
EVALUATION OF M_L - M_C AS A POSSIBLE DEPTH DISCRIMINANT AT LOCAL DISTANCES

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1. SUMMARY

The work presented in this report was recently published in three academic journals: chapters 2–4 correspond to Holt et al. (2019b), chapters 5–7 correspond to Voyles et al. (2020), and chapters 8–10 correspond to Koper et al. (2021). These studies find that M_L - M_C is effective as a local distance depth discriminant for a wide variety of seismic sources: naturally occurring earthquakes in Utah, the Yellowstone region, and Italy; mining induced earthquakes in Utah; hydrologically induced earthquakes in Oklahoma and Kansas; mining or weapons testing and disposal explosions in Utah; and buried, single-fired chemical explosions in Nevada, Washington, and Wyoming. The primary implication is that combining M_L - M_C observations with traditional high-frequency P/S amplitude ratios will likely enhance current capabilities in identifying low-yield ($M < 3$) underground nuclear explosions. As part of this work, we also produced a catalog of 1,545 confirmed surface explosions that occurred in 26 distinct regions of Utah. The contents of a fourth peer-reviewed paper that describes how regional seismic networks have historically supported low-yield nuclear monitoring (Koper, 2020) is not reproduced here since no new results were generated in that paper.

Preliminary work in two additional areas was also accomplished under this contract but is not described in detail here because robust results were not achieved. In one area, we simulated local distance waveforms in realistic Earth models that contained topography, deterministic 3D heterogeneity (basins), and stochastic 3D heterogeneity (scatterers). Initial results were reported in Voyles et al. (2019) and show that coda generation is enhanced for shallow sources however it is unclear which mechanism is most important. In the second area, we experimented with optimizing explicit functionals

of amplitude and duration in an effort to improve upon the ability of M_L - M_C to separate shallow sources from deeper sources. Initial results were reported in Koper et al. (2021) and suggest that minor improvements are possible.

In terms of human resources development, two students were supported by this contract. Jonathan Voyles graduated with a B.S. in geophysics from the University of Utah in 2020 with work from this grant constituting the bulk of his senior thesis. Mr. Voyles won an outstanding student presentation award at the Fall 2019 meeting of the American Geophysical Union (Voyles, et al., 2019) and was admitted to the PhD programs of several top graduate schools. He is currently a student in the PhD geophysics program at Stanford University. Monique Holt is a currently a PhD candidate at the University of Utah with an expected defense date in July 2021. Her PhD thesis is entirely derived from work accomplished under this contract. Recently, Ms. Holt has been accepted into the Bridge to the Faculty postdoctoral research associate program (start date of August 15, 2021) at the University of Illinois Chicago, with a nominal start date of August 15, 2023, as a tenure-track assistant professor in geophysics.

2. INTRODUCTION TO M_L - M_C PORTABILITY

One of the most successful methods of distinguishing earthquakes from nuclear explosions is based on the difference between body wave magnitude (m_b) and surface wave magnitude (M_s) (Bowers and Selby, 2009). For a given M_s , nuclear explosions tend to have higher m_b than earthquakes (e.g., Liebermann and Pomeroy, 1967; Marshall and Basham, 1972), primarily because explosions have source spectra that are more enriched in high frequencies, have simpler radiation patterns, and occur at shallower depths (Stevens and Day, 1985). For the purposes of monitoring the Comprehensive Nuclear-

Test-Ban Treaty, the International Data Center (IDC) in Vienna classifies events as earthquakes not requiring further analysis if they fall above the screening relationship $M_S = m_b - 0.64$ (Selby *et al.*, 2012). In other words, a seismic event must have an m_b that is at least 0.64 units larger than the corresponding M_S for the IDC to consider it a potential nuclear explosion.

