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FAULT SEGMENTATION AND POSSIBLE PORE FLUID EFFECTS IN THE 1992 LANDERS, CALIFORNIA AFTERSHOCK SEQUENCE

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Program Element II. Earthquake Physics and Effects

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Technical Abstract

The lack of a heat flow anomaly and the near fault-normal stress orientation near major fault zones suggest that fault slip during earthquakes occurs at lower stress levels than predicted by laboratory experiments. The involvement of fluids in faulting offers a possible explanation for this discrepancy and may explain other aspects of large earthquake behavior as well. There is independent evidence that fluids and faults interact, and that high fluid pressures occur in fault zones, at least at shallow depths. While fluids have been shown capable of artificially triggering earthquakes in controlled experiments, evidence that fluids play an important role in triggering tectonic earthquakes is circumstantial. We observe that aftershocks within an extensional fault discontinuity after the 1992 Landers, California earthquake occur at an approximately constant rate for over three years following the mainshock, in sharp contrast to the usual behavior of aftershocks. These protracted aftershocks can be understood if pore fluids are present at seismogenic depths and are important in earthquake triggering. We have relocated earthquakes within this fault jog and found that the protracted earthquakes occurred on well-defined subfaults withing the jog, and that the poro-elastic effects provide a viable explanation for the temporal evolution.

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Non-Technical Abstract

Laboratory measurements of rock friction suggest that earthquake faulting should generate a great deal of heat and that this ought to lead to a temperature anomaly near major faults; however, no such anomaly has been observed. The possible lubricating effects of fluids in the Earth's crust could explain this lack of a temperature anomaly, but the evidence that fluids are important to large earthquakes. In this study we found that aftershocks of the 1992 Landers, California earthquake exhibit a unique signature that indicates that fluids are present at the depths at which earthquakes occur and that they can be important both in triggering earthquakes and influencing other aspects of earthquake behavior.

Introduction

The rate of aftershocks *R*, decays with time, *t*, following a large earthquake following Omori's law as $R(t) \sim (t + c)^{-p}$, where *c* is a constant and the exponent, *p*, is ~1. Aftershocks are thought to occur in response to the stress change imposed by the mainshock they follow, but the mechanism behind the time dependence in Omori's law has been debated. Elastic effects act immediately, and can't explain the gradual decay, but visco-elastic relaxation, stress corrosion, and earthquake nucleation under rate- and state-variable friction have all been proposed as possible mechanisms.

Another proposed mechanism invokes processes associated with pore fluids. A pore pressure decrease will occur where the mean normal stress decreases and a pore pressure increase will occur where the mean normal stress increases. The change in pore pressure, ΔP for undrained conditions can be related to the change in the mean normal stress, $\Delta\sigma_{kk}$, as: $\Delta P = B\,\Delta\sigma_{kk}$, where Skempton's coefficient, *B*, a function of elastic moduli for drained and undrained conditions, is equal to one for fluid saturated soils and ranges between 0.5 and 0.9 for a range of rock types. With time, this undrained state evolves to the drained state as fluids flow and re-equilibrate in response to pore pressure gradients.

Fluids can trigger earthquakes by inducing shear stress through poro-elastic consolidation of regions that underwent changes in mean normal stress in the mainshock. In the undrained state, changes in the mean normal stress will be effectively buffered by changes in pore pressure. This effect will diminish during the transistion to drained conditions and induce changes in shear stress that can trigger aftershocks. Fluids can also trigger aftershocks through changes in the effective normal stress. Under the Coulomb failure criterion, faulting will occur when the shear stress, τ, exceeds the sum of the cohesion, *C*, and the effective normal stress multiplied by the coefficient of friction, μ:

$$\tau > \mu(\sigma - P) + C, \tag{1}$$

where the effective normal stress is the difference of the normal stress, σ, and the pore pressure, *P*, and the cohesion is thought to be small for faults in the Earth. In the presence of pore fluids, *P*, will be time dependent and if the pore pressure increases with time an earthquake may be triggered.

