The slow decay of aftershocks triggered by the August 2011, Mineral, Virginia earthquake

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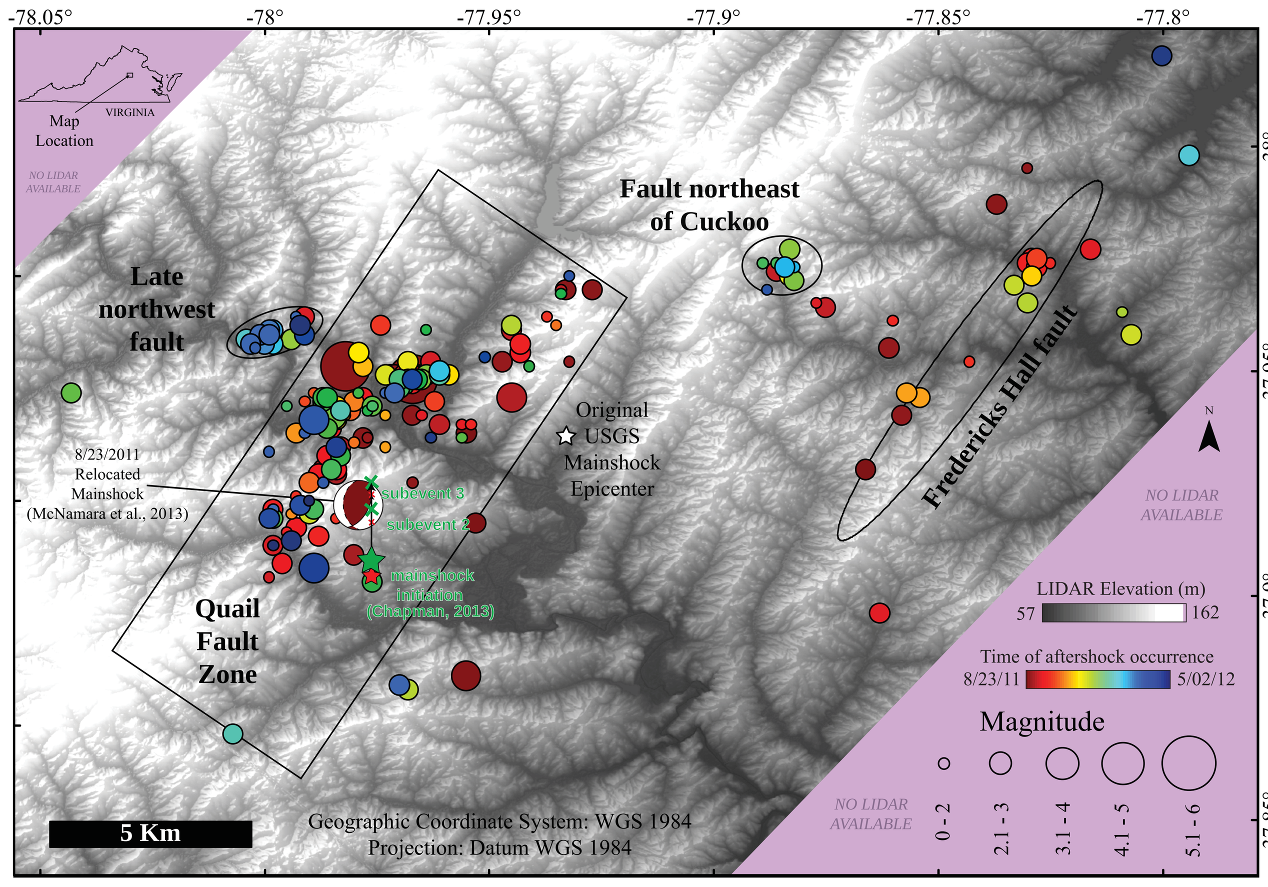
ABSTRACT