Both m_b and M_S are traditionally measured at teleseismic distances with m_b reflecting P-wave energy at a period near 1 s and M_S reflecting Rayleigh wave energy at a period near 20 s (Lay and Wallace, 1995). Several authors have extended the definition of M_S to shorter periods with the goal of enabling $m_b:M_S$ comparisons to function as a source discriminant for small seismic events recorded at regional distances (e.g., Pomeroy *et al.*, 1982; Lilwall, 1988; Bonner *et al.*, 2003; Bonner *et al.*, 2006; Russell, 2006). For small seismic events that are recorded only at local distances (< 150 km), direct analogs of M_S are difficult to construct. At these distances, it is common to observe body waves (Pg and Sg) without the presence of the surface wave-like Lg , which is usually dominant at regional distances. Rg is often observed at local distances for shallow sources (Båth, 1975), and its presence or amplitude is used as a depth indicator (Langston, 1987; Kafka, 1990; Zeiler and Velasco, 2009; Ma and Motazedian, 2012; O'Rourke and Baker, 2017; Tibi *et al.*, 2018a; Kolaj, 2018), but it is not observed consistently enough to be used as the basis of a magnitude scale for arbitrary-depth seismic events.

The most common magnitude scale used at local distances is M_L , a local magnitude that is directly related to the original Richter magnitude scale (Richter, 1958). Local magnitudes measure the largest horizontal amplitude on a seismogram that has been corrected with the instrument response of a Wood-Anderson seismometer. In

practice, M_L often reflects peak S_g amplitude at a period near 0.8 s. Woods *et al.* (1993) observed that the ratio of M_L to the logarithm of the scalar seismic moment, M_0 , was an effective source discriminant in the western U.S. at regional distances. For a given $\log_{10}[M_0]$, Woods *et al.* (1993) found that M_L for explosions was on average 0.5 units larger than for earthquakes. Therefore, $M_L:M_0$ functioned as a regional-distance version of $m_b:M_S$, with M_L taking the place of m_b and $\log_{10}[M_0]$ taking the place of M_S . Woods *et al.* (1993) attributed the success of $M_L:M_0$ as a source discriminant to the compactness of the explosion source, which leads to the preferential enrichment of high frequencies relative to earthquake sources.

For small events at regional distances, it is difficult to estimate M_0 by inverting time-domain waveforms for moment tensors because of the uncertainty in short-period Green functions. This problem is exacerbated for small events recorded at local distances, and it is uncommon to estimate moment tensors for such events. An alternative magnitude scale that has historically been used by seismic network operators to measure the size of small events recorded at local distances is based on signal duration and is sometimes referred to as M_D , m_d , or m_τ (e.g., Lee *et al.*, 1972; Real and Teng, 1973; Herrmann, 1975; Bakun 1984). In general, the duration is measured on a short-period vertical component channel beginning with the first-arriving P wave and typically ending when the amplitude of the latest-arriving coda wave reaches the pre-event noise level. Because the duration magnitude depends on the duration of the coda, it is referred to as M_C in seismic catalogs produced by the University of Utah Seismograph Stations (UOSS) (Pechmann *et al.*, 2006).

Recent work (Koper *et al.*, 2016) has shown that the difference between local and duration magnitude (M_L-M_C) is a sensitive function of source depth in the Utah region. In Utah, the two magnitude scales were designed to be seamless, and for source depths > 6 km the mean M_L-M_C residual is close to zero. However, for events shallower than ~ 6 km, M_L-M_C on average is negative and becomes increasingly negative as source depth approaches the surface. This suggests that M_L-M_C may be useful as a depth discriminant at local distances, highlighting especially shallow seismic events that deserve follow-up attention as potential explosions, similar to how $m_b:M_S$ comparisons are used to highlight suspicious sources at regional and teleseismic distances.

