

RESEARCH LETTER

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Key Points:

- Aftershocks as large as or larger than the main shock occur outside the initial rupture
- The dearth of large aftershocks within the main shock rupture area is evidence of elastic rebound
- Aftershock spatial distribution is consistent with main shock source scaling and stress triggering

Supporting Information:

- Texts S1 and S2, Figures S1–S8, and Tables S1 and S2

Correspondence to:

N. J. van der Elst,
nvanderelst@usgs.gov

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Larger aftershocks happen farther away: Nonseparability of magnitude and spatial distributions of aftershocks

Nicholas J. van der Elst^{1,2} and Bruce E. Shaw²
¹U.S. Geological Survey Earthquake Science Center, Pasadena, California, USA, ²Lamont Doherty Earth Observatory, Columbia University, Palisades, New York, USA

Abstract Aftershocks may be driven by stress concentrations left by the main shock rupture or by elastic stress transfer to adjacent fault sections or strands. Aftershocks that occur within the initial rupture may be limited in size, because the scale of the stress concentrations should be smaller than the primary rupture itself. On the other hand, aftershocks that occur on adjacent fault segments outside the primary rupture may have no such size limitation. Here we use high-precision double-difference relocated earthquake catalogs to demonstrate that larger aftershocks occur farther away than smaller aftershocks, when measured from the centroid of early aftershock activity—a proxy for the initial rupture. Aftershocks as large as or larger than the initiating event nucleate almost exclusively in the outer regions of the aftershock zone. This observation is interpreted as a signature of elastic rebound in the earthquake catalog and can be used to improve forecasting of large aftershocks.

1. Introduction

Earthquakes commonly set off cascading sequences of aftershocks, some of which can be as large as or larger than the initiating event. While aftershocks are quite well characterized from a statistical standpoint [Felzer et al., 2004; Gu et al., 2013; Helmstetter et al., 2005; Helmstetter and Sornette, 2003; Knopoff et al., 1982; Ogata, 1998; Reasenber and Jones, 1989; Utsu et al., 1995], their physical origin is not completely understood. Aftershocks may be driven by stress concentrations due to heterogeneities in main shock slip [Benioff, 1951] or by stress transfer (static or dynamic) to neighboring faults strands or segments [Freed, 2005; King et al., 1994].

Aftershocks that relax stress concentrations along the main rupture surface may be limited in size, because the scale of residual stress concentrations should be smaller than the initial rupture. Aftershocks that respond to stress transfer beyond the initial rupture patch face no such limitation in size. Instead, the stress increase due to the main shock should create larger contiguous patches near the threshold for failure. An aftershock that nucleates in this outer region may thus have a higher likelihood of propagating away into a large earthquake, perhaps even growing larger than the main shock. (Note that the main shock would then be reclassified as a foreshock. For simplicity, we define the first event in a cluster as the main shock or “initiating event” and define all subsequent earthquakes as aftershocks, regardless of relative magnitudes [Felzer et al., 2004]).

It has previously been shown that consecutive earthquakes along the San Andreas fault are separated by a minimum distance that scales with the rupture length of the first event, consistent with stress relaxation on the initial rupture [Rubin and Gillard, 2000]. The idea that interevent distance is additionally influenced by the finite length scale of the aftershock rupture remains to be demonstrated.

If aftershocks inside and outside the initial rupture patch have different magnitude distributions, this has major importance for probabilistic hazard estimates in the near term after a large earthquake. Operational earthquake forecasting (earthquake forecasts updated in real time based on recent earthquake history) typically require the specification of probabilistic kernels specifying magnitude, position, and time of potential aftershocks [Jordan and Jones, 2010]. A well-known example of such a statistical model is the Epidemic-Type Aftershock Sequence (ETAS) model, in which earthquake occurrence is treated as a point process and space, time, and magnitude kernels are typically assumed to be independent [Ogata, 1998]. These types of statistical models have had good success in retrospective and prospective forecasting of

moderate-magnitude earthquakes ($M < 5$) [Schorlemmer *et al.*, 2010] but have been criticized for ignoring the physical processes of stress transfer and relaxation. Previous attempts to combine ETAS and finite-fault-based models have found that some elements of elastic rebound and stress relaxation must be included in order to prevent self-exciting aftershock sequences from “blowing up” [Field, 2011, 2012].