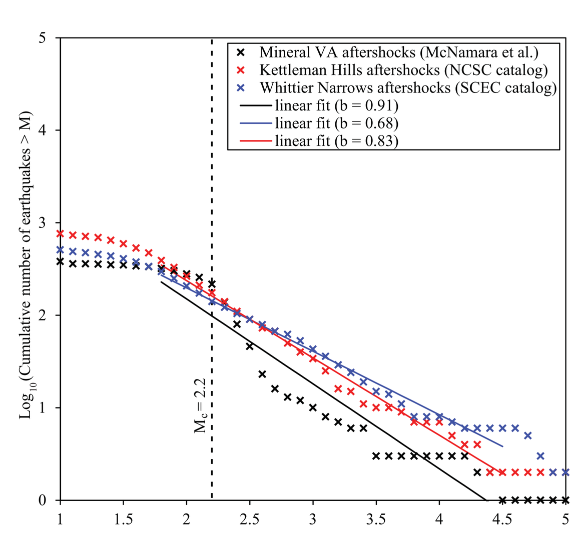
On August 23, 2011, a Mw 5.8 earthquake, one of the larger earthquakes in the eastern U.S. in over a century, struck near the town of Mineral, Virginia. A multi-institution deployment of seismometers in the epicentral region of the Mineral earthquake yielded the best recorded aftershock sequence in the eastern U.S. and has offered a rare opportunity to study the decay of aftershocks in an intraplate setting. The Mineral earthquake was a reverse faulting event, and comparison with two reverse faulting earthquakes in California (the 1985 Mw 6.1 Kettleman Hills and 1987 Mw 5.9 Whittier Narrows earthquakes) has revealed variations in the rate and duration of aftershock sequences. The rate in the California aftershock sequences decreased to two or fewer events per day 20 days after the mainshock. Aftershocks of the Mineral earthquake decreased in a power law decay fashion for the first 10 days after the mainshock, but then increased to more than two events per day at about ~25 and 100 days after the mainshock. Each catalog was constrained using a Mc = 2.2 and to events located <15 km from the mainshock. Modified Omori's law curves fit to each sequence yielded a low p-value of 0.76 for the Mineral earthquake compared to p-values of 1.13 and 1.25 for the Kettleman Hills and Whittier Narrows earthquakes (respectively), indicating a significantly slower decay of aftershocks from the Mineral earthquake. This slow decay rate can be attributed in part to the delayed occurrence of earthquakes along the aftershock-delineated Fredericks Hall (~25 days after the mainshock) and late northwest (~100 days after the mainshock) faults. Structural heterogeneities, stress, and temperature in the crust are all cited as factors responsible for causing variations in p-value. The crust in the eastern U.S. is older and colder than in many tectonically active regions. These characteristics could explain its prolonged aftershock decay rate. The slow decay of aftershocks from the Mineral earthquake may also support the hypothesis that aftershock duration is inversely proportional to fault stress rate, according to which aftershocks in active tectonic margins may last only a few years whereas aftershocks in intraplate regions may endure much longer.

EARTHQUAKE AND AFTERSHOCK INFORMATION



Aftershocks of the Mineral earthquake from McNamara et al. (2013) with aftershock fault zones delineated by Horton et al. (2014). Progression of subevents from mainshock initiation (Chapman, 2013) is shown by the arrow. Aftershocks are superimposed on the 1/9 arc-second light detection and ranging (LIDAR) elevation data collected post-earthquake available from the National Elevation Dataset. Correlations between aftershocks and LIDAR data are discussed in Horton et al. (2014)

Temporary seismic station in epicentral region of the Mineral earthquake
Steve Ploetz, a field engineer, installs a temporary USGS seismic station named PTRD in Spotsylvania County, Virginia, one of over 30 installed by a variety of organizations within three days after the mainshock. Photo taken thanks to Alana Leeds who agreed to meet with me during the days immediately following the mainshock in the epicentral region near the town of Mineral, VA.



Magnitude of completeness for aftershock databases
Cumulative number of aftershocks by magnitude (M) within a 15 km radius of the Mineral, Kettleman Hills, and Whittier Narrows earthquakes. I applied a common magnitude of completeness (M_c) of 2.2 to each catalog before fitting the modified Omori's decay law curve. Corresponding b-values are derived from linear fits over the $1.8 \leq M \leq 4.5$ range. The p-values indicate that the aftershock decay rate of the Mineral earthquake was much slower than the decay rate of aftershocks triggered by the California earthquakes.