It is unclear if the M_L-M_C depth sensitivity in Utah is the result of particular geologic conditions, such as a shallow low-velocity waveguide, or if it is a more general phenomenon. To investigate this issue, we analyze the depth dependence of M_L-M_C as reported in regional seismic catalogs for the areas around Yellowstone National Park, Oklahoma and Kansas, and Italy. The magnitude range is $\sim 0-5$ for both scales in all regions, and the large majority of amplitude and duration measurements are made at source-receiver distances of 50–200 km. We analyze M_L-M_C only for earthquakes with accurate depths, requiring that the distance to the nearest station (D_{MIN}) is less than 1.0–1.4 times the focal depth (Gomberg *et al.*, 1990). These regions vary in physiography and geology and host a variety of earthquake types including those induced by waste-water injection and naturally occurring earthquakes related to tectonic and volcanic processes. Furthermore, the magnitudes in these regions are calculated by different monitoring agencies using slightly different techniques. We perform a series of robustness tests in

each region to assess the significance of M_L - M_C variation with depth and discuss the results.

3. METHODS, ASSUMPTIONS, AND PROCEDURES FOR M_L - M_C PORTABILITY

3.1. The Utah Region

The UUSS seismic catalog, which consists of natural and mining-induced earthquakes but no explosions, reports locations and magnitudes for ~1000–2000 earthquakes in the Utah region each year. For the purposes of reporting to the Advanced National Seismic System (ANSS; ANSS Technical Integration Committee, 2002), the UUSS authoritative region is defined by latitudes of 36.75–42.50°N and longitudes of 114.25–108.75°W. Event information, network metadata, and methodological details are released in quarterly reports, which are available from the UUSS website (quake.utah.edu). Coda duration magnitude (M_C) is reported for nearly all (> 99%) events in the catalog. The fraction of earthquakes with local magnitudes (M_L) is currently ~50%, which has increased from ~10% in 2000 because of the growing number of broadband stations in the Utah regional seismic network.

UUSS calculates M_L at broadband stations using the equation

$$M_L = \log_{10}[A] - \log_{10}[A_0] + S \quad (1)$$

where A is half of the maximum peak-to-peak amplitude (mm) on a simulated Wood-Anderson seismometer, $\log_{10}[A_0]$ is the California distance correction from Richter (1958), which varies from -1.4 to -4.9 as distance varies from 0 to 600 km, and S is a static station correction, which varies from -0.43 to 0.21 for stations used by UUSS (Pechmann *et al.*, 2007). Maximum amplitudes are averaged from the two horizontal

components to estimate a station M_L , and M_L determinations from a minimum of two stations are averaged to estimate an event M_L . For earthquakes in the Utah region, UUSS calculates M_C at short-period, vertical-component stations using the equation

$$M_C = -2.25 + 2.32\log_{10}[\tau] + 0.0023\Delta, \quad (2)$$

where τ represents the signal duration in seconds, or the time difference from the P onset until the ground velocity falls below $0.01724 \mu\text{m/s}$, and Δ is the epicentral distance in km. UUSS calculates duration using a pre-defined ground velocity amplitude, instead of the amplitude from a segment of pre- P noise, to improve consistency. This approach is especially helpful during swarm sequences, when P waves often arrive within the coda of a previous earthquake. In these cases, the coda-decay curve is fit to the data before a new P -wave arrives and it is extrapolated to intersect the pre-defined cutoff value. No station corrections are used for M_C . In the standard UUSS procedure, each event M_C is estimated by averaging values from at least 3 stations.

The constants in equation 2 were derived such that M_C would provide an unbiased estimate of M_L in cases where there were not enough broadband recordings to estimate M_L directly; however, Koper *et al.* (2016) examined nearly 7,000 earthquakes that occurred in the Utah region between 1982–2016 and found that M_C was on average 0.136 units larger than M_L . This bias was nearly eliminated when $\sim 3,000$ mining induced earthquakes were excluded. The mining induced earthquakes had a mean $M_L - M_C$ of -0.388, while the remaining $\sim 4,000$ tectonic earthquakes had a mean $M_L - M_C$ of 0.048. Example waveforms from a mining induced earthquake (depth 350 m) and tectonic earthquake (depth 12.9 km) with similar epicenters are shown in Figure 1. Mining induced earthquakes in Utah are extremely shallow (< 2 km), and Koper *et al.* (2016)