Aftershocks that are large with respect to their initiating event are relatively rare. Only about 1–6% of earthquake sequences in California involve aftershocks larger than the main shock [Felzer *et al.*, 2004; Jones, 1985]. The largest aftershocks are the most likely to cause damage and also the most likely to violate the point process approximations of the statistical models. Motivated by the physical intuition that larger aftershocks may be more dependent on larger-scale processes of stress relaxation and transfer than smaller aftershocks, and by the need to focus forecasting efforts on the most damaging earthquakes, we take a closer look at the spatial distribution of large aftershocks with respect to the rupture zone of their initiating event. Specifically, we ask whether aftershocks as large as or larger than their main shock follow the same spatial distribution as smaller aftershocks.

2. Method

Our analysis consists of two steps: (1) identify main shocks that are isolated from background activity or other aftershock sequences and (2) measure the spatial distribution of aftershocks with respect to these main shocks, using early aftershocks as an estimate of the main shock rupture centroid.

2.1. Identifying Main Shocks

An exclusion window is used to isolate main shock-aftershock sequences [Reasenber, 1985]. We define main shocks as events larger than $M_{4.0}$ that are not preceded by earthquakes of the same magnitude or larger within 100 days and 20 km. (After the 1993 $M_w 7.3$ Landers earthquake, we visually define a somewhat larger polygon to exclude all Landers aftershocks from being treated as main shocks). We define aftershocks as occurring within 10 km and 100 days of the initiating main shock. This is a somewhat long time window, and we also analyze time windows as short as $3.2 (10^{0.5})$ days. The exclusion window approach cannot perfectly identify causal relationships between events, but it has the benefit of being commonly used, simple, and reproducible [Felzer and Brodsky, 2006; Shearer and Lin, 2009].

We use high-precision cross correlation and double-difference relocated catalogs. For Northern California we use the northern California double-difference (NCDD) relocated catalog of Waldhauser and Schaff [2008], and for Southern California, we use the Hauksson, Yang, and Shearer (HYS) catalog [Hauksson *et al.*, 2012]. These catalogs are accurate to 100 m or less on the scale of an aftershock zone. For small events ($< M_4$), the waveform relocations reflect relative hypocentroids, but for large events ($> M_4$) the relocations rely more heavily on differential arrival times and reflect relative hypocenters [Hauksson *et al.*, 2012]. For small events, the difference between hypocenter and hypocentroid is negligible, but there may be some ambiguity about location type for events around M_4 . For the purposes of this study, we interpret all locations as approximate nucleation points. To make sure that the results are not biased by this feature of the catalogs, we also analyze a catalog of absolute hypocenter locations [Northern California Earthquake Data Center, 2014]. We restrict the catalog of main shocks to those with relative location errors ≤ 0.5 km. The catalogs overlap over some of their range; in these areas we choose the hypocenter with the smaller error estimate. We also exclude two areas where earthquakes are dominated by swarms: The Geysers and Long Valley Caldera. The remaining 511 isolated main shock-aftershock sequences are mapped in Figure 1, 30 of which have aftershocks larger than the main shock. These latter sequences are plotted with their aftershocks in Figure S1 (supporting information).

2.2. Running Centroid Locations

In an innovative approach, we measure aftershock distance relative to the centroid location of all prior aftershock activity for that sequence (running centroid distance). Our intention is to use the aftershock centroid as a proxy for the main shock rupture. This is a more physically meaningful point of reference than the main shock hypocenter, when considering stress transfer and relaxation. (Moment centroid solutions do exist for most of the main shocks in this study. However, these solutions are not incorporated into double-difference relocations, limiting their usefulness.) To ensure a robust estimate of the aftershock

