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Some Facts about Aftershocks to Large Earthquakes in California

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Earthquakes occur in clusters. After one earthquake happens, we usually see others at nearby (or identical) locations. To talk about this phenomenon, seismologists coined three terms—"foreshock", "mainshock", and "aftershock". In any cluster of earthquakes, the one with the largest magnitude is called the mainshock; earthquakes that occur before the mainshock are called foreshocks while those that occur after the mainshock are called aftershocks. A mainshock will be redefined as a foreshock if a subsequent event in the cluster has a larger magnitude.

Aftershock sequences follow predictable patterns. That is, a sequence of aftershocks follows certain global patterns as a group, but the individual earthquakes comprising the group are random and unpredictable. This relationship between the pattern of a group and the randomness (stochastic nature) of the individuals has a close parallel in actuarial statistics. We can describe the pattern that aftershock sequences tend to follow with well-constrained equations. However, we must keep in mind that the actual aftershocks are only probabilistically described by these equations. Once the parameters in these equations have been estimated, we can determine the probability of aftershocks occurring in various space, time and magnitude ranges as described below.

Clustering of earthquakes usually occurs near the location of the mainshock. The stress on the mainshock's fault changes drastically during the mainshock and that fault produces most of the aftershocks. This causes a change in the regional stress, the size of which decreases rapidly with distance from the mainshock. Sometimes the change in stress caused by the mainshock is great enough to trigger aftershocks on other, nearby faults. While there is no hard "cutoff" distance beyond which an earthquake is totally incapable of triggering an aftershock, the vast majority of aftershocks are located close to the mainshock. As a rule of thumb, we consider earthquakes to be aftershocks if they are located within a characteristic distance from the mainshock. This distance is usually taken to be one or two times the length of the fault rupture associated with the mainshock. For example, if the mainshock ruptured a 100 km length of a fault, subsequent earthquakes up to 100-200 km away from the mainshock rupture would be considered aftershocks. The fault rupture length was approximately 15 km in the 1994 Northridge earthquake, and 430 km in the great 1906 earthquake.

An earthquake large enough to cause damage will probably be followed by several felt aftershocks within the first hour. The rate of aftershocks dies off quickly with time —the rate of aftershocks is proportional to the inverse of time since the mainshock. Thus the second day will have approximately 1/2 the number of aftershocks of the first day and the tenth day will have approximately 1/10 the number of the first day. Again, remember that these patterns describe only the mass behavior of aftershocks; the actual times, numbers and locations of the aftershocks are random, while tending to follow these patterns.

In the region of the mainshock, we call subsequent earthquakes "aftershocks" as long as the rate at which earthquakes are occurring in that region is greater than the rate before the mainshock. How long that will be depends on the size of the mainshock (bigger earthquakes have a higher rate of aftershocks so it stays above background longer) and how active the region was before the mainshock (if the region was seismically relatively quiet before the mainshock, the rate of aftershocks remains above the background rate for a longer time.)

Bigger earthquakes have more and larger aftershocks. The bigger the mainshock the bigger the largest aftershock will be, *on average*. The difference in magnitude between the mainshock and largest aftershock can range from 0.1 to 3 or more, but averages 1.2 (a M5.5 aftershock to a M6.7 mainshock for example). Smaller aftershocks are more numerous than large ones. Aftershocks of all magnitudes die in with time at the same rate. However, since the overall rate dies off, all magnitudes become less common with time. We have seen large aftershocks months or even years after the mainshock.

Reasenberg and Jones (1989) quantified these facts into an expression for the rate of aftershocks as a function of time (t) and magnitude (M):

$$\lambda(t,M) = 10^{(a+b(M_m-M))}(t+c)^{-p}$$

where and a, b, c, and p are constants and M_m is the magnitude of the mainshock (Equation 4, Reasenberg and Jones, 1989). Once these parameters are determined for a sequence, the probability of an aftershock of magnitude M_1 or greater, starting at time S for a time of length T is given by:

$$P = 1 - \exp\left[-\int_{M_1}^{\infty} \int_{S}^{T} \lambda(t,m)\, dt\, dM \right]$$

Reasenberg and Jones also showed that the values of *a, p* and *b* are approximately normally distributed for aftershock sequences in California. The mean values of these parameters are a = -1.67, p = 1.08, b = 0.91, c = 0.05, which they termed the generic California aftershock sequence. The generic aftershock sequence has a close parallel to climatological models. These models describe the average or expected phenomenon, while tacitly acknowledging that individual (aftershock or weather) patterns will vary. The generic aftershock model is the best model of an aftershock sequence until the parameters for an individual sequence can be determined. These parameters can usually be reliably estimated with one to two days of aftershock data.