hypothesized that the shallow depth increased M_C relative to M_L . This idea was supported by an analysis of 795 tectonic earthquakes in Utah with high-accuracy depths, which showed that $M_L - M_C$ became increasingly negative as focal depth became shallower than ~5–6 km. Koper *et al.* (2016) also observed that mean $M_L - M_C$ values were negative for likely explosions in 7 out of 8 blasting areas in the Utah region. These results demonstrate that $M_L - M_C$ can distinguish between shallow anthropogenic-or-tectonic seismicity and deeper tectonic seismicity in Utah and provide motivation for the current study.

3.2. The Region Around Yellowstone National Park

Yellowstone National Park houses a portion of the Yellowstone Plateau, a 17,000 km² area that encompasses the past and present Yellowstone volcanic field (Yellowstone Volcano Observatory, 2006). The volcanic system is fed by a mantle plume (Schmandt and Humphreys, 2010) that has created a large magma reservoir of 200–600 km³ in the crust (Farrell *et al.*, 2014). The prolific seismicity in Yellowstone is characteristic of large, hydrothermal systems (Farrell *et al.*, 2014) and the many earthquake swarms have been attributed to the changing stresses that result from the migration of magma and magmatic fluids (Massin *et al.*, 2013; Shelly *et al.*, 2013).

UUSS produces a second earthquake catalog for the region around Yellowstone National Park. For the purposes of ANSS reporting, the UUSS authoritative region is defined by latitudes of 44.00–45.17 °N and longitudes of 109.45–111.33 °W. The Yellowstone earthquake catalog is available from the UUSS website in quarterly installments (quake.utah.edu). The annual number of earthquakes in the Yellowstone

region varies from ~700–4,000. In 2017, for example, UUSS located 3,427 earthquakes in Yellowstone, of which 1,390 (40%) had an M_L and 3,407 (99%) had an M_C . The M_C equation for Yellowstone was developed independently from the Utah relation (equation 2) and is described as

$$M_C = -2.60 + 2.44\log_{10}[\tau] + 0.0040\Delta. \quad (3)$$

UUSS calculates M_L for earthquakes in Yellowstone using the same expression (equation 1) and distance corrections as in Utah.

To examine the depth sensitivity of M_L - M_C in Yellowstone, we started with 4,457 earthquakes that UUSS had located in the region between 1 October 2012 and 31 December 2017 for which both M_L and M_C were estimated. In October 2012, UUSS began using new software to locate events—which included a change in the reference datum such that all focal depths are now reported relative to sea level—and so we chose 1 October 2012 as the start date for our analysis to ensure a uniform catalog over time. For convenience, we changed the depths to be relative to the average elevation of 2 km, which eliminated most of the negative depths in the original catalog. We filtered this catalog down to 4,275 events by removing outlier M_L - M_C values. We defined an outlier as an M_L - M_C value that exists outside of the outer fence—three times the interquartile range above and below the third and first quarter, respectively. We further reduced the catalog to 3,358 events by requiring D_{MIN} to be either less than the focal depth or 1 km. In Figure 2, we present a map of the ~3,300 Yellowstone earthquakes and the corresponding variation in M_L - M_C with depth. There is a noticeable increase in M_L - M_C from 0 to 10 km in depth, the range in which the waveforms of a potential nuclear explosion might be ambiguous. A weighted least squares regression line fit to the depth-

binned M_L - M_C data between 0 and 10 km depth has a slope of 0.030 with a 95% confidence interval of ± 0.007 .