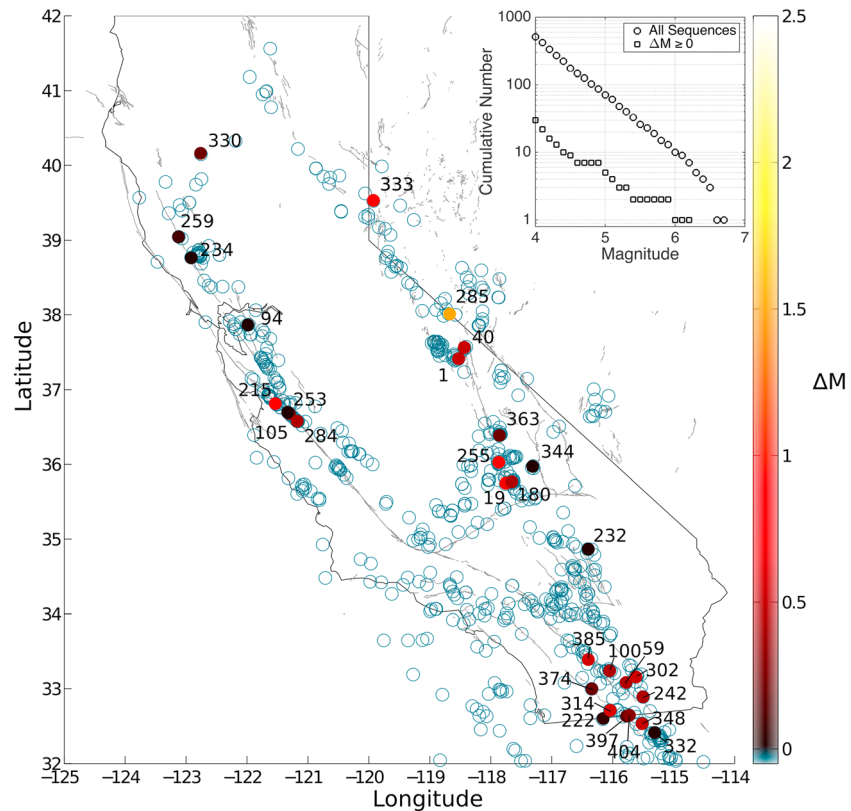


Figure 1. Location of $M4.0+$ main shocks used in this study. Filled circles are sequences in which the largest aftershock has higher magnitude than the main shock (color scaled to the difference in magnitude.) Numbers correspond to sequences plotted in Figure S1 and listed in Table S1.

centroid, we require at least seven aftershocks in the sequence before we start measuring running centroid distances. Finally, since large aftershocks themselves perturb the stress field, we cut off the analysis at the first aftershock larger than the main shock.

We report both the absolute distance to each aftershock and the ranked distance. In this scheme, an aftershock that is closer to the running centroid than all previous aftershocks has a ranked distance of 0, an aftershock falling at the median distance of previous activity has a ranked distance of 0.5, and an aftershock that is the most distant aftershock yet has a ranked distance of 1. The ranked distance rescales each aftershock sequence by its spatial extent and allows us to compare aftershock zones of different magnitude main shocks without making assumptions about the precise form of the spatial kernel.

2.3. Main Shock Length Scale

We can also normalize the aftershock distances by the expected main shock source radius. This is less robust than the nonparametric ranked distance approach but may yield additional insights into the spatial relationship between aftershocks and main shocks.

An order of magnitude estimate of the rupture radius is [Kanamori and Anderson, 1975]