A distinguishing characteristic of pore-fluid models is the role of the mean normal stress. Large fault-zone discontinuities, where changes in mean normal stress are both large and predictable, present a clear opportunity to search for pore fluid earthquake triggering. Fault discontinuities are often large enough to be manifest in the surface trace, and extend throughout seismogenic depths. They are classified as *compressional* if faulting leads to compression (mean normal stress increase) between the two fault segments or *extensional* if faulting leads to extension (mean normal stress decrease). For an extensional discontinuity, pore fluid effects predict a protracted aftershock sequence and for a compressional discontinuity, pore fluid effects predict an abbreviated aftershock sequence relative to what would otherwise occur.

Within an extensional discontinuity the mean normal stress will decrease and hence the normal stress, σ, acting across a potential fault plane will tend to decrease as well, but so will the pore pressure. Thus, if fluids are present, the right-hand side of (1) will not change as much as if pore fluids were absent and relatively few aftershocks will be triggered immediately after the mainshock (undrained response). As pore fluids flow in response to pore pressure gradients, the pore pressure decrease will decay, but the normal stress change will not. Thus, as the medium drains, the effective normal stress, $\sigma - P$, will decrease and tend to unlock potential aftershock fault planes resulting in a protracted aftershock sequence.

The 1992 Landers, California earthquake ruptured over 85 km with several prominent extensional fault discontinuities. The overall aftershock sequence of the Landers earthquake follows Omori's law, so that we can characterize the temporal behavior of aftershocks using that as a standard. In figure 1 we divide the aftershock zone into subareas that extend 5 km to either side of the fault trace. Within each of these we plot the cumulative number of aftershocks against time after the mainshock. The curves in figure 2 show that for most of the fault the aftershocks accumulate rapidly shortly after the mainshock, with the rate gradually decreasing, as Omori's law predicts. Areas 11-15 behave in a similar fashion to the other areas for the first 6 months after the mainshock; however, after that they show a distinctly different behavior, with an approximately constant aftershock rate.

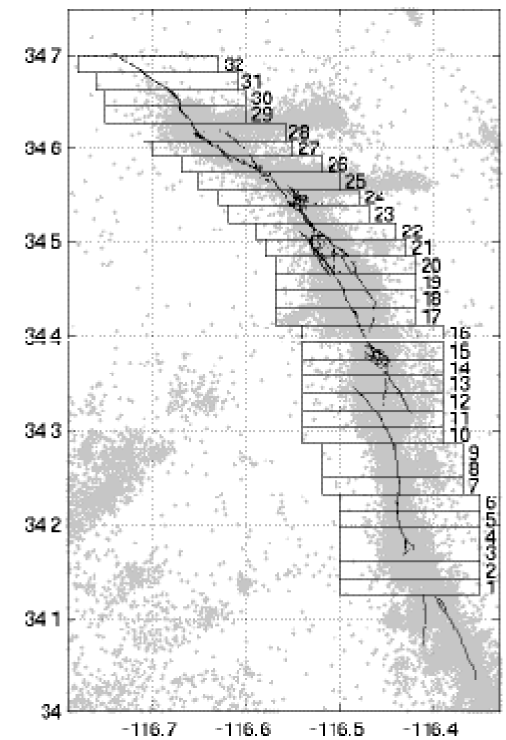
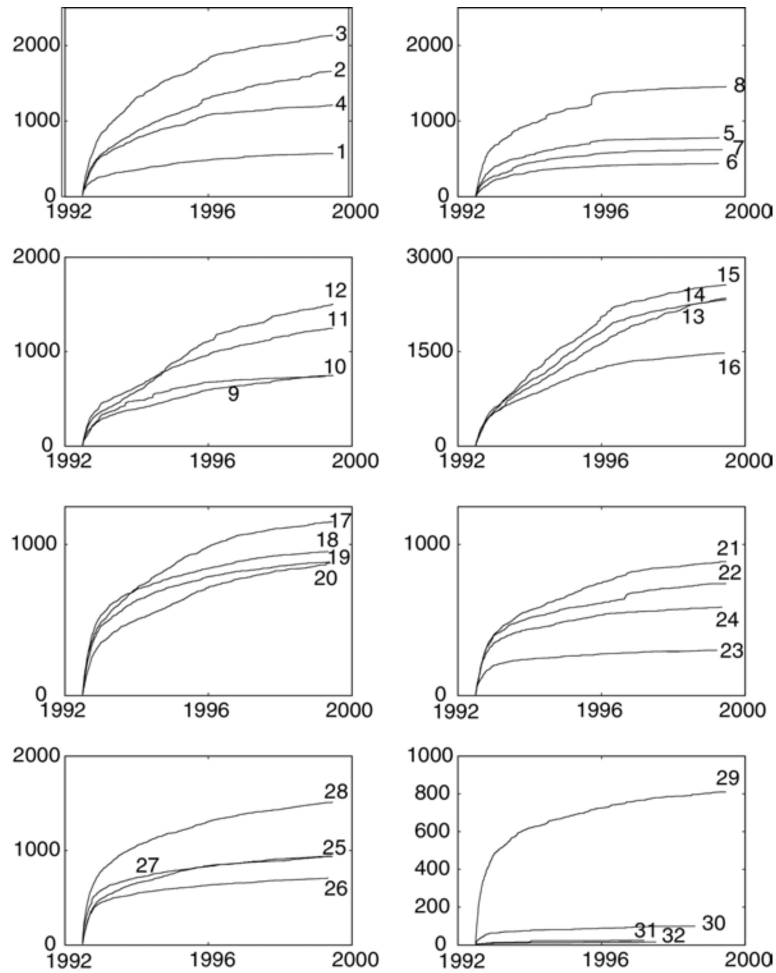


