Pure appl. geophys. 161 (2004) 2369–2378
0033 – 4553/04/122369 – 10
DOI 10.1007/s00024-004-2569-3

Pure and Applied Geophysics

Anomalous Seismicity and Accelerating Moment Release Preceding the 2001 and 2002 Earthquakes in Northern Baja California, Mexico

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Abstract—An algorithm recently developed by RUNDLE *et al.* (2002) to find regions of anomalous seismic activity associated with large earthquakes identified the location of an $M_w = 5.6$ earthquake near Calexico, Mexico. In this paper we analyze the regional seismicity before this event, and a nearby $M_w = 5.7$ event, using time-to-failure algorithms developed by BOWMAN *et al.* (1998) and BOWMAN and KING (2001a,b). The former finds the radius of a circular region surrounding the epicenter that optimizes the time-to-failure acceleration of seismic release. The latter optimizes acceleration based on the expected stress accumulation pattern for a dislocation source. Both methods found a period of accelerating seismicity in an optimal region, the size of which agrees with previously proposed scaling relations. This positive result suggests that the Rundle algorithm may provide a useful technique to identify regions of accelerating seismicity, which can then be analyzed using signal optimization time-to-failure techniques.

Key words: Seismicity, seismic hazard assessment, earthquake prediction, earthquake physics, earthquake stress interactions.

Introduction

Many large earthquakes are preceded by a regional increase in seismic energy release. This phenomenon, called ‘‘accelerating moment release’’ (AMR), is due primarily to an increase in the number of intermediate-size events and occurs within a distance R of the main shock that scales with magnitude. AMR has been observed before large earthquakes in many locations (see summary by JAUMÉ and SYKES, 1999).

All of these observations are ‘‘postdictions’’ in the sense that the location of the main event was known and used as the center of the search pattern. The challenge is to use AMR in a predictive mode. One approach has been to use a circle of radius R (corresponding to a prescribed magnitude M in the scaling relation described below) to search a grid for accelerating activity (see PAPAZACHOS and PAPAZACHOS, 2001;

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ROBINSON, 2000; BREHM and BRAILE, 1999; YANG *et al.*2001). Another approach is to search each element of a grid for activity that currently exceeds its long-term average. Figure 1 shows such a grid search recently published by RUNDLE *et al.* (2002). This paper is interesting because it postdicted several large events (marked by triangles on the figure), however especially because the algorithm predicted a moderate-sized event in an area of anomalously high activity which experienced a $M_w = 5.6$ event subsequent to the paper's publication. In this paper we explore this