$$R = \left(\frac{7 M_0}{16 \Delta\sigma} \right)^{1/3}, \quad (1)$$

where $\Delta\sigma$ is the stress drop, and M_0 is the seismic moment given by

$$M_0 = 10^{1.5M_w + 9}. \quad (2)$$

Substituting equation (2) into equation (1) gives

$$R = 10^{0.5(M_w - M_{ref})}, \quad (3)$$

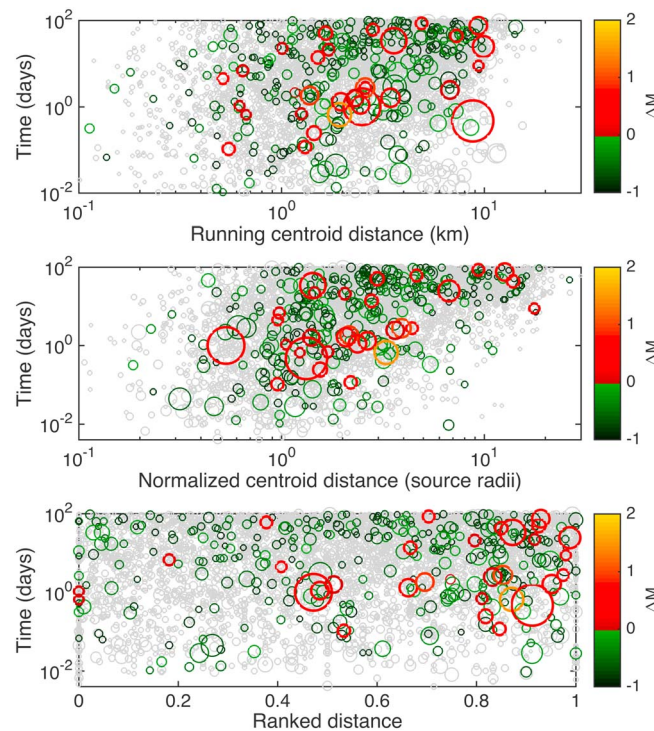


Figure 2. (top) Distance of aftershocks with respect to the running centroid location of previous aftershocks for $M4-7$ main shocks. Circles are scaled to aftershock magnitude and colored according to the difference between aftershock and main shock magnitude ΔM . Grey circles are aftershocks with $-2 \leq \Delta M < -1$. (middle) Running centroid distance normalized by main shock source radius (equation (3)). (bottom) Ranked distance with respect to the running centroid.

shock magnitude $\Delta M = M_{AS} - M_{MS}$. We compute a running average of the ranked distance (smoothed over one magnitude unit) and compare this to confidence limits from repeated random sampling of smaller aftershocks ($-2 < \Delta M < -1$). Mean aftershock distance begins to increase at $\Delta M = -1$, and the populations of small and large aftershocks are distinct (above 99% confidence) for $\Delta M = 0$. The trend of increasing distance grows more pronounced for even larger ΔM , although the paucity of events reduces the statistical significance. This pattern persists if we measure distances with respect to the final centroid location of all aftershocks (up to and including the first larger aftershock) rather than the running centroid (Figure S2).

The interior of the aftershock zone is strikingly devoid of large aftershocks. The minimum distance to the aftershocks appears to increase with ΔM (Figure 3). No aftershocks with $\Delta M > 0.5$ occur in our catalog within the interior ~50% of the aftershock zone. The probability of seeing such a deficit by chance, given the distribution of smaller aftershocks, is less than 0.5%.

To show that the signal is not an artifact of the relocated catalogs, we also analyze the Advanced National Seismic System catalog of absolute hypocenters, using main shocks of $M4.5$ and above (~1 km source radius) to account for the greater location uncertainty. The trend of increasing ranked distance for larger aftershocks persists, reaching 95% significance at $\Delta M = 0$ (Figure S4).

3.2. Aftershock Hypocentral Distance

There is no tendency for larger aftershocks to occur farther away when measured from the main shock hypocenter (Figure S3). This supports the idea that main shock slip—not nucleation—drives aftershock occurrence. Large aftershocks do occasionally nucleate near the main shock hypocenter, but only when the main shock hypocenter itself is at the margin of the aftershock zone. We will revisit the distribution of separations between main shock hypocenter and aftershock centroid below.

where $M_{\text{ref}} = 2/3 \log_{10}(\Delta\sigma/16/7)$ is the magnitude at which $R = 1$ km. For example, assuming a stress drop of 3 MPa, the source radius of a $M4$ earthquake is 0.53 km. The spatial extent of an $M4$ main shock is therefore within the resolution of the relocated catalogs (~0.1 km). We will confirm below that the aftershock zone indeed scales in a manner very similar to equation (3). We will not worry about minor differences between the catalog magnitudes and moment magnitudes for which equation (2) is defined.

3. Results

3.1. Aftershock Running Centroid Distance

The running centroid distances are plotted in Figure 2. Larger aftershocks tend to be clustered in the outer regions of the aftershock zone. This becomes strikingly clear when plotted as ranked distance. Several of the larger aftershocks are the most distant aftershocks in their respective sequences.