Figure 1. Map showing Landers surface rupture in black, aftershocks in gray, together with boxes used to examine temporal dependence of aftershock seismicity. The results are not sensitive to the width of the boxes provided they are centered on the fault and of sufficient half-width to account for horizontal earthquake location errors of several km.

The protracted aftershocks are not attributable to variations in the network detection threshold because the detectability threshold for the Landers aftershock sequence changes only gradually from south to north due to variations in network coverage. A rate change resulting from changes in network coverage would act over spatial scales comparable to the station spacing and would include adjacent straight segments of the fault where the aftershock decay is normal. The protracted aftershocks span a number of contiguous bins, and their signature is both robust with respect to the dimensions of the area considered and statistically significant.

We tested the significance by fitting the modified form of Omori's law to the first 180 days of aftershocks in each bin. We then compared the prediction of subsequent aftershocks with the observations. A significant surplus of aftershocks at the 95% confidence level was observed for bins 11-14 situated within the fault jog, but for only 3 of 28 bins outside of the fault jog. The protracted aftershocks are not attributable to secondary aftershock sequences following one or several large aftershocks because no large aftershocks are observed in these areas. This is apparent in the steady, rather than episodic, accumulation of aftershocks (figure 3). Finally, we note that the aftershocks on the jog do not simply follow Omori's law with a low p-value. The normalized chi-squared measure of misfit is very high for only 4 of the boxes in figure 2 (boxes 1, 11-13). For these four boxes, three of which are situated in the jog, Omori's law does not adequately describe the temporal behavior. This can be illustrated in Figure 4, which compares the fit of Omori's law to the observed aftershocks in a straight section of the fault with that in the fault discontinuity. We conclude that the protracted aftershocks represent a failure of Omori's law to describe the data, not simply a relatively slow decay manifest as a low *p* value as observed in some instances.



number of aftershocks with time for the boxes in figure 1. The protracted aftershocks appear most clearly as a trend of approximately constant slope for boxes 11-16 from 0.5 to 3.5 years after the Landers mainshock. This straight line behavior represents a constant aftershock rate rather than the decay predicted by Omori's law.

The protracted aftershocks are situated directly within the most prominent extensional offset in the fault trace and as indicated earlier, suggest that pore fluid effects play an important role in aftershock triggering. We can get a clearer view of the spatial extent of protracted aftershocks by considering smaller areas and using a simple measure of aftershock decay. Figure 4 shows how closely the protracted aftershocks are confined within the discontinuity between the Johnson Valley and Homestead Valley faults. The short scale length of the effect precludes viscoelasticity of the lower crust, which would operate over spatial scales at least as large as the depth of faulting (~15 km). Nucleation under a rate- and state-variable friction law has been used to explain aftershock decay, however, it predicts the same form of response for either a change in shear or normal stress and thus would not explain our observations either. In the absence of pore-fluid effects, it predicts the same time dependence outside vs. inside the discontinuity.

