$) derived from geodetic SCEC CMM 3 velocity field. (d) Contributions from co- and postseismic deformation of M>6.5 earthquakes since 1812 to the evolving stress field in southern California. Stress is assumed to be uniform prior to the starting period.

Introduction

Several retrospective analyses have proposed that significant increases in moment release occurred prior to many large earthquakes of recent times. However, the finding of Accelerating Moment Release (AMR) strongly depends on the choice of several parameters (magnitude range, area being considered surrounding the events, time period prior to the large earthquake) and the AMR analysis may appear as a data-fitting exercise with no new predictive power. As AMR may relate to a state of high stress around the eventual next epicenter, it is interesting to compare the AMR results to models of stress accumulation in California. Instead of assuming a complete stress drop on all surrounding fault segments implied by the back-slip stress lobe method [*Bowman and King*, 2001], we consider that stress evolves dynamically, punctuated by the occurrence of earthquakes and governed by the elastic and viscous properties of the lithosphere [*Freed et al*., 2007]. We generate several sensitivity tests of the method, as well as a first grid-search analysis for a few large events in Southern California. We also present here a comparison of a more general AMR analysis from 1965 to today with maps of Coulomb stress changes due to all M≥7.0 since 1812, subsequent postseismic relaxation and interseismic strain accumulation.

The AMR concept and data

It has been found that an increase in the number of intermediate earthquakes occurs before a large event, which produces a regional increase in the cumulative Benioff strain. This cumulative Benioff strain can be fit by a power law time-to-failure relation (Bowman et al., 1998), which has the following form:

$$\varepsilon(t) = A + B(t_c - t)^m$$

and

$$\varepsilon(t) = \sum_{i=1}^{N(t)} \sqrt{E_i(t)}$$

where ε(t) is the Benioff strain, N is the number of earthquakes considered, E is the energy of individual earthquakes, tc is the time of the large earthquake and A is the value of the Benioff strain when t=tc. The energy of each particular seismic event is defined as:

log(E)=4.8+1.5Ms

To quantify the AMR, we examine the ratio called c-value between the root-mean-square of a power-law time-to-failure function versus a linear fit to the cumulative energy of events. When the c-value is smaller than 0.7, we may consider a case of AMR. The cumulative Benioff strain is then better fit by a power law than by a linear trend.

In the case of using a circular search area for AMR, several parameters (magnitude range, area surrounding the events, time period prior to large earthquake) are required according to the choice of the mainshock studied and the AMR results depends on them.

We study the seismicity of southern California obtained from the ANSS catalog between 32N and 40N latitude since 1910 with a minimum magnitude 3.5. We extract events for AMR calculations following the systematic approach employed in previous studies. We use Nutcracker, a stress and seismicity analysis software to perform all the AMR calculations.

Grid search of AMR for three California earthquakes

Figure 2 presents two different maps for two large earthquakes of California: Kern County in 1952 and Loma Prieta in 1989. Each map shows the c-values obtained by a grid search analysis over southern California using the same parameters used by *Bowman et al*. *[*1998]: radius of the circular search, period of time and magnitude range. The location of the mainshock is indicated by the star, the seismicity used in the search is represented by black dots.

The first grid search analysis was done with the goal of testing the concept of AMR and to answer the question: Can one find other regions of small c-values with the same parameters outside of the mainshock area?

On the contrary, the two mainshocks are located in the main areas of small c-values at the time of the respective main shocks. The choice of AMR parameters made by Bowman does not result in other potential regions of apparent AMR. However we still have to adjust the three parameters according to the mainshock we study.

