1998 Progress Report

Relationship of Aftershocks to Mainshock Rupture of the Landers Earthquake

Kerry Sieh, Jing Liu, and Egill Hauksson
California Institute of Technology

Introduction

What do aftershocks tell us about the structural geology of faults that produce large earthquakes? Their almost universal association with large earthquakes means that they must be caused by stresses induced by the mainshock rupture. But do they represent re-rupture of the mainshock ruptures? Or do they constitute a structural damage zone around the mainshock ruptures? Answers to these questions have an important bearing on the meaning of aftershock statistics and the physics of large earthquakes.

The 1992 Landers mainshock and aftershocks comprise an exceptionally well recorded earthquake sequence. Thus they afford an unusual opportunity to explore these questions. Most aftershocks of the Landers earthquake have hypocenters within a few km of the mainshock ruptures. This suggests that they might have been produced by re-rupture of the principal rupture planes of the mainshock. It is conceivable, in fact, that the aftershocks represent slip on portions of the mainshock ruptures that sustained lesser slip during the mainshock. However, many of the catalog aftershock locations are more than a kilometer from the principal fault ruptures. This suggests that the aftershocks might represent failure of minor faults near the main faults. Thus, the aftershocks might constitute a structural damage zone that surrounds the mainshock rupture, rather than the re-rupture of mainshock faults.

Last year, we proposed to test these competing hypotheses. Such a test of these and related hypotheses is important for understanding the nature of faulting. Are irregularities in slip distribution, such as those suggested by seismographic and geodetic inversions ([*Wald and Heaton*, 1994]; [*Hudnut et al.*, 1994]) smoothed out by re-rupture during aftershocks? Do proximal aftershocks occur where stresses calculated from mainshock slip distribution encourage failure? We proposed to relocate all 100,000+ aftershocks, using a new 3-D crustal-velocity model. Then we would investigate which of those aftershocks *could* and which *could not* have been produced by slip on the mainshock ruptures. We proposed to test the degree to which the moment of those events near the mainshock ruptures could have smoothed the mainshock slip distributions determined from geodetic and seismographic inversions and surface-rupture mapping. We also proposed to determine whether or not focal mechanisms of aftershocks are consistent with local stresses induced by the mainshock ruptures.

Progress in 1998

We relocated the proximal Landers aftershocks, using an improved 3-D model of crustal velocity than was used to create the catalogue locations. The new, regional 3-D Vp and Vp/Vs models were calculated on a 15-km grid across southern California (Hauksson, in preparation, 1999). Explosions set off for earlier trapped mode studies provided calibration for absolute locations. Our new locations have relative errors of only 0.2 to 0.5 km in the horizontal and 0.5 to 1.0 km in the vertical dimension. As part of our detailed studies of the Landers aftershocks we used high resolution Vp and Vp/Vs models with a 5-km-grid-scale regional model. This model was used to relocate all of the 60,000+ aftershocks.

We then calculated the distribution of aftershock moment and population as a function of distance from the mainshock fault (Figure 1). For this we used the new aftershock locations and our detailed map of the Landers surface ruptures.

Results

The distribution of aftershocks shows that most of the aftershocks represent a broad damage zone centered on the mainshock ruptures. It also shows that the damage zone decreases in intensity away from the principal ruptures (Fig. 1). Only about 8% of the proximal Landers aftershocks have sources within a 0.5 km of the mainshock ruptures. Only about 23% have sources within 1.5 km of the mainshock ruptures. If each aftershock represents one fault or fault patch, this indicates that the great majority of aftershocks represent slip on faults off of the principal rupture planes. The distribution of moment with respect to distance from the mainshock ruptures is less stark, but similar. Only about 16% of the aftershock moment were produced by sources within half a km of the principal faults, but about 60% were generated within 1.5 km. This distribution of sources mimics the pattern of cataclasis commonly seen in the blocks adjacent to a major fault zone – large numbers of fractures in the adjacent kilometer or so, increasing in number and total shear toward the main fault.

