LLNL-TR-814889

LAWRENCE LIVERMORE NATIONAL LABORATORY

Aftershocks of a Chemical Explosion in Granite from the Source Physics Experiment Phase I

S. R. Ford

September 25, 2020

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Aftershocks of a Chemical Explosion in Granite from the Source Physics Experiment Phase I

Sean R. Ford

Lawrence Livermore National Laboratory, Livermore, California 94550, USA

September 21, 2020

1 Introduction

The Source Physics Experiment (SPE) is a multiphase experiment to better understand explosion source physics and thereby improve explosion monitoring. The first phase (Phase I) examined the explosion source in a hard-rock medium and took place in a granite outcrop called the Climax Stock section of the Nevada National Security Site (NNSS). This series of chemical explosions are called the Wet Granite Geology (WGG) events, but are usually referred to simply as the SPE events (i.e., SPE-1, SPE-2, etc.). Event information for the chemical explosions is given in Table 1.

The study of explosion aftershocks can aid in understanding of in-situ stresses [Parsons and Velasco, 2009] and be used as a discriminant for earthquakes [Ford and Walter, 2010]. Sweeney and Harben [2011, 2012] reported no observed aftershocks for SPE-1 and -2, respectively. They calculated a minimum magnitude of observation based on the noise floor of the seismic array and predicted at least one or two events in the week after the events using the hard-rock aftershock model from Ford and Labak [2016]. Possible explanations for the null observation ranged from instrumental - poor seismometer coupling, to physical - the shallow depth of burial was unable to access the deep tectonic stress that causes some explosion aftershocks.

We extend the analysis of Sweeney and Harben [2011, 2012] to the largest of the SPE Phase I chemical explosions, SPE-5, which was approximately a 5 tonne TNT-equivalent shot at 76.5 m depth. This event registered as an $M_L 2$ on the University of Nevada, Reno seismic network and should produce a measurable aftershock sequence.

Table 1: SPE Phase I, Wet Granite Geology events

Name	Date (DOY#)	Time	Yield [kg*]	Depth [m]	M_L (UNR+)
SPE-1	2011/05/03 (123)	22:00:00.011	87.9	54.9	
SPE-2	2011/10/25 (298)	19:00:00.012	997	45.7	
SPE-3	2012/07/24 (206)	18:00:00.448	905	47.2	
SPE-4Prime	2015/05/21 (141)	18:36:00.000	89	87.2	0.7
SPE-5	2016/04/26 (117)	20:49:00.000	5035	76.5	2.0
SPE-6	2016/10/12 (286)	18:36:00.000	2245	31.4	1.6

* TNT-equivalent

+ University of Nevada, Reno

Day Of Year

Table 2: Events correlated with SPE-4Prime that occurred within a week of SPE-5 along with the number of detections when the event was used as a template

Event No.	Date (DOY#)	Time	Correlation	No. of Detections
1+	2016/04/26 (117)	20:49:00	0.233	NA*
2	2016/04/26 (117)	23:57:57	0.245	10
3	2016/04/27 (118)	00:01:41	0.265	47
4	2016/04/27 (118)	01:11:25	0.252	22
5	2016/04/27 (118)	01:21:56	0.254	12
6	2016/04/29 (120)	08:24:46	0.295	17