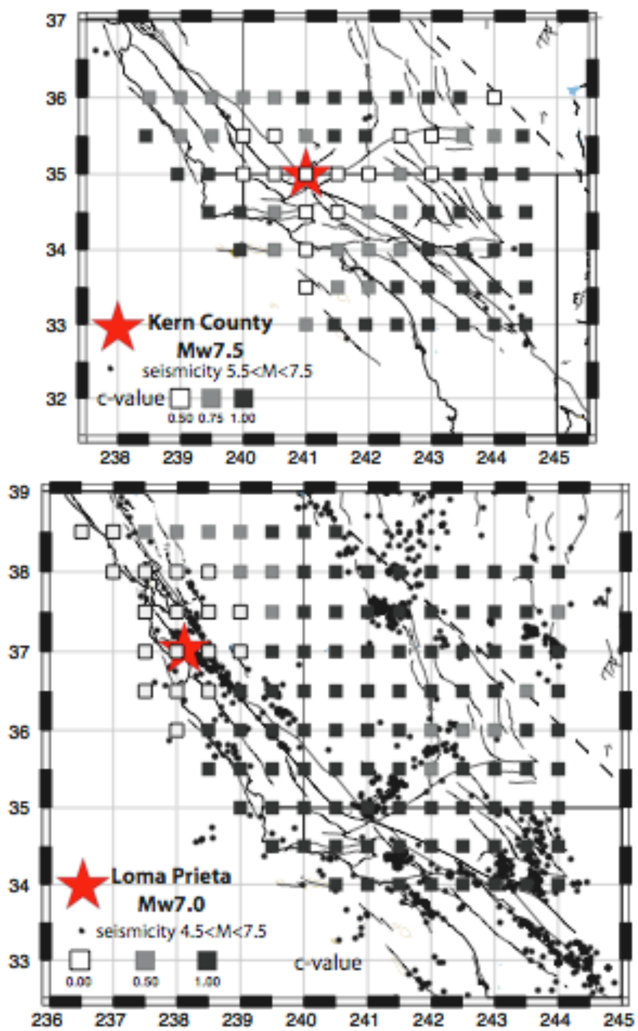

Figure 2. Grid search analysis of AMR for Kern County and Loma Prieta.

AMR grid search maps versus stress change maps

The AMR concept can be interpreted as a data-fitting exercise since there is no general relationship between the radius of the search, the magnitude range and the period of time before the mainshock according to its magnitude. However, based on the results of Bowman et al. (1998), the AMR circular search seems to be optimal between 150 km and 250 km around a magnitude 6.5-7.5 event. Figure 3 presents maps of c-values for a possible M7 event in southern California, using a 30-year period of time and three radii: 150 km, 200 km and 250 km. The occurrence of large earthquakes during the tested period increases the c-value, meaning that there is no significant AMR at that time and location. Once the seismicity associated with this event is no longer included in the data set, the results are in better agreement with the seismicity. This is particularly the case for Loma Prieta in 1989 and for Hector Mine in 1999.

Figure 3 also presents a comparison between the AMR grid search results and models of stress change over southern California in order to evaluate if areas inferred to be highly stressed also exhibit significant evidence of accelerating seismicity. Rather than assuming a complete stress drop on all surrounding fault segments implied by the back-slip stress lobe [*Bowman and King*, 2001], we consider that stress evolves with time from contributions of coseismic, postseismic and interseismic processes, governed by the elastic and viscous properties of the lithosphere. This emphasizes the importance of postseismic relaxation processes in time-dependent stress transfer and resulting earthquake hazard. Except for the contributions from the largest earthquakes, there is no large variation in the stress pattern with time. The AMR and stress change maps do not look similar when there are many large earthquakes in the periods of the AMR calculations. However, they present similar features in 1985 and 1995.