A minority of aftershocks occurred within a km or so of the mainshock rupture surface. Our location errors allow (but do not require) these events to be on the principal mainshock ruptures. Figure 2 shows the distribution of aftershock moment along the fault rupture. The red line represents cumulative aftershock moment as nominal slip along the mainshock faults. This would be the average slip on the fault plane that continues to a depth of 15 km -- the base of the aftershock zone. Note that the nominal aftershock slip ranges from about a mm to about a cm along the northern half of the fault. Along the southern half of the fault, nominal afterslip ranges from about 1 to 3 cm, except along two curious sections where it ranges above 3 cm to as high as about 30 cm.

What general conclusions can we draw from this distribution of nominal afterslip? First, nominal seismic slip along *most* of the fault during the aftershocks is 1/100th to 1/1000th the slip that occurred during the mainshock (Fig. 3). Thus, most of the large variations in slip derived from geodetic and seismographic inversions of the mainshock (Wald and Heaton, 1994; Hudnut and others, 1994; and others) have not been lessened substantially by slip during aftershocks.

Only in the two sections of highest nominal aftershock slippage, 15 to 20 km north and 5 to 20 km south of the epicenter (Fig. 3), does nominal slip during aftershocks compare with slip during the mainshock. It is probably significant that these two sections of the mainshock rupture had little or no rupture during the mainshock. These two sections displayed the least continuity and least slip of the entire mainshock rupture. The southern section includes a 5-km section devoid of ruptures and geologic faults and two faults that suffered <20 cm of dextral slip in the mainshock (Fig. 2). The northern 5-km section is at the northern end of a large stepover in the fault that contained a thrust-fault rupture and a marked low in coseismic slip. Spotila and Sieh (1999) showed that in this region the geologic faults have not yet integrated to form one contiguous structure. In both the northern and southern regions of high nominal aftershock-slip, integrated geologic faults are absent. Thus it may be surmised that the high degree of aftershock activity belies high residual stresses at the ends of geologic faults that ruptured in 1992 and in prior events as well.

Finally, our analysis hints at a variation in b-values along the Landers rupture. Values range from about 0.8 to 1.2 (Fig. 2). The variation may relate to complexity of the rupture zone. We calculate lower values for rupture segments that are the simplest – for example, the northern section of the rupture (Camp Rock fault) and the four sections along the southern third of the rupture (Johnson Valley and Eureka Peak faults). Sections that experienced greater complexity of rupture during the mainshock have higher b-values. Hence, the structural observations appear to be qualitatively consistent with the aftershock statistics – where there is a larger population of minor faults, there are larger numbers of small earthquakes relative to larger ones. This observation would lend credence to the hypothesis that the aftershocks are occurring on small faults rather than on the principal mainshock ruptures. This also suggests that b-values are a property of the degree of structural comminution of a block of crust and are not a property of an individual fault. This, of course, would have important implications for understanding the physics of fault behavior. Perhaps crustal blocks, rather than individual faults, experience a Gutenberg-Richter distribution of slip events. If this is so, then the behavior of individual faults might be closer to a characteristic behavior (Wesnousky, 1996).

References

Hauksson, E., L.M. Jones, K. Hutton, and D.E.-. Phillips, The 1992 Landers Earthquake Sequence: Seismological Observations, *Journal of Geophysical Research*, *98* (B11), 19,835-18,858, 1993.

Hudnut, K.W., Y. Bock, M. Cline, P. Fang, Y. Feng, J. Freymueller, X. Ge, W.K. Gross, D. Jackson, M. Kim, N.E. King, J. Langbein, S.C. Larsen, M. Lisowski, Z. Shen, J. Svarc, and J. Zhang, Co-Seismic displacements of the 1992 Landers earthquake sequence, *Bull.Seism.Soc.Am.*, *84* (3), 625-645, 1994.

Spotila, J., and K. Sieh, *J. Geophys. Res.*, in preparation, 1999.

Wald, D.J., and T.H. Heaton, Spatial and Temporal Distribution of Slip for the 1992 Landers, California, Earthquake, *Bulletin of the Seismological Society of America*, *84* (No. 3), 668-691, 1994.