To check the robustness of this result, we systematically varied the width of the depth bin and the good-depth criterion prior to performing the weighted least squares regression (Figure 3). We used depth bin sizes of 1, 2, and 3 km, and D_{MIN} /focal depth (H) ratios of 1.0, 1.2, and 1.4, for a total of nine distinct combinations. There were 3,358 Yellowstone events with either D_{MIN} less than the 1 km bin or H less than 1.0. The most relaxed good-depth criteria ($D_{\text{MIN}} < 3$ or $H < 1.4$) yielded 3,761 events. We calculated the 95% confidence interval of the slope to ensure that it was positive, and we calculated the coefficient of determination (r^2) to assess the goodness of fit. We also investigated the influence of the overall depth range for which M_L - M_C appears to vary linearly by varying the maximum depth of the fit from 7 to 18 km. We find that all nine cases exhibit high r^2 values (0.721–0.995) and a statistically significant increase (slope > 0.0 at 95% confidence) in M_L - M_C values within the first 10 km.

Additionally, we checked the effect of individual magnitude uncertainties on the M_L - M_C relationship with depth. Each magnitude from the most constrained depth catalog was used as the mean of a normal distribution with a standard deviation of 0.1 (Arabasz *et al.*, 2016). Individual magnitudes were randomly selected from the distributions and used to recalculate M_L - M_C slope values to 10 km depth for 1 km depth bins. This process was repeated 1,000 times to ensure stability. In all cases, the slope remained above zero at the 95% confidence level. All slopes also remained above zero using double the standard deviation, 0.2. It was not until a standard deviation of 0.3 that 2 of the 1,000 slopes included zero in their 95% confidence bounds.

3.3. Oklahoma & Kansas

Since 2008 the rate of seismicity has dramatically risen in Oklahoma and Southern Kansas. This increase is anthropogenic and largely the result of deep wastewater injection (Ellsworth 2013; Weingarten *et al.*, 2015). In response, the density of seismic stations in the region has also increased dramatically in recent years. As a result, there now exists a unique catalog of accurately characterized (location and magnitude) earthquakes within the Central United States. Between July 24, 2013, and August 12, 2017, the NEIC characterized 8,731 earthquakes in the Oklahoma/Kansas border region. Owing to the anthropogenic nature of these earthquakes, their depths are very shallow and mainly occur at 0–10 km.

As part of its automated event processing, the NEIC calculates both M_L and M_C (referred to internally as M_d). Local magnitudes are calculated following the method outlined by the IASPEI Commission on Seismological Observation and Interpretation Working Group (Bormann *et al.*, 2009), following:

$$M_L = \log_{10}[A] - 1.11\log_{10}[R] + 0.00189R - 2.09 \quad (4)$$

where A is the amplitude (nm) measured on the horizontal waveforms filtered to match the response of a Wood-Anderson seismograph, and R is the hypocentral distance in km. A 25% trimmed mean is applied to remove outlying observations. M_d is calculated using

$$M_d = -0.87 + 2.0\log_{10}[\tau] + 0.389\Delta^\circ \quad (5)$$

where Δ° is the epicentral distance in degrees. As with M_L , a 25% trimmed mean is applied. The coefficients used by the NEIC in the M_d calculation are region dependent. In

the case of Oklahoma and Kansas, the NEIC defaults to local magnitude coefficients originally derived for California (Richter, 1958).

The catalog was reduced to 8,496 events after M_L-M_C outlier removal and further reduced to 1,628 events after screening out earthquakes with weakly-constrained depths (we required either $D_{\text{MIN}} < 1$ or $H < 1.0$; Figure 4). Example waveforms of a shallow and deep event of similar magnitude are shown in Figure 5. Similar to our observations in Yellowstone, M_L-M_C in Oklahoma/Kansas gradually increases with depth over the range of 0–8 km. A linear model accounts for 86.0% of the variance and yields a slope of 0.022 ± 0.010 m.u./km, where the error bound represents a 95% confidence region. We applied similar robustness tests to the Oklahoma/Kansas dataset as we did for the Yellowstone dataset (Figure 6). For all depth bin sizes and H ratios, we find positive slopes with 95% confidence.