Day Of Year

+ SPE-5

* SPE-5 clipped nearby stations so could not be used as a template

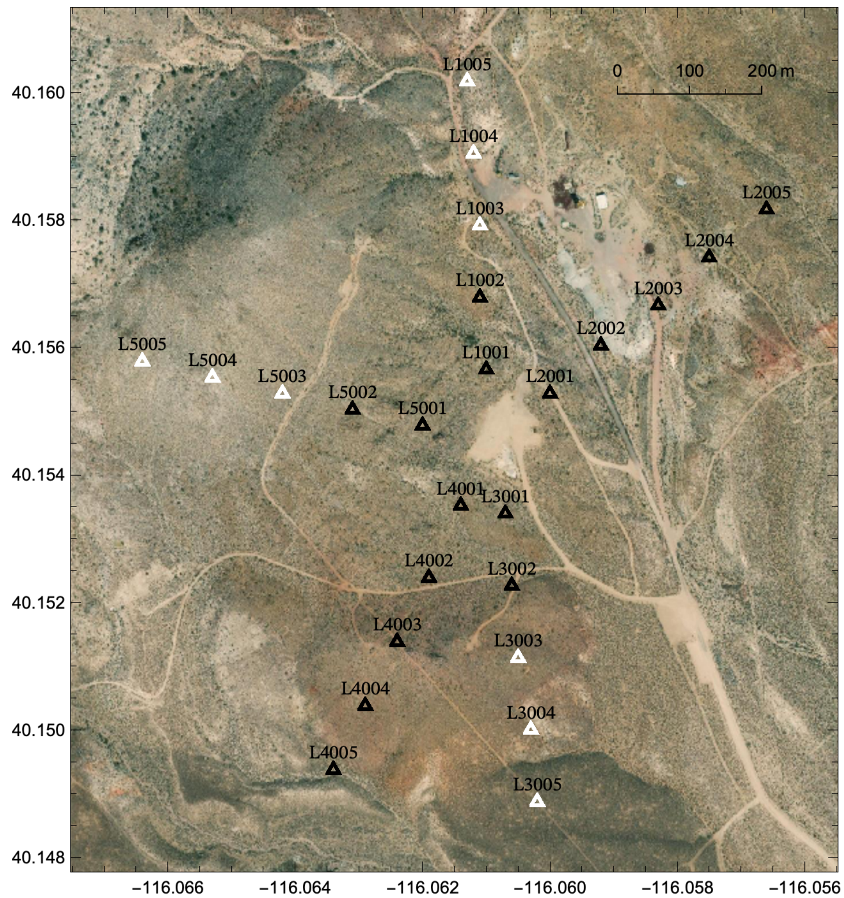

Figure 1: Map of the Source Physics Experiment Phase I region. The events took place beneath the pad in the center. Stations that contributed to the SPE-4Prime template are shown with white triangles.

2 Data

Epochs of available continuous data are from 2015100 to 2015141, 2016013 to 2016054, and 2016104 to 2016354, where the first four numbers are the year and the last three are the day-of-year. Since the first epoch doesn't have any days after SPE-4Prime and the second epoch doesn't contain a SPE explosion, we will focus on the third epoch (2016104 to 2016354) which contains SPE-5 and SPE-6. We set the data stream to be stations on Lines 1, 3, and 5 at 300, 400, and 500 m distance for a total of nine three-component sites (white triangles in Figure 1). Although there are closer stations (black triangles in Figure 1), we opted for a little bit of distance to allow for some scattering and move-out of the wavefield, which we hoped would allow for a little more variability in capturing related aftershocks. The template is 2 s recordings of SPE-4Prime at these stations filtered between 1 and 32 Hz. The duration and bandwidth are chosen such that high-frequency amplitudes from small, repeating events could be detected.

3 Results

The SPE-4Prime template was used to scan through the data stream starting at the SPE-5 origin time and ending a week later. Six events were detected that correlated with SPE-4Prime (CC > 0.05) so amplitudes relative to a known event could also be calculated. The events occurred within a few days of SPE-5 and are given in Table 2. Figure 2 shows the event with the greatest correlation that occurred on 2016/04/29 (120) at 08:24:46 along with the SPE-4Prime template in blue. The additional red traces in the figure are shown to allow for waveform comparison with the SPE-4Prime recordings. The observed move-out on stations in the array indicate that these events occurred laterally near the center of the array, which is at SPE surface ground zero.

We then ran these initial detections as templates for detectors in a period starting at SPE-5 and ending two weeks later. However, this time we used the closest stations at 100, 200, and 300 m. The use of stations closer to the shot point should enhance the detectability of events. However, since recordings of SPE-5 were clipped at these closer stations it could not be used as a template. The use of different templates should enhance the variability of detected events. The number of detections per template are given in the last column of Table 2. An example of an additional detection made using a template from a detection in the initial run is in Figure 3. The template (in blue) is Event 5 (Table 2) which detected an event that occurred on 2016/05/12 (133) at 13:02:16.