Wesnousky SG, The Gutenberg-Richter or characteristic earthquake distribution, which is it? Reply, B SEISMOL SOC AM 86: (1) 286-291 Part A FEB 1996

Zachariasen, J., and K. Sieh, *J. Geophys. Res.*, in preparation, 1999.

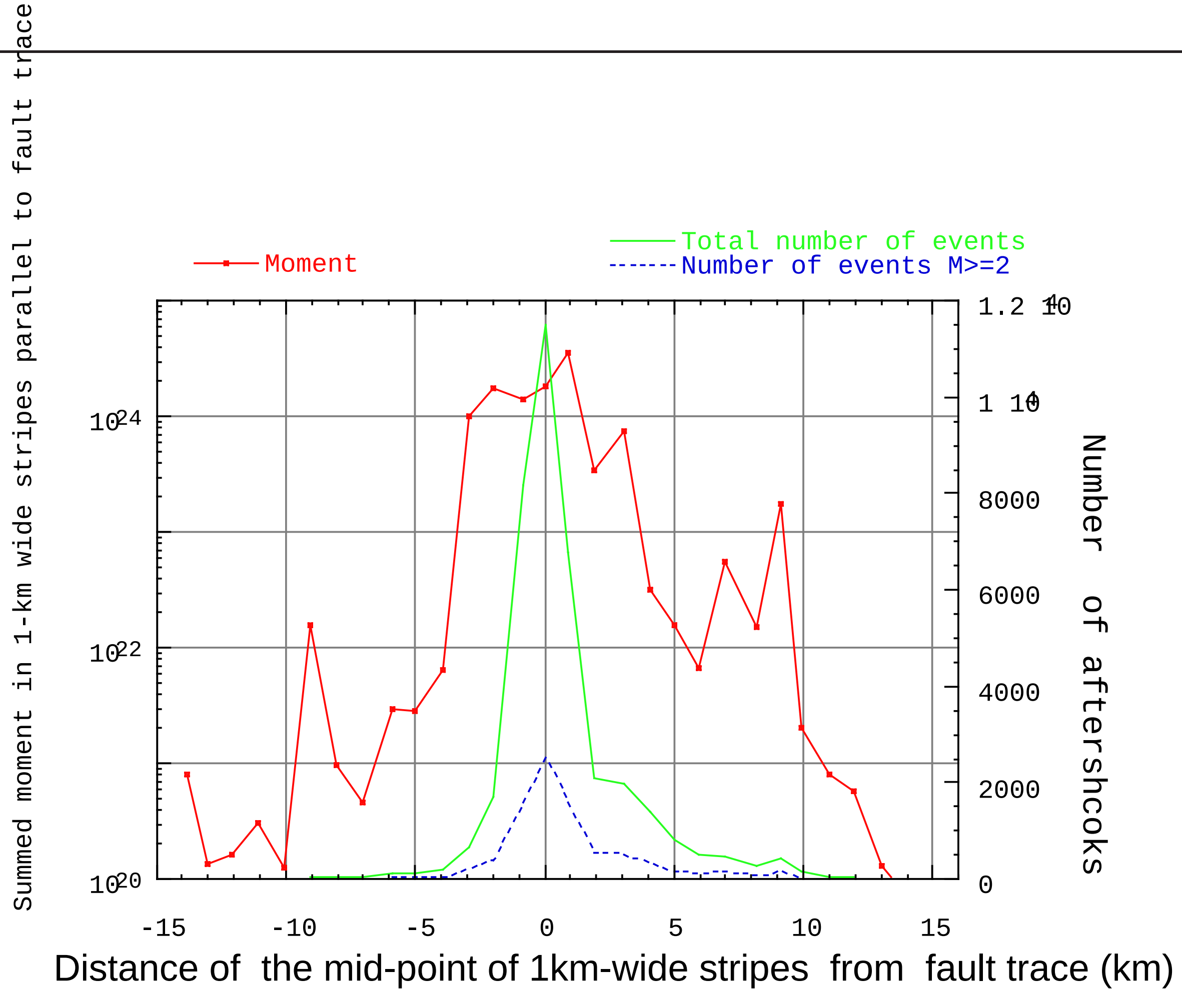

Figure 1. Histogram of distance of Landers aftershocks from the surface traces of the principal mainshock fault ruptures. Only a small percentage of the aftershocks occurred close enough to the principal ruptures to be candidates for re-rupture of the principal mainshock fault planes. This suggests that most of the aftershocks represent a structural damage zone around the principal faults.