3.4. Italy

To compute the local magnitudes of earthquakes in Italy, the National Institute of Geophysics and Volcanology (INGV) uses an automatic procedure. Velocity data are converted to ground displacement and then convolved with the response of the Wood-Anderson seismometer. A distance correction factor is applied to account for the attenuation characteristics of the Italian peninsula (Gasperini *et al.*, 2002). The reported local magnitude is an average of all the values computed at different seismic stations (Castello *et al.*, 2007). Duration magnitude is computed using the formula

$$M_C = 2.49 \log_{10}[T] - 2.31 + S \quad (6)$$

where T represents the signal duration in seconds and S is a station correction factor.

Italy has the largest earthquake catalog in this study with 62,066 crustal earthquakes (depth < 30 km) occurring between April 16, 2005, and April 30, 2012. This catalog was reduced to 28,722 events after removing M_L - M_C outliers and applying a depth-quality constraint of $H < 1.0$ (Figure 7). M_L - M_C clearly increases with depth up to 30 km with a slope of 0.018 ± 0.001 m.u./km accounting for 96.7% of the variance. As expected from the clearly linear slope, robustness tests reveal non-zero slopes for bin widths of 1, 2, and 3 km, and H values of 1.0, 1.2, and 1.4.

The behavior of M_L - M_C with depth for Italy is somewhat different than for Utah, Yellowstone, and Oklahoma/Kansas in that a strong positive slope continues to depths of ~30 km. A possible explanation for this behavior is the variety of tectonic settings that the INGV catalog covers. In general, the tectonics of Italy are controlled by the interaction between the Africa and Eurasia plates (e.g., Chiarabba *et al.*, 2005), where the convergence is accommodated by fragmentation of the west-dipping subduction with the consequent deformation of the Alps and Apennine mountain chains. In an attempt to remove geologic bias from the M_L - M_C versus depth trend, we subdivided Italy into three regions: the Alps, the Apennines, and southern Italy and Sicily where site effects have been documented as behaving differently (Castello *et al.*, 2007; Figure 8).

Region A is located in northern Italy and contains the fewest earthquakes; 624 events with the most strictly defined, well-constrained depths. M_L - M_C behaves differently in this region than in Italy as a whole. Region B hosts 86% of the Italian catalog (53,198 events reduced to 26,595 events with good depths) and, as expected, looks very similar to the M_L - M_C distribution shown in Figure 7. Region C has 1,452 good-depth earthquakes out of 5,413 total and also behaves differently than Region B. Though Regions A and C

do not have a perfectly increasing M_L-M_C with depth, both regions have a non-zero slope with 95% confidence.

3.5. Summary

M_L-M_C increases from 0–9 km depth for earthquakes in Utah, Yellowstone, Oklahoma, and Italy (Figure 9). Additionally, the slopes are statistically the same within 95% confidence regions, suggesting a robust, globally-repeatable phenomenon is responsible for the M_L-M_C depth dependence. This result also implies that M_L-M_C can work as an event screener for purposes of treaty verification, indicating especially shallow seismic events that require follow-up attention as possible explosions. However, the regional differences in the static offset of M_L-M_C , which we attribute to differences in how precisely each network calculates magnitudes, means that magnitude scales in various regions of interest will likely need to be calibrated before M_L-M_C can be used as an event screener.