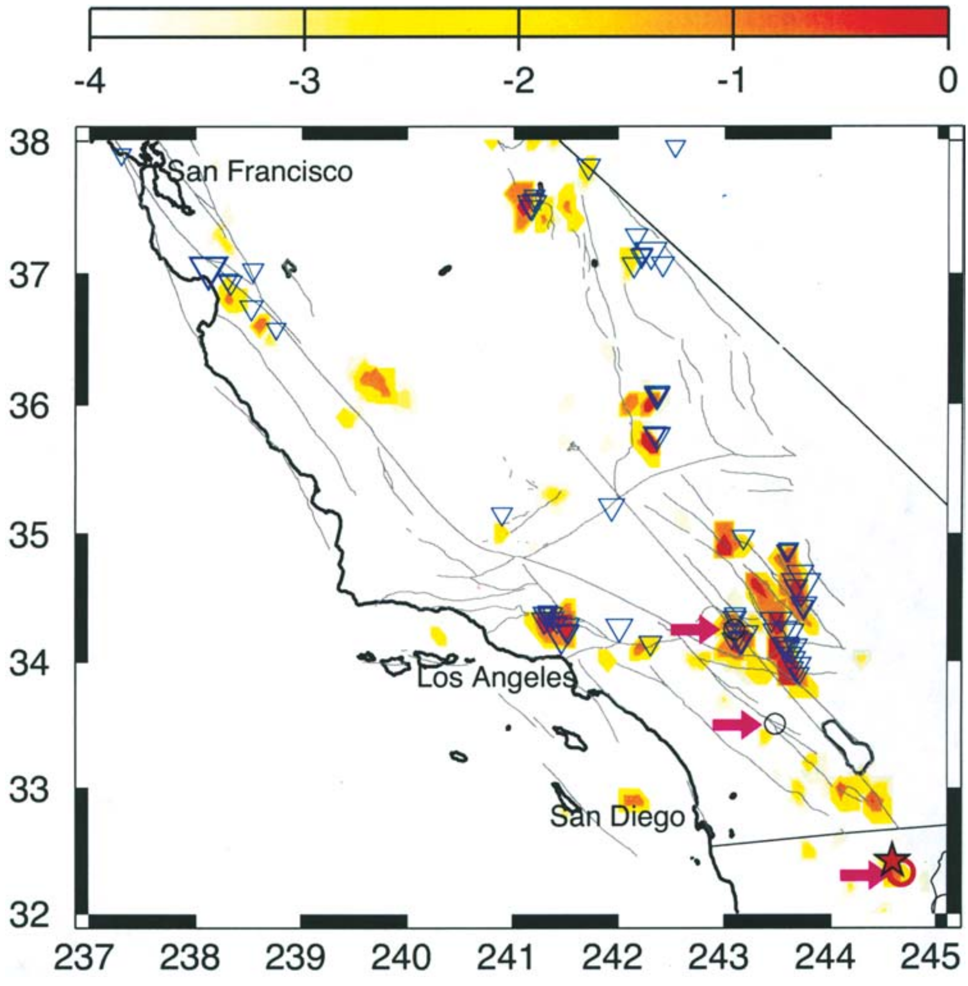


Figure 1
Regions of anomalous seismicity found by RUNDLE *et al.* (2002). Warmer colors indicate regions of increasingly anomalous activity (see TIAMPO *et al.*, 2002 for details). Triangles are events that occurred during the learning phase of their algorithm. Circles are events that occurred after the learning phase, but before the end of the study (highlighted by pink arrows). The red circle in the southeastern quadrant of the map is the December 8, 2001 $M_w = 5.7$ event. The star indicates the location of a M_w 5.6 event that happened on February 22, 2002, after the paper's submission.

event using the full AMR analysis to see if the anomalous activity detected by RUNDLE *et al.* (2002) is consistent with the AMR hypothesis.

AMR preceding the 2002 Calexico Earthquake

The $M_w = 5.6$ Calexico earthquake, shown as the star in Figure 1, occurred on February 22, 2002 about 29 miles south of Calexico, Mexico along the eastern flank of the Sierra Cucapa in Baja California. It was preceded on December 8, 2001 by a similar $M_w = 5.7$ earthquake to the southeast (red circle on the map in Fig. 1). In our analysis we treat the earthquakes as a double event and consider any precursory activity to apply to the pair. We first analyze precursory regional seismicity using the optimal circle method developed by BOWMAN *et al.* (1998). We then apply a more sophisticated stress accumulation method recently developed by BOWMAN and KING (2001a,b).

The Optimum Circle Method

In this approach, the cumulative Benioff strain is calculated for seismicity within a sequence of circles of increasing radius R. For each circle the cumulative Benioff strain is fit to a straight line and to a time-to-failure equation of the form

$$\varepsilon(t) = A + B(t_c - t)^m, \tag{1}$$

where cumulative Benioff strain at time t is defined as

$$\varepsilon(t) = \sum_{i=1}^{N(t)} [E_i(t)]^{1/2}. \tag{2}$$

In equation (1), t_c is the time of the event, E_i is the energy release of the i-th event, m is assumed to have a value of 0.3, and A and B are adjustable parameters. A fit parameter ξ is defined as the ratio of the sum of the squared residuals from the fit of equation (1) to the sum of the squared residuals from a linear fit. Figure 2 shows this parameter as a function of the analysis radius R for the 2002 Calexico event.