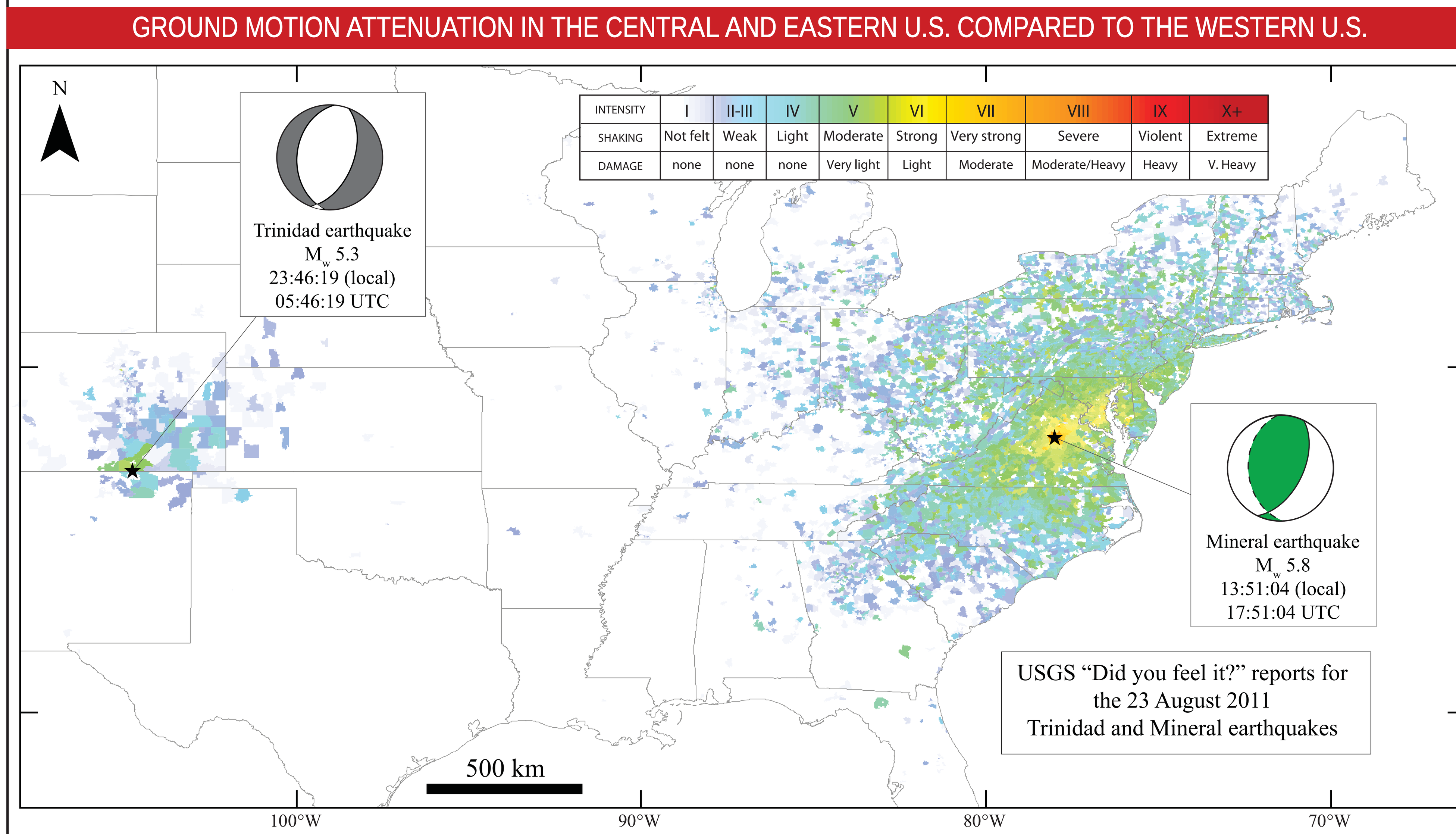
Earthquake moment release, stress drop, duration, and surface displacement

Earthquake Name	M_w	Moment Release (N.m)	Stress Drop (MPa)	Source duration (seconds)	Maximum Predicted Vertical Surface Displacement (modeled) (mm)	Maximum Vertical Surface Displacement (observed) (mm)
Mineral	5.7	5.75E+17	40 -75	3	90	
Kettleman Hills	6.1	1.60E+18		16	60	10.18
Whittier Narrows	5.9	7.00E+17	17.5 ± 5.0		38	50