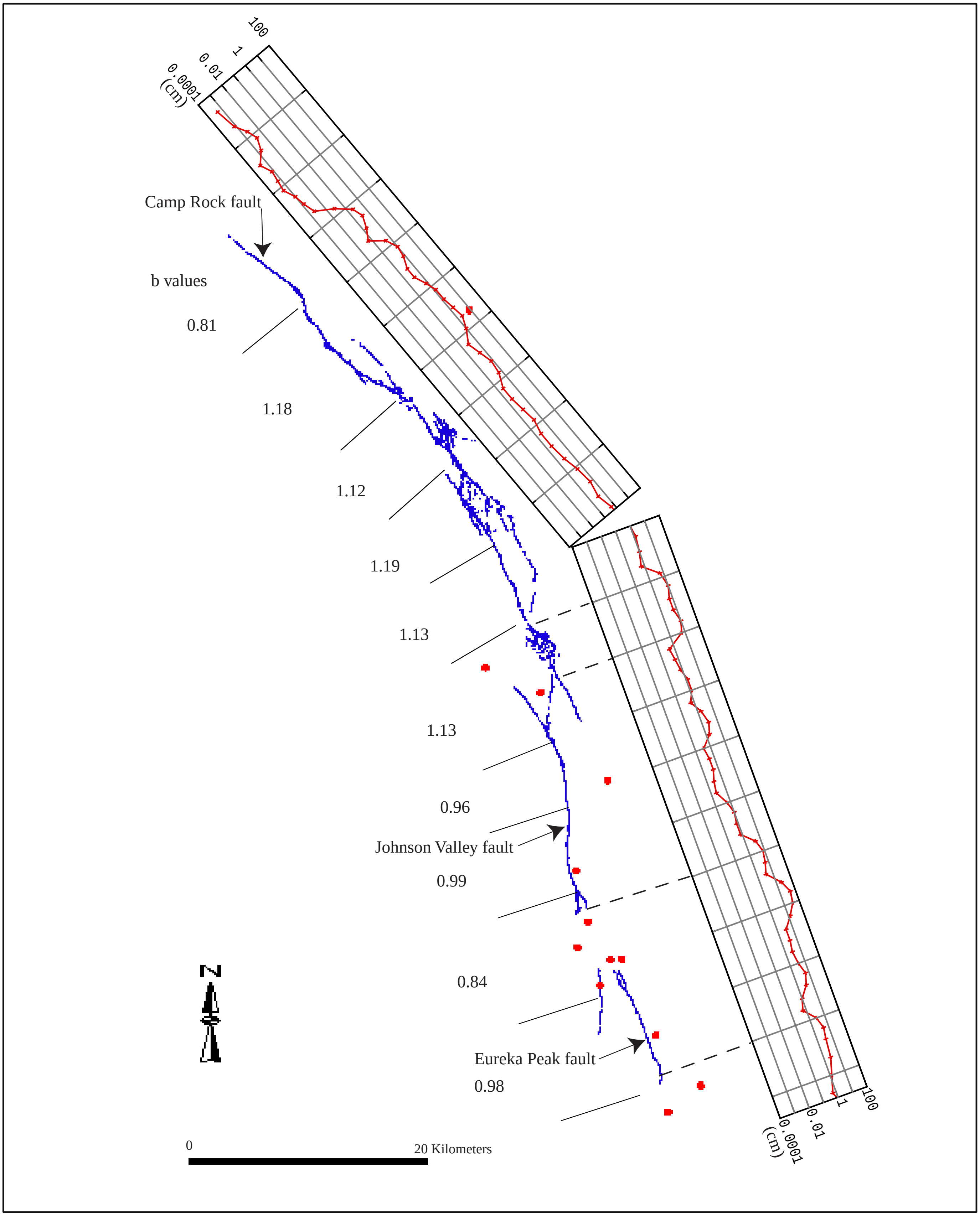

Figure 2. Map of the mainshock ruptures of the Landers earthquake (blue) and graph of nominal, cumulative slip associated the near-fault aftershocks. The nominal slip associated with the aftershocks is generally 1 mm to 1 cm, about 0.01 to 0.001 of the values of slip during the mainshock rupture. This suggests that irregularities in slip during the mainshock have not been significantly smoothed by re-rupture during aftershocks. Two segments of higher nominal afterslip may coincide with the least structurally mature sections of the mainshock rupture. The relationship of aftershock b-values to structural character of the