Note that the fit of equation (1) relative to a linear increase is optimal for $R = 60 \pm 10$ km, as indicated by the minimum in the ξ parameter. Figure 3 shows that this optimal R is consistent with the scaling relations found by BOWMAN *et al.* (1998) and other investigators.

The Stress Accumulation Method

Previous works have used simple geometrical shapes to define regions of accelerating seismicity. BOWMAN and KING (2001a,b) have advanced this analysis

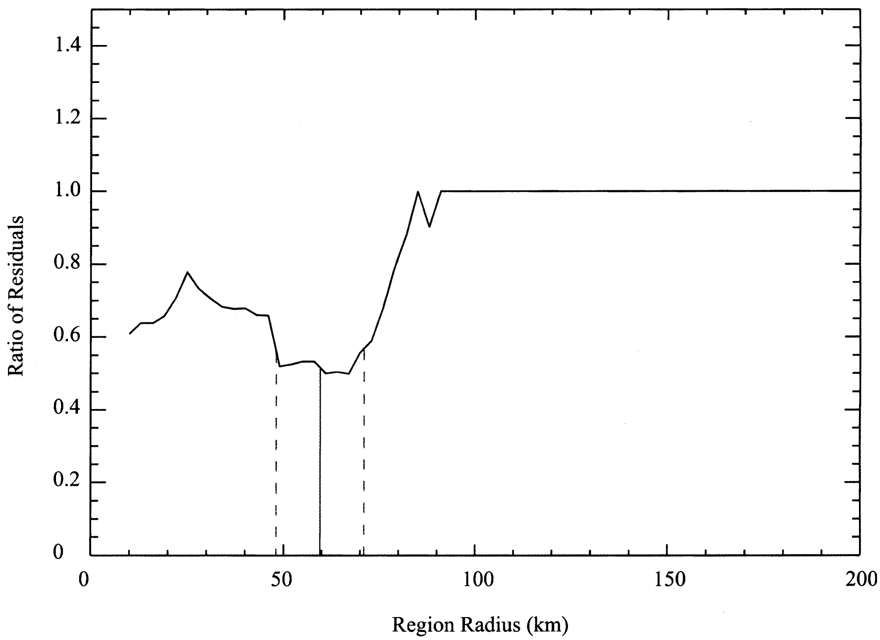


Figure 2
Ratio of residuals, ξ, as a function of region radius, R, found using the optimum circle method. The minimum occurs at 60 $\pm$ 10 km.

by using a simple backslip dislocation model to identify the areas around a known event where accelerating moment release is expected. Their approach is schematically illustrated in Figure 4 which shows the stress field created by summing a combination of slip (either seismic or aseismic) on adjacent segments and creep on a planar extension of the fault at depth. This stress field is identical to the stress field that would be created by slipping the locked patch with the opposite sense of motion (Fig. 4b). In a simple single-fault model, this is equivalent to the stress shadow from the previous large event on the fault being eroded by tectonic loading and stress transfer. The physical basis of the backslip model is developed by SAVAGE (1983), and its relationship to both regional seismicity and more conventional Coulomb models is fully described by KING and BOWMAN (2002).

The Calexico earthquakes occurred on two neighboring fault segments in two discrete events of roughly equivalent size. This requires a generalization of the model of BOWMAN and KING (2001a,b) to account for multiple events. The essential physics of the loading remains the same. However, in the case of multiple events, the stress field created by the loading at depth is accommodated on two or more parallel or *en echelon* structures in the seismogenic crust (Fig. 4c). Since the stress accumulation