Multiple institutions including the United States Geological Survey (USGS), Virginia Polytechnic Institute and State University (Virginia Tech), Lamont-Doherty Earth Observatory of Columbia University, University of Memphis Center for Earthquake and Research Information (CERI), Lehigh University, Incorporated Research Institutions for Seismology (IRIS), and Cornell University deployed temporary seismometers in the source region immediately following the mainshock [Horton and Williams, 2012]. This aftershock detection seismic network was in place approximately three days after the mainshock and deployed through May 2, 2012, allowing a timeframe of 253 days (~8 months) to capture the characteristics of the aftershock decay sequence. An initial catalog of detected aftershocks is available on the USGS website for the Mineral earthquake at http://earthquake.usgs.gov/regional/ceus/se082311a/aftershocks.php, however we used an improved version of this catalog that used a hypocentroidal decomposition algorithm to prepare a catalog of calibrated, relocated aftershocks spurred by the August 2011 Mineral earthquake [McNamara et al., 2013]. We used a preliminary version of this catalog to characterize the decay rate of aftershocks in the epicentral region of the Mineral earthquake and compare them to the aftershock decay rate produced by the California earthquakes.

We used earthquake catalogs publically available from the Northern California Earthquake Catalog and the Southern California Earthquake Data Center (based on permanent seismic networks) to characterize the aftershock decay rate of the Kettleman Hills, Northern California, and Whittier Narrows, Southern California, earthquakes for comparison to the Mineral earthquake. Comparisons of the magnitude frequency relations indicated earthquakes less than magnitude 2.2 were not consistently detected from the temporary seismic network deployed in the epicentral region of the Mineral earthquake and events less than ~1.8 were not detectable in the region of the Kettleman Hills and Whittier Narrows events. Therefore we used a Mc of 2.2 in order to consistently compare the aftershock decay rate of the Mineral earthquake to these California events.

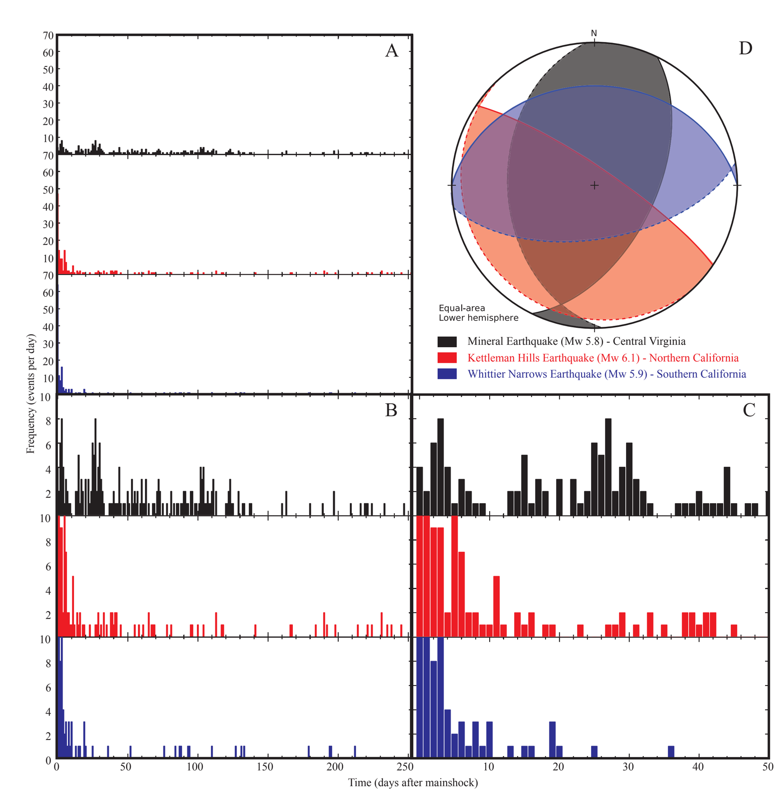
GROUND MOTION ATTENUATION IN THE CENTRAL AND EASTERN U.S. COMPARED TO THE WESTERN U.S.