Figure 3 shows the ranked distance of the aftershocks as a function of the difference between the aftershock and main

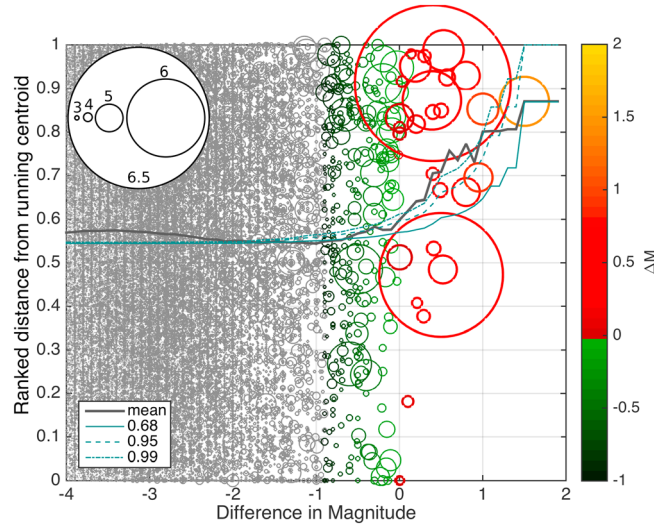


Figure 3. Ranked aftershock distance with respect to the centroid location of previous aftershocks. Circles are scaled to aftershock magnitude. Solid black line is the running average over one magnitude unit. Teal lines are 68–99% confidence bounds on the mean from repeated random sampling of the smaller aftershocks ($-2 \leq \Delta M \leq -1$).

distance r from a point on the fault. For an infinite planar fault $N(r)$ would be $2\pi r$. Accounting for the finite seismogenic thickness w , and assuming a uniform distribution of main shocks over this depth, Shaw [1993] derived an expression for $N(r)$:

$$N(r) = \begin{cases} 4r \left[\frac{\pi}{2} - \frac{r}{w} \right] & r \leq w \\ 4r \left[\sin^{-1} \left(\frac{w}{r} \right) - \frac{r}{w} \left(1 - \sqrt{1 - \frac{w^2}{r^2}} \right) \right] & r \geq w \end{cases} \quad (5)$$

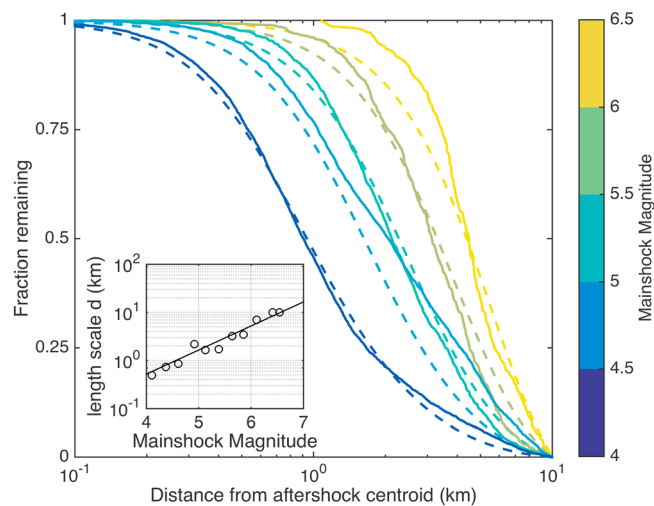


Figure 4. Distribution of aftershock running centroid distances as a function of main shock magnitude, for the first 3.2 days after the main shock. Dashed lines show equation (4) with fixed parameters $\lambda = 0.5$, $\gamma = 3.0$. (inset) Circles show aftershock zone length scale d estimated from nonoverlapping main shock magnitude bins using equation (4). Solid line is the source scaling predicted by equation (6) with $\lambda = 0.5$ and $M_{\text{ref}} = 4.56$.

3.3. Aftershock Zone Scaling With Main Shock Magnitude

We stack the aftershock sequences in order to reveal the spatial distribution of aftershocks around the main shock rupture centroid (Figure 4). The first obvious feature of this distribution is that aftershock zone size increases with the magnitude of the main shock in a manner that is consistent with increasing main shock rupture length.

The spatial distribution of aftershocks is consistent with a power law kernel of the form

$$p(r) \propto N(r) (r^2 + d^2)^{-\gamma/2}, \quad (4)$$

where d is an internal length scale that sets the transition to power law decay with slope γ [Powers and Jordan, 2010]. The function $N(r)$ describes the increase in available nucleation sites with

Here we have slightly modified the equation of Shaw [1993] to describe just the geometrical correction, so $N(r) \cong 2\pi r$ in the limit $r \ll w$ and $N(r) \cong 2w$ in the limit $r \gg w$.