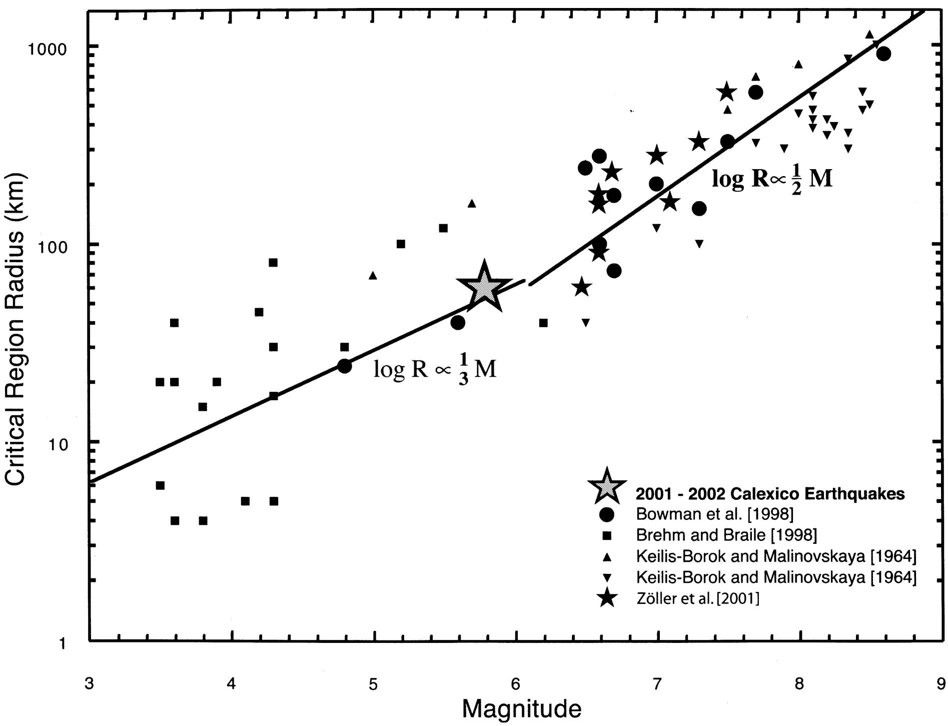
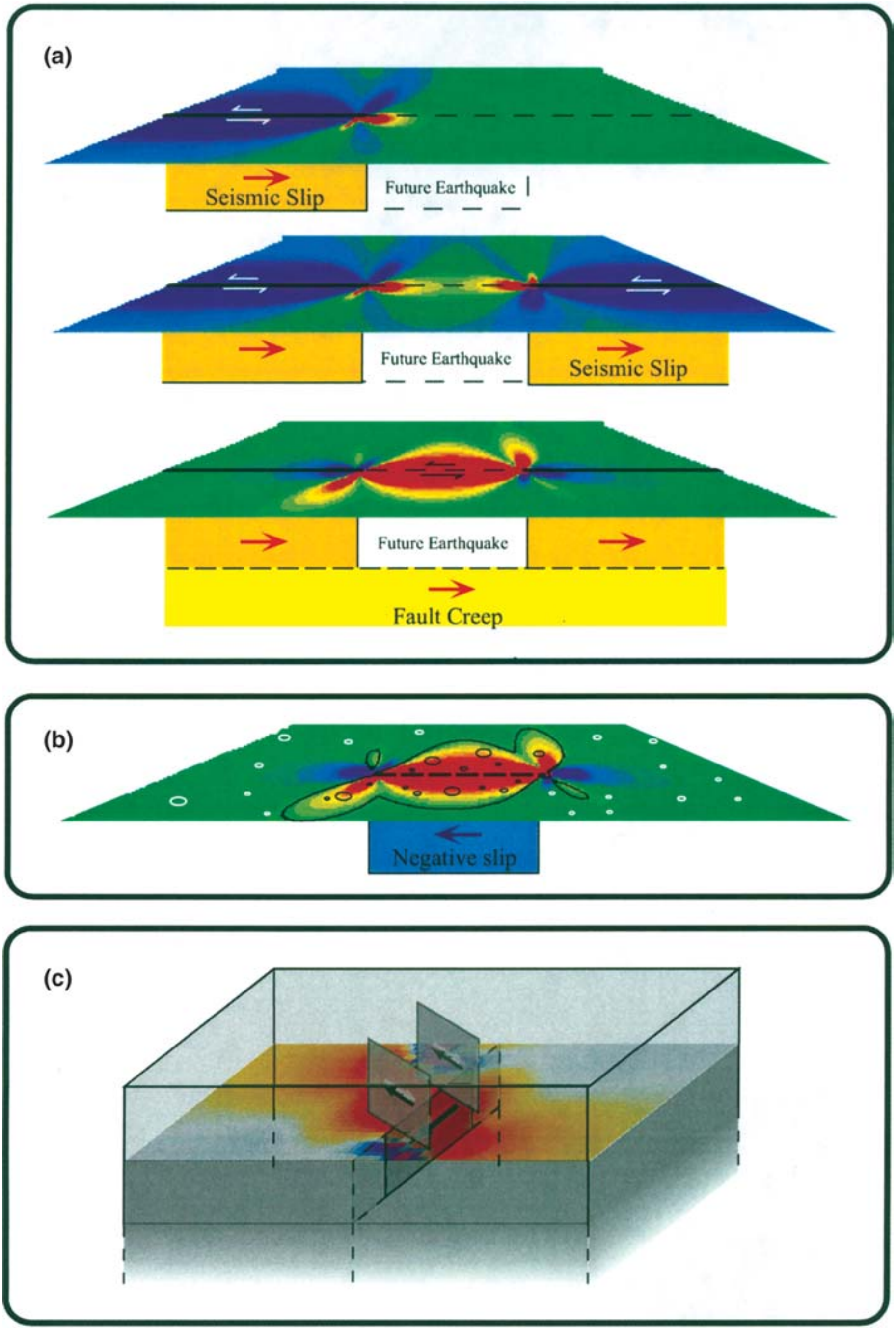