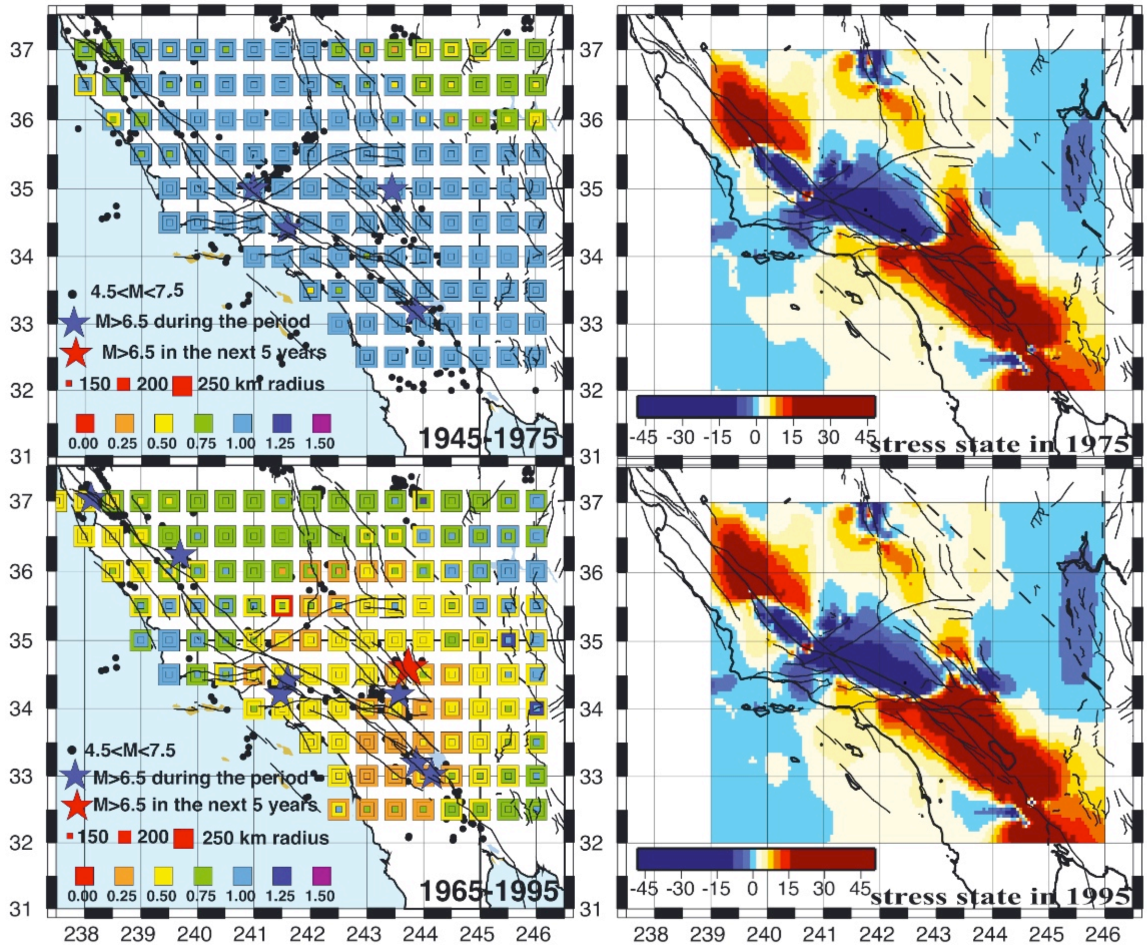

Figure 3. Examples of comparison of maps of c-values from AMR circular grid search and of state of stress (bars) for 1975 and 1995.

Discussion and future work

The present work shows the first grid search analysis done for AMR. Adjusting three major parameters of the AMR circular search (radius of the circular region, magnitude range of background seismicity and time period considered), the results of the AMR are positive for large earthquakes in southern California. The comparison of a more general AMR grid search over southern California and stress maps from 1965 to 2005 shows more variable results. The AMR is sensitive to the time and location of larger events during the period of time considered. If a large shock occurs near the beginning of the tested period, the c-value will be larger at the end of the period than if the major earthquake occurs later.

More research has to be done especially in the direct comparison of the stress state with seismicity patterns. It would be interesting to remove all the aftershock sequences and test again the similarity between AMR and stress change in southern California. Also, the work should evolve from an AMR circular search to a direct evaluation of a correlation between areas of high stress and AMR.

References

Bowman, D., and G. C. P. King (2001), Accelerating seismicity and stress accumulation before large earthquakes, *Geophys. Res. Lett.*, *28*, 4039-4042.

Bowman, D. D., J. Clark, and N. Ikeda (2003), Accelerating moment release as a tool for seismic hazard assessment in southern California, *Paper presented at the 2003 Annual Meeting, Southern California Earthquake Center, Oxnard, Calif.*

Bowman, D. D., G. Ouillon, C. G. Sammis, A. Sornette, and D. Sornette (1998), An observational test of the critical earthquake concept, *Journal of Geophysical Research*, *103*, 24,359-324,372.

Bufe, C. G., S. P. Nishenko, and D. J. Varnes (1994), Seismicity trends and potential for large earthquakes in the Alaska-Aleutian region, *Pure and Applied Geophysics*, *142*, 83-99.

Bufe, C. G., and D. J. Varnes (1993), Predictive modelling of the seismic cycle of the greater San Francisco bay region, *Journal of Geophysical Research*, *98*, 9871-9883.