We assume that d in equation (4) scales with main shock magnitude in a form similar to the main shock source scaling (equation (3))

$$d(M_{\text{ms}}) = 10^{\lambda(M_{\text{ms}} - M_{\text{ref}})}, \quad (6)$$

where M_{ms} is the main shock magnitude and M_{ref} is a reference magnitude for which $d = 1$ km. We fit the four parameters λ , γ , w , and M_{ref} (equations 4–6) by maximum likelihood (MLE), using aftershocks with $\Delta M < 0$, $t < 3.2$ days, and $r < 10$ km. The MLE fit gives $\hat{\lambda} = 0.53$ and $\hat{\gamma} = 2.93$ ($\hat{M}_{\text{ref}} = 4.60$, $\hat{w} = 7.39$ km), remarkably close to the theoretical source scaling of $\lambda = 0.5$ (equation (3)) and $\gamma = 3$ expected for stress decay from a double-couple dislocation (for which

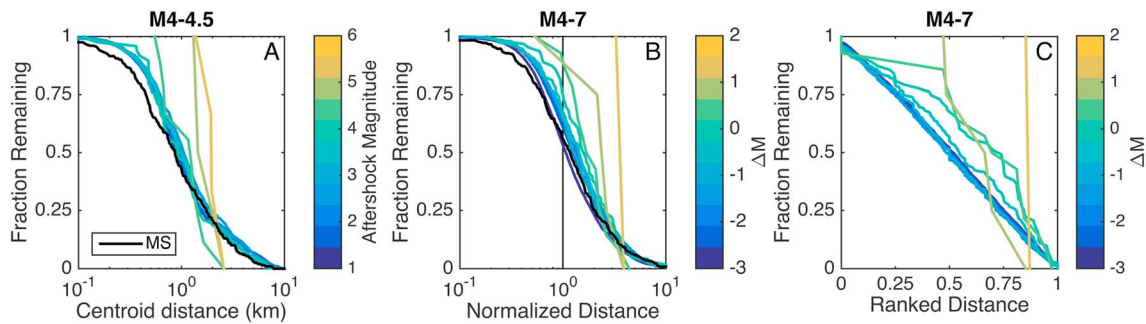


Figure 5. Spatial distribution of aftershocks as a function of *aftershock* magnitude, for the first 3.2 days of aftershocks. (a) Running centroid distance to aftershocks of $M4-4.5$ main shocks. Black line (MS) is the distribution of distances between the main shock hypocenter and aftershock centroid. (b) Aftershock centroid distance normalized by main shock rupture length (equation (6)), for $M4-7$ main shocks. (c) Distribution of ranked aftershock distance.

the MLE is $\hat{M}_{\text{ref}} = 4.56$ and $\hat{w} = 7.82$ km). Considering that the geometrical correction $N(r)$ (equation (5)) assumes a boxcar distribution of aftershock depths (Figure S8), we find the agreement between the best fit and theoretically constrained parameters to be very compelling (see also Text S2, supporting information). It should be noted, however, that the interpretation of the power law slope in terms of the physics of earthquake triggering has been the subject of some controversy [Felzer and Brodsky, 2006; Richards-Dinger et al., 2010].

Assuming $\lambda = 0.5$ and equating the length scale d (equation (6)) with the radius of the source R (equation (3)), we find that $\hat{M}_{\text{ref}} = 4.56$ corresponds to a stress drop $\Delta\sigma = 3.0$ MPa. This stress drop is in very close agreement with the average stress drop for California earthquakes [Abercrombie, 1995; Hanks, 1977], supporting the interpretation that the internal length scale of the aftershock spatial kernel is controlled by the length of the main shock rupture.

3.4. Aftershock Zone Scaling With Aftershock Magnitude

We first stack the raw aftershock distances for $M4-4.5$ main shocks, for which the source dimensions should be relatively consistent, and confirm that the spatial distribution of larger aftershocks is shifted outward with respect to smaller aftershocks (Figure 5a).