mainshock ruptures may indicate that b-value is a property of crustal volumes, not of individual faults.

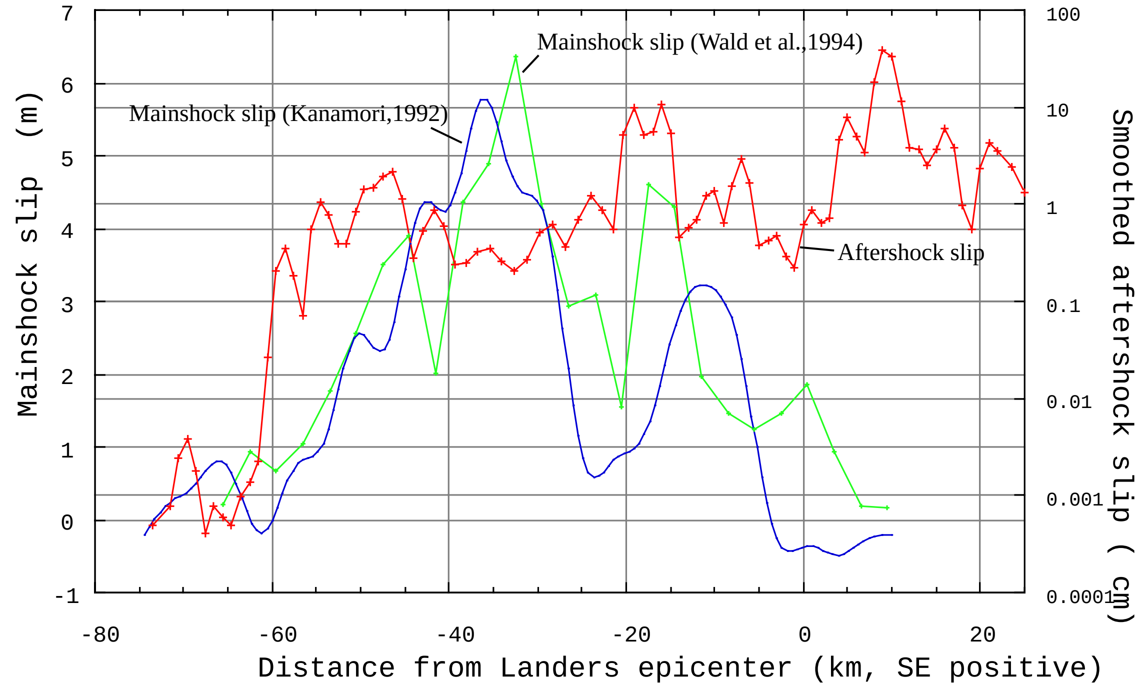

Figure 3. Comparison of mainshock right-lateral slip and nominal cumulative slip during aftershocks. Mainshock slip determined from seismic and geodetic inversions is highly irregular. Nominal aftershock slip increases southeastward more than an order of magnitude, but is generally 0.01 to 0.001 of the mainshock slip values. Two anomalously high regions of nominal aftershock slip, 15-20 km northwest and 5-20 km southeast of the mainshock epicenter, coincide with regions of structural immaturity of the mainshock faults.