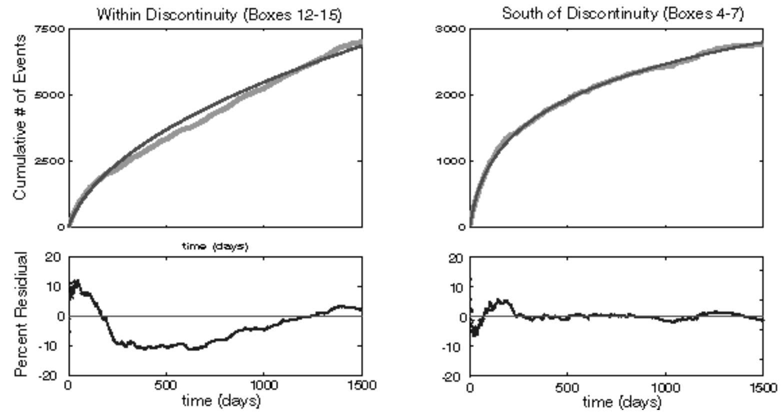


Figure 3. Fit of the accumulation of aftershocks to the modified Omori's law for aftershocks clearly within (left panels) and outside of (right panels) the large fault discontinuity. Best fit to aftershocks within the discontinuity has an exceptionally low *p* value of 0.55 (slow decay rate); moreover, a X^2 test indicates these data are inconsistent with the modified Omori's law at the 95% confidence level. For aftershocks outside of the discontinuity we find a normal *p* value of 0.9 and a X^2 test indicates that this model provides an adequate fit to the data.

Other areas also appear to show a protracted aftershock sequence. Near the southern end of the surface rupture there is another prominent area of protracted aftershocks. The surface rupture bifurcates and terminates in this region, so it is difficult to assess whether this activity might also be attributed to pore-fluid effects. We also observe protracted aftershock activity in the smaller offset between the Homestead Valley and Camp Rock-Emerson faults, but the effect is subtle. There is a small compressional offset in the Camp Rock-Emerson fault, but evidence for an abbreviated aftershock sequence at this location is equivocal. Aftershocks on the straight fault segments show a decay consistent with Omori's Law.

Fluid effects have been independently implicated from post-seismic deformation measurements for this earthquake and the effect was seen most prominently in the same Johnson Valley-Homestead Valley fault jog. The surface deformation was centered on the fault trace; however, while the protracted aftershocks were located to the west of the fault trace. The difference may be attributable to changes in the fault geometry and slip distribution with depth. The decay time for poro-elastic effects in the surface deformation was 270 days, rather than ~3 years as we have found, and the depth of the source of the deformation anomaly was modeled as 0-4 km. The protracted seismicity extends to depths of 8 km, and the longer duration of the effect in the aftershocks is consistent with an expected decrease in permeability with increasing depth.

It is ironic that the signature of pore-fluid triggering is manifest as a violation of Omori's law, given that Omori's law was the property of aftershock sequences that pore fluid effects were originally invoked to explain. We note, however, that the theory was developed for aftershock decay on a planar fault and that the three dimensional structure of fault discontinuities and the complex and variable permeability structure of fault zones and their surroundings may confound specific predictions.

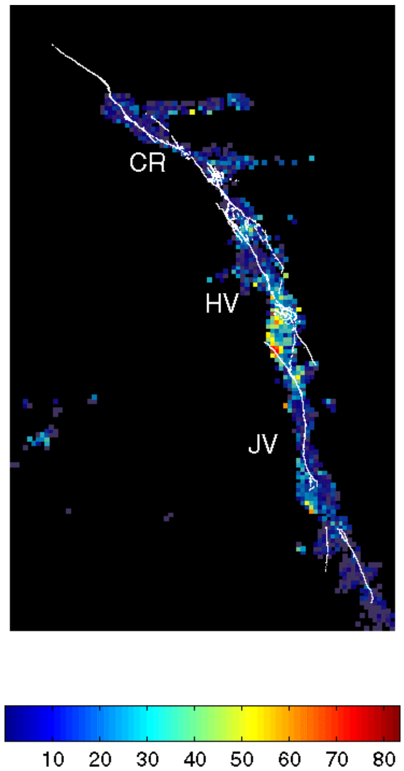


Figure 4. Relative aftershock rate displayed as the percentage of aftershocks in years 1 and 3 following the mainshock that occurred in year 3. Instances of less that 8 total aftershocks within each 0.01 by 0.01 degree box are not plotted. Areas of protracted aftershocks (relatively more aftershocks at later times) show as warm colors (green to red). These are most prominent in the large extensional discontinuity between the Johnson Valley (JV) and Homestead Valley (HV) faults and at the southern end of the rupture. The extensional discontinuity between the Homestead Valley and Camp Rock/Emerson (CR) faults also shows a protracted aftershock sequence, though the effect is subtle. Straight segments of faults plot as cool colors, consistent with decay of the aftershock rate with time.