Comparison of the USGS Community Internet Intensity maps for the August 23, 2011 Mw 5.8 Mineral, Virginia, and Mw 5.3 Trinidad, Colorado, earthquakes. Shaking from the Mineral earthquake was felt over a region at least three times larger than the Trinidad earthquake. Intensity is reported by zipcode was obtained from the USGS event pages from these earthquakes (see Data and Resources Section). Earthquake times are in Coordinated Universal Time (UTC). Maximum intensity for the region surrounding the Mineral earthquake was VII and V for the Trinidad earthquake. Geographic Coordinate System: WGS 1984. Projection: Datum WGS 1984.

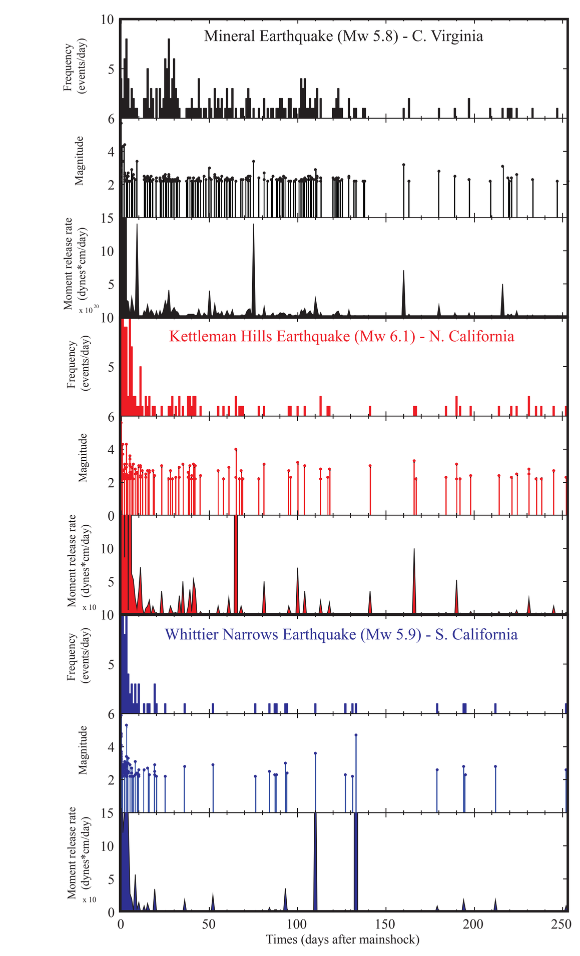
AFTERSHOCK OCCURRENCE OVER TIME AFTER MAINSHOCK

Aftershocks following the Mineral, Kettleman Hills, and Whittier Narrows earthquakes



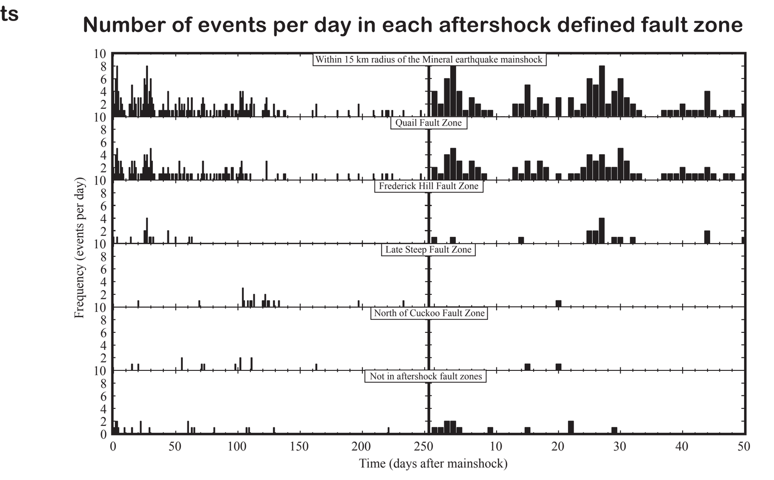
Time series showing the number of aftershocks per day following the Mineral Virginia (black), Kettleman Hills (red), and Whittier Narrows (blue) mainshocks. The temporary seismic network in the Mineral region was not in place until ~3 days after the mainshock, therefore assumed large numbers of aftershocks immediately following the mainshock were not detected. Plot A shows each sequence with the y-axis scaled to 70 events per day. Plot B shows the same dataset with the y-axis scaled to 10 events per day. Plot C rescales the x-axis to zoom in on the first 50 days of the aftershock sequence. Plot D shows Global CMT focal mechanism solutions for each event which indicate thrust sense motion and similar dip magnitudes. Solid lines represent rupture planes associated with each earthquake and auxiliary planes are dashed (Table 3-1) [*Grohmann and Campanha*, 2010; *Grohmann et al.*, 2011].