We then look at the distribution around main shocks of all magnitudes ($M4-6.7$), this time normalizing each aftershock zone based on the main shock magnitude (equation (6)). Again, aftershocks larger than their main shock ($\Delta M \geq 0$) occur farther away than smaller aftershocks (Figure 5b).

Interestingly, the distribution of small aftershocks with respect to the aftershock centroid is very similar to the distribution of main shock hypocenters with respect to the aftershock centroid (Figure 5a, black line). The similarity in distribution suggests that there may be some physical similarity between asperities that nucleate main shocks and those that nucleate aftershocks.

Finally, we stack the ranked distances for all sequences. This normalizes aftershock distances on a sequence-by-sequence basis without assuming anything about the spatial kernel. Aftershocks larger than their main shock are systematically shifted to larger ranked distances (Figure 5c).

4. Discussion

4.1. Previous Measurements of Spatial Decay

Previous studies on aftershock spatial distribution have found $1.4 \leq \gamma \leq 2.5$ [Felzer and Brodsky, 2006; Hardebeck, 2013; Marsan and Lengliné, 2010; Powers and Jordan, 2010; Shearer, 2012]. In general, studies that use a geometrical correction come up with larger values of γ . Hardebeck [2013] used a volumetric geometrical correction for the finite seismogenic thickness to obtain a lower limit of $\gamma = 1.8$ but could not constrain an upper bound. If we fit the linear density directly by least squares, with no geometrical correction, we find $\gamma \approx 1.77$, more or less consistent with other studies lacking a geometrical correction (Figure S6). However, the geometrically corrected model using equation (5) gives a substantially better fit to the data (Text S1, supporting information).

4.2. Comparison With ETAS Simulated Catalogs

The pattern of increasing separation with increasing aftershock magnitude is not reproduced by simulated (ETAS) earthquake catalogs in which aftershock distance depends only on the main shock magnitude (supporting information). The observation is thus unlikely to be merely a result of contamination by other nearby aftershock sequences in the application of the exclusion/inclusion criteria.

4.3. Nonseparability of Space and Magnitude Kernels

While it is clear that aftershocks with magnitude larger than their main shock occur farther away, it is not entirely clear how that tendency should be expressed in a probability kernel similar in form to equation (4). The data suggest that the spatial kernels must incorporate both the main shock and aftershock length scales. The observed features could be reproduced by a model in which the initial rupture acts as a (probabilistic) barrier to aftershock growth. Only aftershocks that nucleate relatively far away have room to grow to magnitudes exceeding that of the main shock. At the very least, our observations demonstrate that aftershock magnitude and location cannot be treated as entirely separable.

4.4. Implications for Earthquake Forecasting

The data show that the areas of greatest concern for large aftershocks are outside the initial rupture. One of the current challenges in time-dependent, short-term earthquake forecasting is to unify fault-based representations of earthquakes [Field *et al.*, 2015] with statistical branching models for earthquake interactions [Gerstenberger *et al.*, 2005]. The empirical magnitude-dependent spatial kernels plotted in Figure 5 may serve as a useful starting point.

For this observation to be useful for aftershock forecasting, we need rapid determinations of rupture extent. The success of the running centroid measurement suggests that the aftershock centroid is an effective proxy for the rupture centroid.

5. Conclusion

We have examined high-precision relocated earthquake catalogs in California and found that larger aftershocks tend to occur farther from the centroid of previous activity than smaller aftershocks. We interpret this as evidence of stress relaxation on the main shock rupture patch. The difference in aftershock spatial distribution is most apparent for aftershocks with magnitude equal to or greater than the main shock.

We have found quantitative support for the idea that aftershock spatial decay is dominated by static stress transfer in the near field (several rupture lengths). By applying a novel correction for the changing geometry of the aftershock zone with distance, we find that the transition to power law decay occurs at the edge of the estimated main shock rupture, with an estimated stress drop of 3 MPa. The decay beyond this distance is consistent with the r^{-3} scaling expected for static stress falloff from a double-couple dislocation.

This observation can improve forecasting of the locations of large aftershocks after a main shock. The hazard posed by an earthquake larger than the initiating event is centered on the locus of previous small aftershocks but is distributed over a wider annulus surrounding the main shock rupture extent. Spatial probability kernels must therefore treat magnitude and position together in order to better forecast the largest, most damaging aftershocks.

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