The protracted aftershocks in the Landers aftershock sequence suggest that fluids at seismogenic depths play an important role in the earthquake process. Others have suggested that pore fluids may have triggered aftershocks of the Landers earthquake and the Landers sequence is not the only one in which pore fluid triggering has been hypothesized. What distinguishes our results is that the signature of pore fluids is particularly clear because of the large and predictable change in mean normal stress in the fault discontinuity and the temporal and spatial distribution of the signal are not readily explained by other mechanisms.

It remains unclear how important such effects are for earthquake triggering in general. The mean stress is nodal along the fault plane for a uniform planar fault, which will make it difficult to evaluate its possible role in triggering most aftershocks; however, there are other situations in which the signature of pore fluids may be recognizable. For example, earthquakes that have prominent off-fault aftershock sequences ought to show asymmetry in their temporal decay. Evidence for such behavior has not been widely sought after, but it appears to occur at least in some cases.

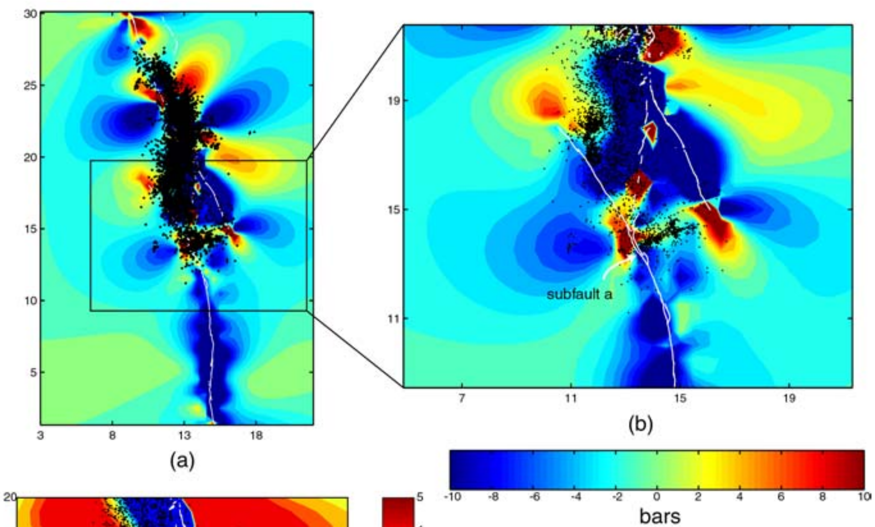
The analysis of the temporal dependence of triggering has been submitted to *Nature* as:

Beroza, G. C., E. E. Zanzerkia, and K. R. Felzer, A signature of pore fluuid triggering in the Landers earthquake sequence, *Nature,* (submitted).

The relocation and poro-elastic analysis of stress triggering (figure 5) were part of Eva Zanzerkia's Ph.D. thesis:

Zanzerkia, E. E., "Towards an Understanding of Seismic Triggering Through Precise Earthquake Locations", Ph.D. Thesis, Stanford University, Stanford, California, 2003.

These are currently being prepared for publication.



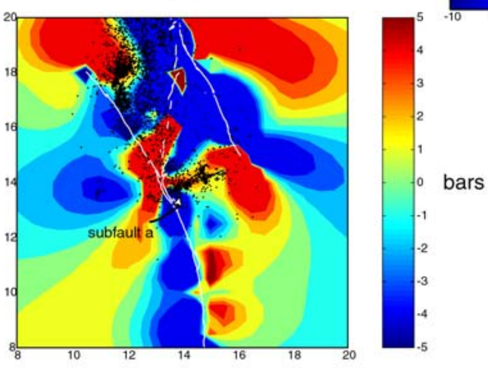


Figure 5. This figure demonstrates that the relocated seismicity on subfault a within the jog (left) is consistent with triggering due to poroelastic effects. We model the net effect of the transition from drained to undrained conditions by differencing elastic stress change analysis for differing values of Poisson's ratio.

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