Aftershock frequency, magnitude, and moment release for Mineral versus California events



Aftershock frequency, magnitude, and moment release rate over time for the Mineral, Kettleman Hills, and Whittier Narrows aftershock sequences. Aftershocks ranging from magnitudes 3 to 4 occurring fifty or more days after the mainshock generated significant increases in the moment release rate. The change in moment release over time does not appear to explain major differences shown by the aftershock decay curves.

Number of events per day in each aftershock defined fault zone



Time series showing number of aftershocks per day in the aftershock zone and each named aftershock fault zone shown in Figure 3-4 [*Horton et al.*, 2012]. The majority of recorded aftershocks occurred on the Quail Fault zone immediately following the mainshock, while the aftershocks that define the Fredericks Hall fault zone and Late Steep fault zone occurred ~25 and ~100 days, respectively, after the mainshock.

The rate at which aftershocks decayed in response to the Mineral, Virginia, earthquake was much slower than the events from the Kettleman Hills and Whittier Narrows events in California, despite the similarity in their depths, magnitudes, and focal mechanisms. The delayed occurrences of aftershocks in the Fredericks Hall (~25 days after the mainshock) and Late northwest fault zones (~100 days after the mainshock) appear to be the proximal causes for the slow decay rate of aftershocks from the Mineral earthquake. Our modeling of Coulomb stress change indicates that the Late northwest fault zone falls in a stress trigger zone produced by the Mineral earthquake. The transfer of stress from the Mineral earthquake may have promoted failure in the region between the surface and the tip of the blind rupture from the mainshock, thus triggering the aftershocks that define the Late Steep fault zone. The dip of the Fredericks Hall fault zone is not well defined by aftershocks, therefore we do not know its orientation. The aftershocks defining the Fredericks Hall fault zone fall within the transition zone between positive and negative Coulomb stress for faults oriented like the mainshock's rupture, indicating that it is unlikely stress transfer from the mainshock alone triggered these aftershocks.

CALCULATION OF AFTERSHOCK DECAY RATE

The rate of aftershocks, typically smaller magnitude events following the mainshock, tends to increase most rapidly immediately following the mainshock and less often over time. This decay of aftershocks over time follows a power law relationship known as Omori's Law [Omori, 1894]:

$$n(t) = \frac{K}{t + c'}$$

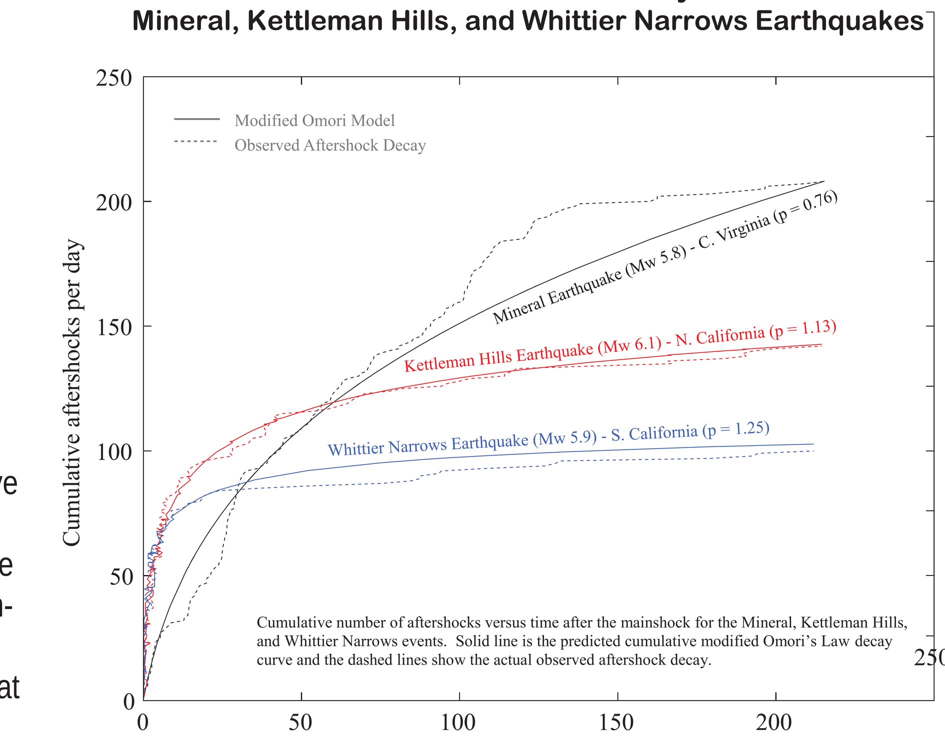
where n(t) is the number of aftershocks per unit time above a given magnitude (Mc), t is the time measured from the mainshock, and K and c are constants [Shearer, 2009]. This relationship is often generalized to the modified Omori's law [Utsu et al., 1995]:

$$n(t) = \frac{K}{(t + c)^{p'}}$$

which permits a more general power law relation where the exponent p is typically close to 1. The p value reflects the decay rate of the aftershock sequence, where values greater than 1 would have relatively rapid decay rates and values less than 1 would have relatively slower decay rates. K is the aftershock productivity and is dependent on the total number of events in the sequence and the parameter c relates to the rapid decrease in aftershocks immediately following the mainshock compared to a simple uniform power law decay. The c value marks the transition from the mainshock to the aftershock sequence and can thus provide information about the underlying mechanisms that control the aftershock occurrence [Peng et al., 2006].

We used Matlab scripts based on the earthquake statistics program ZMAP [Wiemer, 2001] to fit modified Omori's law curves to the Mineral, Kettleman Hills, and Whittier Narrows aftershock sequences using a Mc of 2.2 and time elapse of 253 days after the mainshock. The script is designed to bootstrap a curve with the modified Omori's decay law constants for 1 day time intervals. ZMAP is freely available from the ETH Zurich Earthquake Statistics Group at http://www.earthquake.ethz.ch/software/zmap. The scripts used for this analysis were extracted from ZMAP and compiled by Brendan Sullivan, J. Luis, Zhigang Peng, and others in the Geophysics group at Georgia Institute of Technology and are available at http://geophysics.eas.gatech.edu/people/bsullivan/tutorial/StatisticalSeismology.htm. The scripts are accompanied by instructions, a tutorial, and explanations for their use on the website.

Omori's curve for aftershock decay rate of the Mineral, Kettleman Hills, and Whittier Narrows Earthquakes



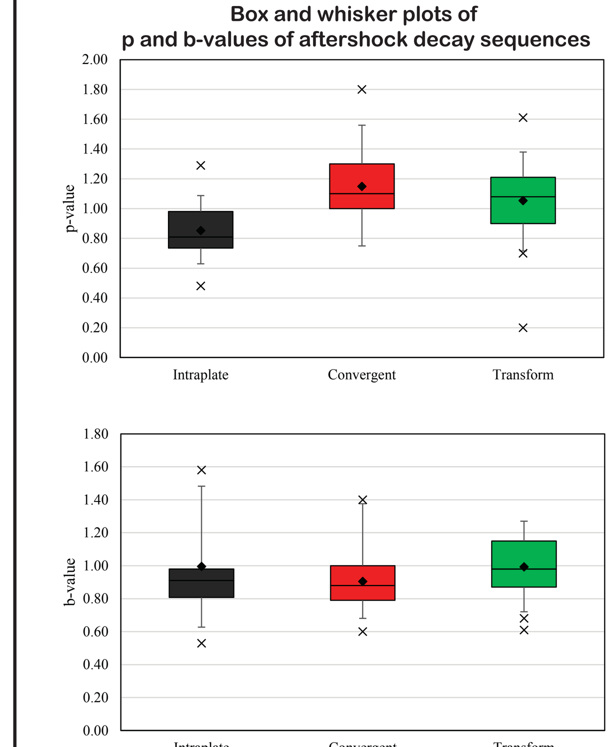
Cumulative number of aftershocks versus time after the mainshock for the Mineral, Kettleman Hills, and Whittier Narrows events. Solid line is the predicted cumulative modified Omori's Law decay curve and the dashed lines show the actual observed aftershock decay.

