The self-organization of aftershocks

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Aftershock distribution

Individual aftershock series fit the usual Gutenberg-Richter magnitude-frequency relation with a b-value that is statistically the same as for the complete distribution. Is it coincidence that the two b-values are the same? We show that clusters compose more than 70% of the complete catalog of Southern California earthquakes; the predominant fraction of the cluster earthquakes are aftershocks. Whereas conventional aftershock identification procedures treat all earthquakes as point events surrounded by a circular zone within which aftershocks might be found, we have been obliged to develop an unconventional identification procedure for aftershocks of the largest main earthquakes, which occur near linear extended rupture traces. Aftershocks of the largest earthquakes in Southern California show a significant jump in the distribution at approximately M=4.7, a magnitude that corresponds to a classical fracture length of about 3 km. The majority of the small aftershocks of the Landers earthquake is found, not coincidentally, in a zone about 3 km in width astride the main fracture trace. The catalog of all identified clusters shows a jump at the same magnitude as above, which only demonstrates that the largest main shocks produce most of the cluster earthquakes.

Main shock distribution

The Gutenberg-Richter frequency-magnitude relation is usually derived from a complete catalog of earthquakes. Since main shocks and aftershocks have different time scales and different driving mechanisms, it is not justified to use the G-R distribution, derived from catalogs that are predominantly composed of aftershocks, to motivate models of tectonic earthquakes. The main shock catalog, which is the residue after clusters have been removed, has a distribution with two dissimilar branches; there may be a third branch. The jump between the two lower magnitude branches occurs at about M=4.7 once again, and is statistically significant at 2σ. The branch of the distribution for $M \leq 4.7$ is well fit by a G-R relation; the distribution for larger magnitudes exhibits great irregularity, and does not suggest a good fit by a G-R relation. If one *assumes* that the intermediate magnitude branch can be fit with a G-R relation, the b-values of the two branches are now different with a statistical significance greater than 2σ. The b-value for the branch with $M > 4.7$ is about 0.55.

There may be a statistically significant spike for the largest main shocks with magnitudes greater than 6.4, which corresponds to the scaling dimension of the thickness of the seismogenic zone, and probably represents characteristic earthquakes. The main shock catalog is not scale-independent.

Self-organization of near aftershocks

The regularities of the Omori and Gutenberg-Richter laws for aftershocks offer an opportunity to simulate these properties by modeling. There are two species of aftershocks: small earthquakes that take place within short distances of the main rupture trace and those that occur at sites that have been in a state of strength-weakening prior to the main shocks. We focus on the aftershocks that occur close to the rupture trace of the main event. The geometry of near aftershocks of the largest main shocks demands that these aftershocks occur in a zone that has been weakened by the main shock. We model aftershocks by a two-stage process. The seismic waves from large main shocks are so strong that they cause (shattering) damage in the region nearby the fault within about 1 sec after the main shock. Fluid from the main fault is injected into the shattered region, thereby initiating the second stage, which is a process of stress corrosion of the asperities between the fractures in the damage zone, and which in turn is the cause of the delay in occurrence of the aftershocks. Accelerated creep causes disappearance of the asperity in an aftershock; the asperity is (almost) immediately re-established after the aftershock. The high pore pressure due to the fluids allows the cracks to remain open throughout most of the aftershock series. The aftershock series endures either until the stress due to the main shock is relaxed completely, or the fluid in the aftershock zone has diffused back into the main fault zone. Thus aftershock series can last many years; aftershocks of the 1952 Kern County earthquake (M=7.5) with $M \geq 3$ are consistent with the Omori rate law to this day, more than 46 years since the main shock. (The larger aftershocks, i.e. those with $M > 4.7$, take place only within a short time after the main shock.) Numerical simulations of the above mechanism yield Omori and Gutenberg-Richter properties. The Omori rate relation arises because of the strength weakening associated with stress corrosion in the damage zone, and the G-R distribution arises because of a prolonged time to healing of the damage; the two processes are independent and no correlation between b- and p-values is to be expected. Because of the heavy damage astride the main fault, there must be a significant stress drop in this region, and hence stress drops in large earthquakes evaluated on the basis of elastic models are underestimated. Because the damage is essentially concurrent with the main rupture, the seismograms from large earthquakes must be expected to be relatively more complex than those for smaller events.