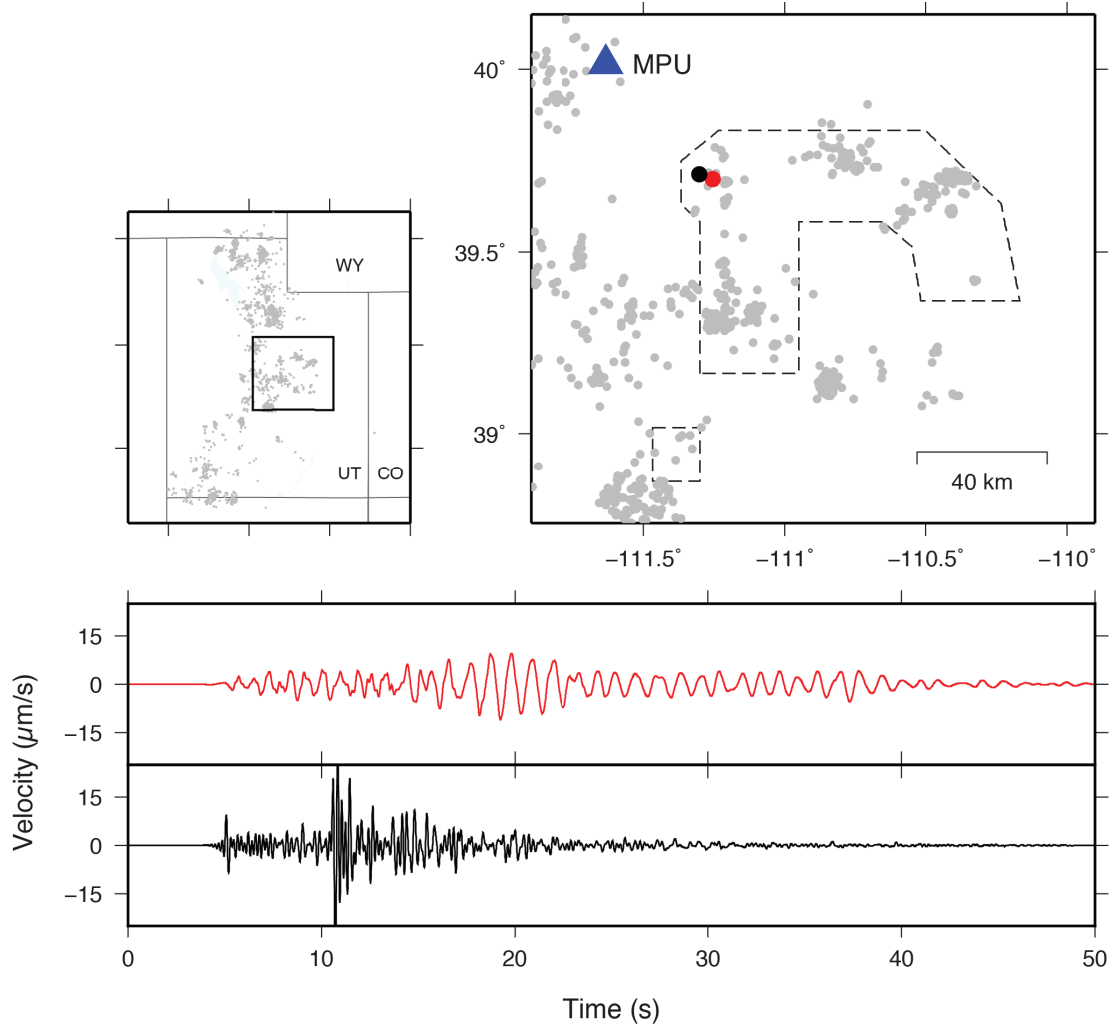


Figure 1. Comparison of a co-located deeper, tectonic earthquake ($M_L = 2.87$, $M_C = 2.92$, depth = 12.9 km) and a shallower, mining induced earthquake ($M_L = 2.48$, $M_C = 2.91$, depth = 350 m) in Utah. (Top Left) A map of Utah (UT), Colorado (CO), and Wyoming (WY) outlining the region shown in the top right. Gray circles represent earthquakes in the U.S.G.S. catalog for this region since 1981. (Top Right) Map of a shallow, mining-induced earthquake (red circle) and a deeper, tectonic earthquake (black circle) overlain on the U.S.G.S. catalog (gray circles). Blue triangle represents the location of U.S.G.S. station MPU. Dashed lines designate coal mining regions. (Bottom) The seismograms of the shallow (red) and deep (black) events as recorded on MPU HHZ and filtered between 1–5 Hz. Signal durations used to calculate M_C for these events are approximately 140 s.