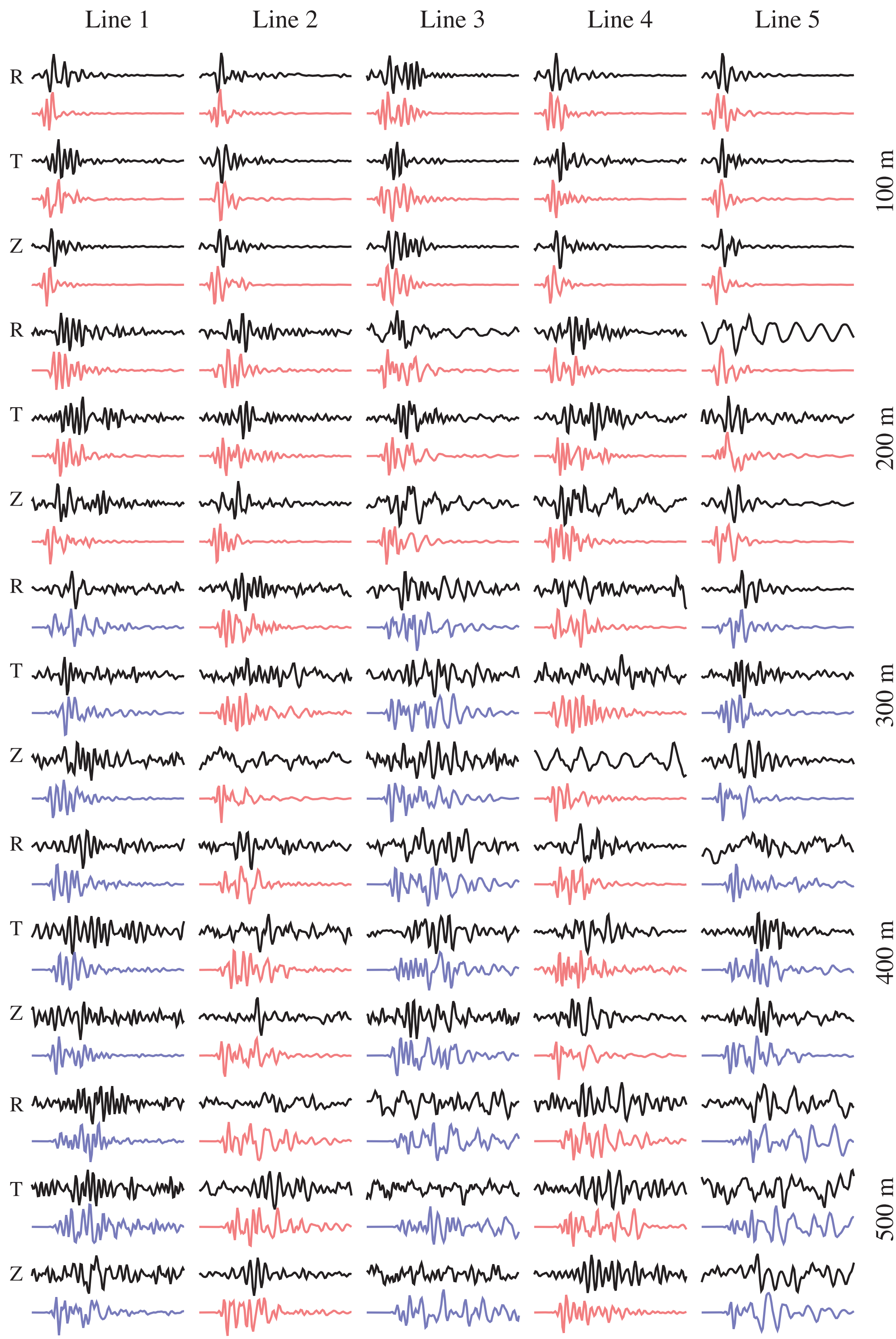
Line 1
Line 2
Line 3
Line 4
Line 5
R
T
Z
100 m
R
T
Z
200 m
R
T
Z
300 m
R
T
Z
400 m
R
T
Z
500 m

Figure 2: (Prior Page) Waveforms of the detected event that occurred on 2016/04/29 at 08:24:46 (black) along with the SPE-4Prime template (blue) and other SPE-4Prime recordings (red) to aid in comparison with the detected event. Each trace is 1 s in duration where R, T, and Z are radial, transverse, and vertical components, respectively. The station name can be determined from the Line number and range, e. g., Line 1 at 100 m is L1001.

4 Discussion & Conclusions

The observed aftershock rates are compared with those predicted using the hard-rock model from Ford and Labak [2016]. To apply the aftershock model an estimate of the minimum magnitude is needed. Sweeney and Harben [2011] report the an average minimum magnitude of detection equal to -2. We can now calculate the probability of an aftershock assuming the average rate follows a Poisson distribution.

Figure 4 shows the predicted range in cumulative number of aftershocks as a function of duration starting a few hours after SPE-5. The expected number along with the 5 and 95% bands are shown. The figure also shows the observed cumulative number of events per 24-hour period starting a few hours after SPE-5, where the symbol is plotted at the end of each 24-hour period. For example, the first point in the observed series is plotted at 3 hours plus 1 day ($d = 9/8$). The model severely under-predicts the number of early aftershocks, so a satisfactory fit is only obtained after delaying the comparison to events beginning a few hours after the explosion. This may be due to an incorrect minimum magnitude of detection, so future work could refine that estimate using observed amplitudes relative to SPE-5.