Figure 3

Critical region radius as a function of magnitude of the main event. This is a composite from studies by BOWMAN *et al.* (1998), BREHM and BRAILE (1998), KEILIS-BOROK and MALINOVSKAYA (1964) and ZÖLLER *et al.* (2001). The large star shows the $R = 60$ km found here for the Calexico earthquakes, which is consistent with optimal radii estimated in the other studies.

model uses the stress field created by the loading from slip on a discrete structure at depth, the most appropriate loading model for these events is a single fault plane cutting both *en echelon* segments. The region of stress increase created by loading this simplified structure can then be used to define the region of accelerating seismicity before the two events.

As discussed by BOWMAN and KING (2001a,b), the stress contour that optimizes the acceleration is used to define the border of the critical region. The optimum stress contour is found by a procedure similar to the optimization of R in the circle analysis. However, for this analysis we extend the procedure by also searching for the best starting time, $t_{\min}$, for the fit to the power-law time-to-failure Equation (1). For a range of values of $t_{\min}$ and R we calculate the fit parameter, ξ, which is again defined as the ratio of the residuals to the power-law and linear fits. The region of accelerating seismicity is then found by searching stress-time space for the lowest value of ξ. Figure 5 shows ξ as a function of minimum stress contour and start time for the Calexico sequence. Note that ξ falls below 0.4 in this analysis,


(a)
Seismic Slip
Future Earthquake
Future Earthquake
Seismic Slip
Future Earthquake
Fault Creep
(b)
Negative slip
(c)