From the generic model, we can estimate the probability of various aftershocks at different times during the aftershock sequence. For instance, Table 1 documents the probability of magnitude 5 or larger aftershocks in specified 30-day periods, as a function of magnitude of the mainshock and time since the mainshock. For example, the probability of a magnitude 5 (or greater) aftershock in the 30-day period starting 7 days after a magnitude 6 mainshock is 0.206. Smaller magnitude aftershocks will be more common and larger magnitude aftershocks less common. For the generic value of b=0.9, a sequence will have 8 times more M≥4 aftershocks, and 8 times less M≥6 aftershocks, as compared to the number of M≥5 events

Table 1. Probability of an M5 or larger aftershock in a 30 day period starting at time S (time since the mainshock) for the generic California aftershock sequence

	S (time in days since the mainshock)								
Mainshock Magnitude	0.01	7	14	30	60	90	120	182	365
5.0	0.123	0.028	0.019	0.011	0.006	0.004	0.003	0.002	0.001
5.1	0.149	0.034	0.023	0.013	0.008	0.005	0.004	0.003	0.001
5.2	0.181	0.042	0.028	0.017	0.009	0.006	0.005	0.003	0.002
5.3	0.218	0.052	0.035	0.020	0.011	0.008	0.006	0.004	0.002
5.4	0.262	0.064	0.043	0.025	0.014	0.010	0.007	0.005	0.002
5.5	0.312	0.078	0.052	0.031	0.017	0.012	0.009	0.006	0.003
5.6	0.369	0.095	0.064	0.038	0.021	0.015	0.011	0.007	0.004
5.7	0.434	0.116	0.079	0.046	0.026	0.018	0.014	0.009	0.005
5.8	0.504	0.141	0.096	0.057	0.032	0.022	0.017	0.011	0.006
5.9	0.579	0.171	0.117	0.070	0.040	0.028	0.021	0.014	0.007
6.0	0.656	0.206	0.142	0.085	0.049	0.034	0.026	0.017	0.008
6.1	0.731	0.248	0.173	0.104	0.060	0.042	0.032	0.021	0.010
6.2	0.802	0.296	0.208	0.127	0.073	0.051	0.039	0.026	0.013
6.3	0.865	0.351	0.250	0.154	0.089	0.063	0.048	0.032	0.016
6.4	0.915	0.414	0.299	0.186	0.109	0.077	0.059	0.039	0.020
6.5	0.952	0.482	0.355	0.224	0.133	0.094	0.072	0.048	0.024
6.6	0.976	0.556	0.417	0.269	0.161	0.114	0.088	0.059	0.030
6.7	0.990	0.633	0.486	0.321	0.195	0.139	0.107	0.073	0.036
6.8	0.997	0.709	0.560	0.379	0.234	0.168	0.131	0.089	0.045
6.9	0.999	0.782	0.637	0.444	0.280	0.203	0.159	0.108	0.055
7.0	1.000	0.847	0.713	0.515	0.334	0.244	0.192	0.132	0.067
7.1	1.000	0.901	0.786	0.591	0.394	0.292	0.231	0.160	0.082
7.2	1.000	0.942	0.850	0.668	0.460	0.347	0.277	0.193	0.100
7.3	1.000	0.970	0.904	0.743	0.533	0.409	0.329	0.233	0.122
7.4	1.000	0.987	0.944	0.813	0.609	0.477	0.389	0.279	0.148
7.5	1.000	0.995	0.972	0.873	0.686	0.550	0.455	0.331	0.179
7.6	1.000	0.999	0.988	0.922	0.760	0.626	0.527	0.391	0.216
7.7	1.000	1.000	0.996	0.957	0.828	0.703	0.603	0.458	0.260
7.8	1.000	1.000	0.999	0.979	0.886	0.776	0.680	0.530	0.310
7.9	1.000	1.000	1.000	0.992	0.931	0.842	0.754	0.606	0.367
8.0	1.000	1.000	1.000	0.997	0.963	0.897	0.823	0.683	0.431