Foreshock Cascade to Failure in the M 6.4 July 4, 2019 Ridgecrest, California Earthquake

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Our current understanding of how earthquakes nucleate leaves open critical questions about the physical processes that occur before dynamic rupture including whether or not foreshocks have other than weak statistical value as a precursor. Two end-member hypotheses that describe the underlying mechanisms are the preslip and cascade model, which take opposing views on the role of aseismic deformation in the nucleation process. Here we examine the foreshocks to the M 6.4 July 4, 2019 Ridgecrest, California earthquake. We used template matching to identify the events, cross correlation and first-motion timing with hypoDD to determine hypocentroids for all event and the initial hypocenters for the M > 2 foreshocks and the initiation point of the mainshock.

The foreshock sequence initiated 2.5 hours before the M 6.4 July 4 mainshock on a northwest-southeast striking fault. The initial events cluster at base of the sequence at 12 km depth. Thirty minutes before the mainshock, the largest foreshock, M 4.0 nucleated on the edge of area ruptured by the first foreshocks and ruptured unilaterally upward and to the northwest (see figure). We estimate a rupture dimension of 250 m, based on spectral ratio measurements. This event was followed by its own aftershock sequence, all located on the periphery of the M 4.0 event, including the M 6.4 which nucleated on the edge of the M_W4.0 rupture (see figure). The foreshocks form a cascade to failure, following the same pattern of closely packed ruptures observed in precision seismological analyses of the M 7.6 1999 Izmit, Turkey (Ellsworth and Bulut, 2018) and M 7.1 1999 Hector Mine, California (Yoon et al., 2019) earthquakes. The absence of repeating earthquakes in all three of the foreshock sequences argues against significant aseismic slip in the initiation process as a silent driver of the foreshock process.

Constraining aseismic slip is notoriously difficult. The M 6.0 2004 Parkfield, California earthquake is one of the few for which aseismic slip can be constrained. Johnston et al. (2006) used borehole straingrams to constrain any possible preslip to no more than M_W 2.2 in a region no larger than 30 m in radius. Note that this is a constraint, as there was no evidence from either strainmeters or seismometers of any signal before the dynamic rupture initiated. For the M 6.4 July 4 Ridgecrest earthquake we detected nothing before rupture initiation on either seismometers or a borehole tensor strainmeter located 18 km from the epicenter. We can, however, place a limit on undetectable aseismic slip during the half hour between the M 4.0 and mainshock. A strain with an amplitude greater than 0.2 nanostrain would have been observed, corresponding to an upper limit of aseismic slip equivalent to M 3.5. Consequently, if aseismic slip occurred it played at most a minor role in foreshock sequence and we can rule out slip acceleration as the time to failure approached.

The Ridgecrest, Izmit and Hector Mine earthquakes all began abruptly without direct evidence of a nucleation process over more than 6 orders of magnitude below the mainshock. In each case the mainshock nucleated on the edge of the foreshock rupture area, in agreement with the cascade model. The observations also agree with the predictions of rate-and-state theory if the laboratory measured meter-scale dimension of the nucleation zone applies to faults in nature.

Figure. Cross sectional view of the foreshocks projected onto the NW-SE striking plane defined by the epicenters. Earthquakes shown by equivalent rupture areas for constant stress drop crack. Initial foreshocks in light gray. Dark gray dot with 95% uncertainty bounds marks the hypocenter of the M 4.0 foreshock and large gray circle rupture area centered on hypocentroid. Its aftershocks in blue. Red dot with 95% uncertainty bounds marks the initiation point of the M 6.4 mainshock.