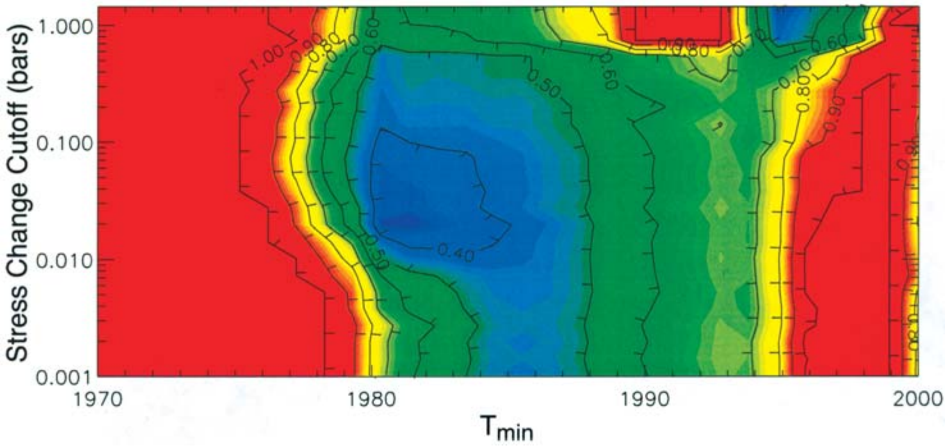


Figure 5
Contour plot of the fit parameter, ξ, as a function of the minimum stress contour and $t_{\min}$. There is a broad, although well-defined range of both the minimum stress cutoff and $t_{\min}$ which minimizes the value of ξ. Note that ξ in the entire blue region falls below 0.45 in this analysis, significantly less than the minimum ξ found by the optimal circle method in Figure 2.

significantly smaller than the minimum ξ found by the optimal circle method in Figure 2.

The start time is well defined in Figure 5 at about 1988, but the minimum stress contour at that date ranges from 0.2 bar to 0.01 bar. As a best fit (Fig. 6), we chose the upper minimum (ΔCFF = 0.2). This corresponds to a smaller effective R since the larger values probably reflect the fact that there is sparse contribution to the seismicity until one reaches the 0.01 bar contour, at which point the fit degrades. The ΔCFF = 0.2 and 0.01 bar contours are shown in Figure 7. Except for the shape, the preferred 0.2 bar contour is seen to be roughly equivalent to $R = 60$ km found in the circle analysis.

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Figure 4
Evolution of Coulomb stresses prior to an earthquake. Red colors indicate positive static stress change, while blue colors indicate negative static stress change. (a) Perspective view of the static stress changes calculated at the Earth's surface. The fault slip at depth is indicated below the calculated stress change field. The three figures depict the cumulative stress changes due to slip on adjacent segments of the fault (top two panels) and loading by aseismic slip on the fault below seismogenic depths (bottom panel). (b) The stress change distribution can be modeled by reversing the sense of slip observed to occur in the earthquake. Regions where stress must have been high prior to the main event are examined for accelerated moment release. The choice of the contour bounding the region is discussed in the text. See BOWMAN and KING (2001) for details. (c) Cartoon illustrating how Bowman and King method can be modified for multiple events. See text for details.