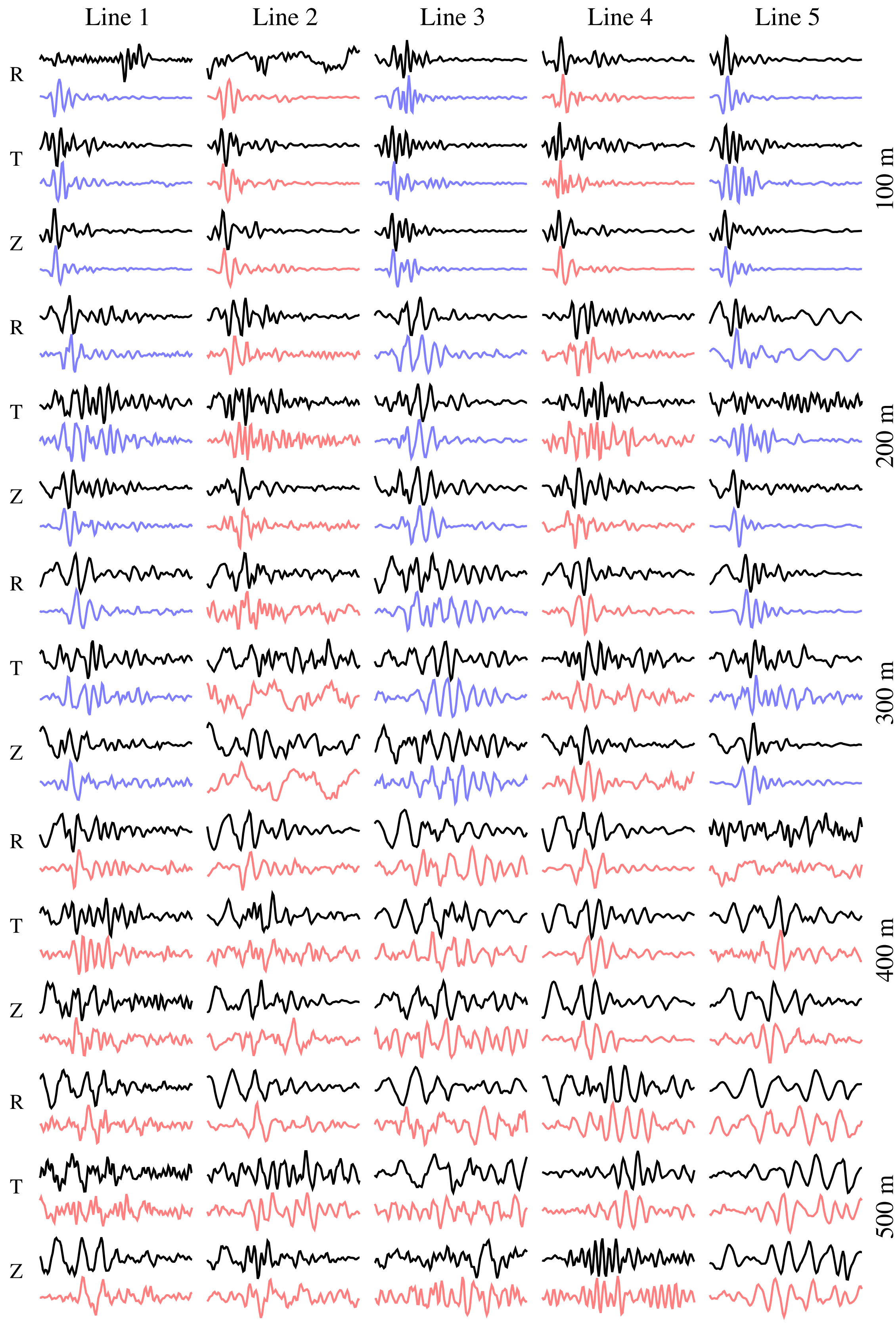
Line 1
Line 2
Line 3
Line 4
Line 5
R
T
Z
100 m
R
T
Z
200 m
R
T
Z
300 m
R
T
Z
400 m
R
T
Z
500 m

Figure 3: (Prior Page) Waveforms of the detected event that occurred on 2016/05/12 (133) at 13:02:16 (black) along with the template (blue), which is Event 5 (Table 2), and other recordings of the template event not used in detection (red). Each trace is 1 s in duration where R, T, and Z are radial, transverse, and vertical components, respectively. The station name can be determined from the Line number and range, e. g., Line 1 at 100 m is L1001.