Aftersock decay study parameters

Earthquake Name	Radial Distance from epicenter that defines area used to extract aftershocks	Magnitude threshold	b-value	p	c	k
Mineral Virginia	15	2.2	0.91	0.76	5	22.6
Kettleman Hills	15	2.2	0.68	1.13	0.746	34.5
Whittier Narrows	15	2.2	0.83	1.25	0.338	24.5

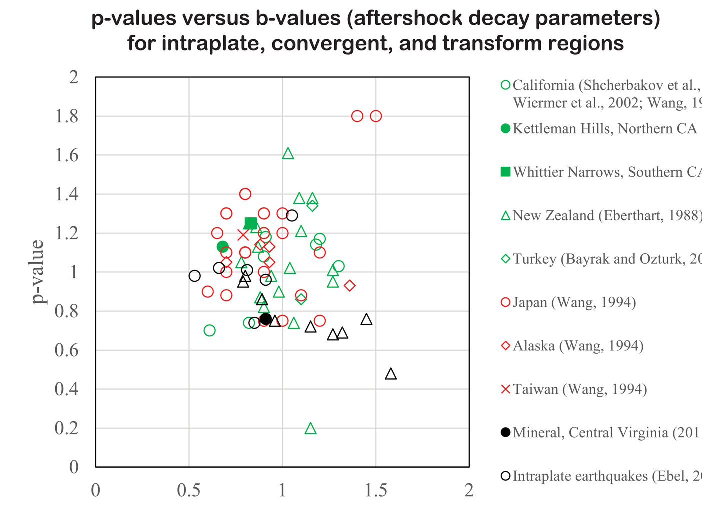
COMPARISON OF AFTERSHOCK DECAY PARAMETERS IN DIFFERENT TECTONIC ENVIRONMENTS

Box and whisker plots of p and b-values of aftershock decay sequences



Box and whisker plots showing the distributions of p-value (A) and b-value (B) parameters associated to aftershock decay sequences in intraplate, convergent, and transform regions [*Wang*, 1994; *Ebertart*, 1998; *Ebel et al.*, 2000; *Wiermer et al.*, 2002; *Bayrak and Osturk*, 2004; *Shcherbakov et al.*, 2005]. The box represents the interquartile range (which represents the middle 50% of the data). The vertical ends of the box are the 25th and 75th percentiles, the whiskers extend to the 95% of the data, and the X symbols represent outliers. Mean values are shown as diamonds and the median values as horizontal lines. These distributions indicate that the majority of aftershock sequences in intraplate sequences have lower p-values, or slower aftershock decay rates, than those in convergent or transform regions.

p-values versus b-values (aftershock decay parameters) for intraplate, convergent, and transform regions



Plot of p-value and b-value for aftershock decay sequences in intraplate, convergent, and transform regions [*Ebertart*, 1998; *Wang*, 1994; *Ebel et al.*, 2000; *Wiermer et al.*, 2002; *Bayrak and Osturk*, 2004; *Shcherbakov et al.*, 2005]. Filled symbols represent the aftershock decay parameters associated with the Mineral (black circle) and Whittier Narrows (green square) events. The Mineral earthquake has a relatively average b-value, but a relatively low p-value caompared to these populations.

The Kettleman Hills and Whittier Narrows earthquakes have p-values that fall within a range of 0.85 to 1.3, the expected range of p-values for Californian earthquakes [Reasenberg and Jones, 1989; Reasenberg and Matthews, 1990]. Reasenberg and Jones [1989] compared the aftershock sequences from sixty-two mainshocks in California and give a p-value of 1.08 for a "generic California" aftershock sequence. Previous aftershock sequences from the following intraplate earthquakes have p-values ranging from 0.74 to 1.29: the 1982 magnitude 5.7 event near Miramichi, Canada, the 1983 magnitude 5.1 event near Goodnow, NY, the 1988 magnitude 6.8 event near Tennant Creek, Australia, the 1978 magnitude 5.7 event near Swabian Jura, Germany, the 1984 magnitude 5.4 event near Lleyn, Wales, and the 1994 magnitude 5.8 event near Roermond, Netherlands [Ebel et al., 2000].

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Main Conclusion

The decay of aftershocks from the Mineral earthquake was significantly slower than the decay rate of the Kettleman Hills and Whittier Narrows earthquakes in California.