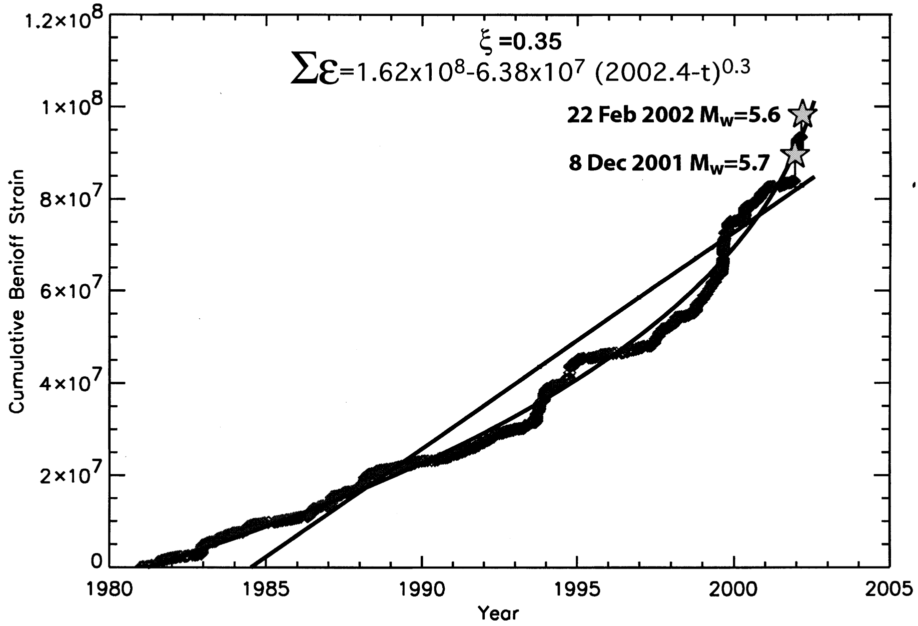

Figure 6
Fit of Equation (1) to the seismicity within the 0.2 bar stress contour since 1981. These parameters represent the smallest stress contour window in which AMR is observed before the Calexico sequence.

Discussion

The area of anomalous activity detected by RUNDLE *et al.* (2002) preceding the 2002 Calexico earthquake is indeed an example of AMR within an optimal region size consistent with previous scaling studies relating R to magnitude. This result suggests a new approach to earthquake forecasting. The RUNDLE *et al.* (2002) algorithm is first used to detect areas of anomalous activity. Within these areas, major faults are identified and potential scenario earthquakes are calculated using the stress recovery method (BOWMAN and KING, 2001a,b; KING and BOWMAN, 2002). Finally, activity within the recovering stress lobes is used to estimate the time and size of any impending large events. It is interesting to note that the optimal radius R can be used in conjunction with the scaling relation (Fig. 3) to estimate the size of the impending event. This offers an alternative, and perhaps more stable, procedure than estimating the size of the impending event from the remaining Benioff strain in the time to failure analysis.

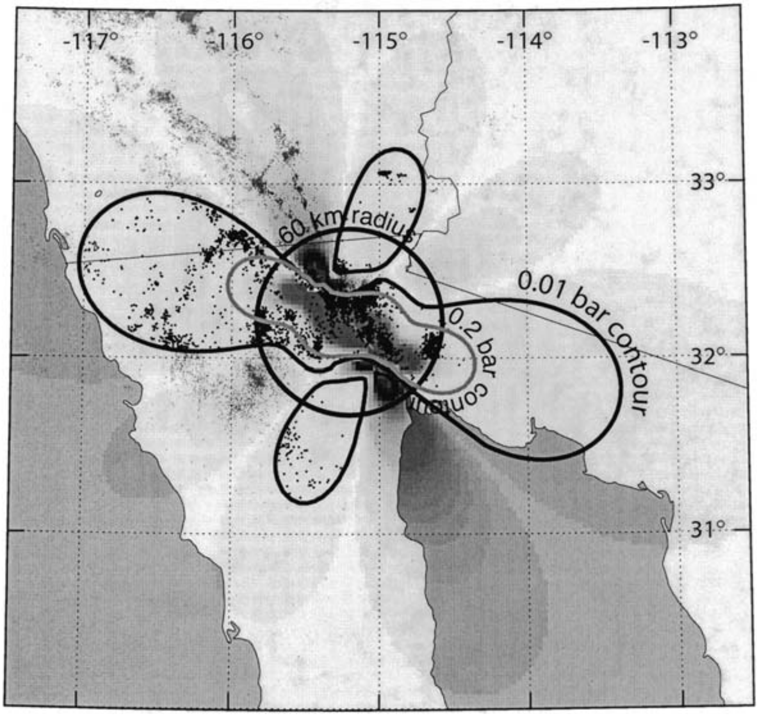

Figure 7
Map of the loading model with three possible critical regions shown. The circle is the region found using the optimal circle method. The 0.2 bar stress contour is outlined in green, and the 0.01 bar is outlined in blue. The seismicity within the 0.2 bar contour is plotted in Figure 6.

Acknowledgements

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 698, INSU contribution number 334 and IPGP contribution number 1885.

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(Received September 27, 2002, revised February 28, 2003, accepted March 7, 2003)