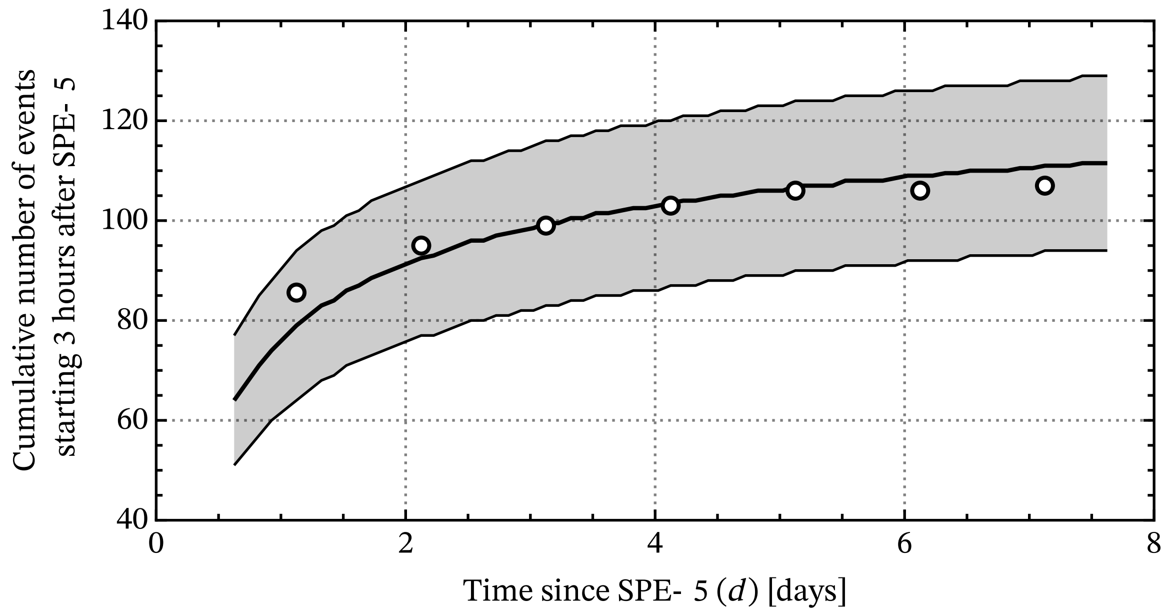

Figure 4: Predicted cumulative number of aftershocks in the week after SPE-5 (with 5-95% bands), where the SPE-5 magnitude is 2 and the minimum magnitude of detection is -2. Predictions are shown for durations beginning 3 hours after SPE-5. The observed number of events per 24-hour period are shown by the circles where the data is plotted at the end of each 24-hour observation period after the initial delay of 3 hours (e.g., the first point is at $d = 9/8$).

Acknowledgements

The Source Physics Experiment (SPE) would not have been possible without the support of many people from several organizations. The authors wish to express their gratitude to the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development, and the SPE working group, a multi-institutional and interdisciplinary group of scientists and engineers. We thank the Survey Department of Mission Support and Test Services, LLC for the ground surface coordinates.

Auspices

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

References

Sean R Ford and Peter Labak. An Explosion Aftershock Model with Application to On-Site Inspection. *Pure and Applied Geophysics*, 173(1), 2016. ISSN 0033-4553. doi: 10.1007/s00024-015-1041-x.

Sean R Ford and William R Walter. Aftershock Characteristics as a Means of Discriminating Explosions from EarthquakesAftershock Characteristics as a Means of Discriminating Explosions from Earthquakes. *Bulletin of the Seismological Society of America*, 100(1): 364–376, 2010. ISSN 0037-1106. doi: 10.1785/0120080349.

Tom Parsons and Aaron A. Velasco. On near-source earthquake triggering. *Journal of Geophysical Research: Solid Earth*, 114(B10), 2009. ISSN 2156-2202. doi: 10.1029/2008JB006277.

J. J. Sweeney and P. Harben. Aftershock Analysis for SPE2. Technical Report LLNL-TR-594153, Lawrence Livermore National Laboratory, Livermore, California, 2012.

J. J. Sweeney and P. E. Harben. Aftershock Analysis for SPE1. Technical Report LLNL-TR-512872, Lawrence Livermore National Laboratory, Livermore, California, 2011.