Deng, J., and L. R. Sykes (1997), Evolution of the stress field in southern California and triggering of moderate-size earthquakes: A 200-year perspective, *Journal of Geophysical Research*, *102*, 9859-9886.

Ellsworth, W. L., A. G. Lindh, W. H. Prescott, and D. G. Herd (1981), The 1906 San Francisco earthquake and the seismic cycle, in *Earthquake Prediction*, edited by D. W. Sinpson and P. G. Richards, American Geophysical Union, Washington, D.C.

Freed, A. M., and R. Bürgmann (2004), Evidence of powerlaw flow in the Mojave desert mantle, *Nature*, *430*, 548-551.

Freed, A. M., and J. Lin (2001), Delayed triggering of the 1999 Hector Mine earthquake by viscoelastic stress transfer, *Nature*, *411*, 180-183.

Freed, A. M., and J. Lin (2002), Accelerated stress buildup on the southern San Andreas fault and surrounding regions caused by Mojave Desert earthquakes, *Geology*, *30*, 571–574.

Freed, A.M., S.T. Ali, and R. Burgmann (2007), Evolution of stress in Southern California for the past 200 years from coseismic, postseismic and interseismic stress changes, Geophys. Journ. Intern., 169, doi: 10.1111/j.1365-1246X.2007.03391.x.

Hardebeck, J.L., K.R. Felzer, and A.J. Michael (2007), Rigorous observational tests contradict the Accelerating Moment Release hypothesis, unpublished manuscript.

Jaumé, S. C., and L. R. Sykes (1999), Evolving towards a critical point: A review of accelerating moment/energy release prior to large and great earthquakes, *Pure and Applied Geophysics*, *155*, 279-306.

Kagan, Y. Y., D. D. Jackson, and Y. F. Rong (2006), A new catalog of southern California earthquakes, 1800-2005, *Seismol. Res. Lett.*, *77*, 30-38.

King, G. C. P., and D. Bowman (2003), The evolution of regional seismicity between large earthquakes, *Journal of Geophysical Research*, *108*, doi:10.1029/2001JB000783.

Lindh, A. G. (1990), The seismic cycle pursued, *Nature*, *348*, 580-581.

Michael, A. J., K. Felzer, and J. Hardebeck (2006), Precursory accelerating moment release: fact or data-fitting fiction, *Seismol. Res. Lett.*, *77*.

Mignan, A., G. C. P. King, D. Bowman, R. Lacassin, and R. Dmowska (2006), Seismic activity in the Sumatra-Java region prior to the December 26, 2004 (Mw = 9.0-9.3) and March 28, 2005 (Mw = 8.7) earthquakes, *Earth and Planetary Science Letters*, *244*, 639-654.

Nutcracker v.X.1.5, geology/fullerton.edu/dBowman/Site/Downloads.html

Pollitz, F., W. H. Bakun, and M. Nyst (2005), A physical model for strain accumulation in the San Francisco Bay region: Stress evolution since 1838, *Journal of Geophysical Research*, *109*, doi:10.1029/2004JB003003.

Robinson, R. (2000), A Test of the precursory accelerating moment release model on some recent New Zealand earthquakes, *Geophysical Journal International*, *140*.

Rockwell, T. K., S. Lindvall, M. Herzberg, D. Murbach, T. Dawson, and G. Berger (2000), Paleoseismology of the Johnson Valley, Kickapoo, and Homestead Valley faults: Clustering of earthquakes in the eastern California shear zone, *Bull. Seism. Soc. Am.*, *90*, 1200-1236.

Rundle, J. B., K. F. Tiampo, W. Klein, and J. S. S. Martins (2002), Self-organization in leaky threshold systems: The influence of near-mean field dynamics and its implications for earthquakes, neurobiology, and forecasting, *Proc. Natl. Acad. Sci. U.S.A.*, *99*, 2514-2521.

Rundle, J. B., D. L. Turcotte, R. Sherbakov, W. Klein, and C. G. Sammis (2003), Statistical physics approach to understanding the multiscale dynamics of earthquake fault system, *Reviews of Geophysics*, *41*, doi:10.1029/2003RG000135.

Sammis, C. G., D. Bowman, and G. C. P. King (2004), Anomalous seismicity and accelerating moment release preceding the 2001 and 2002 earthquakes in Northern Baja California, Mexico, *Pure and Applied Geophysics*, *161*, 2369-2378.