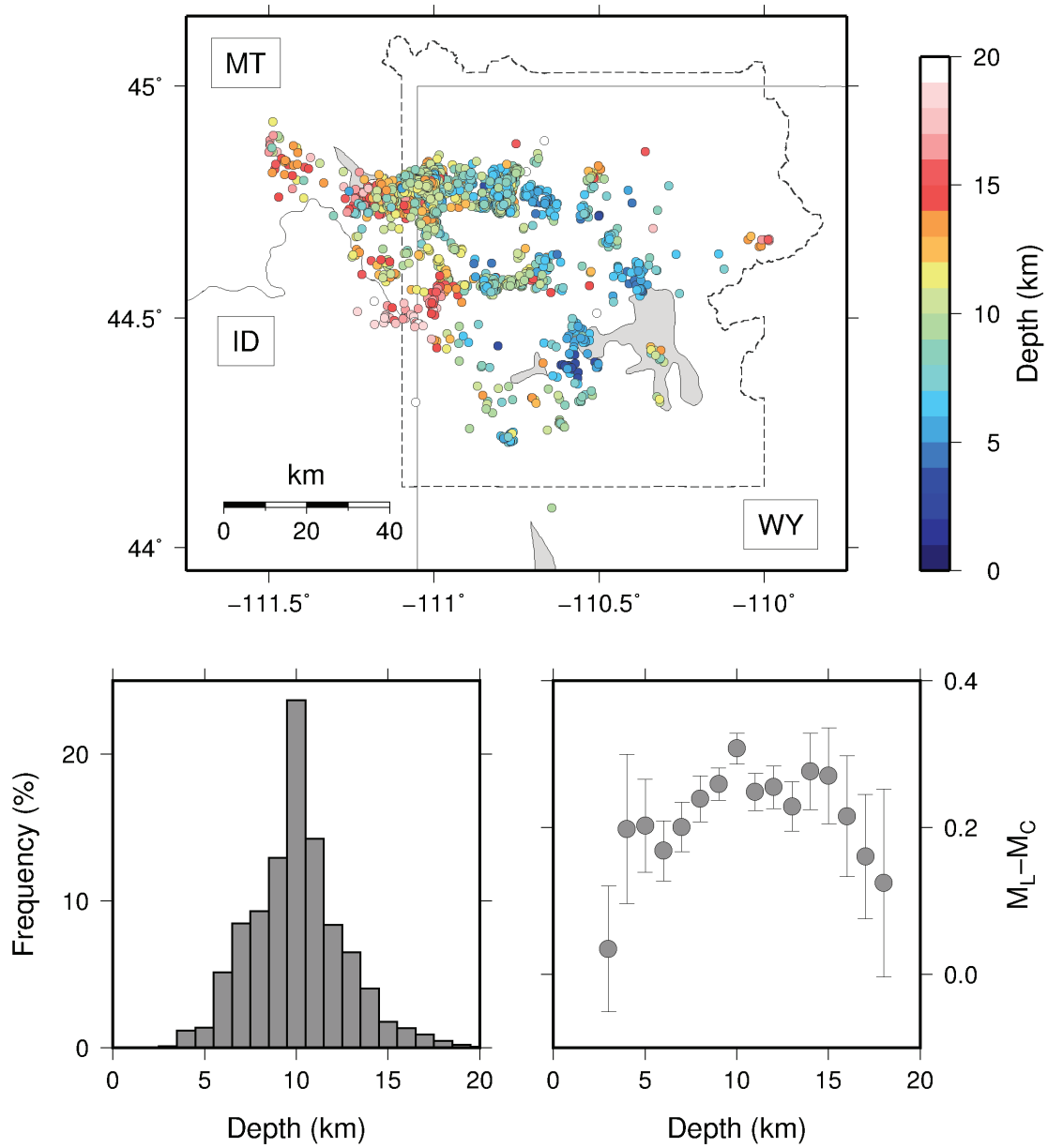


Figure 2. (Top) A map of 3,358 “good depth” earthquakes that occurred between October 2012 and December 2017 in the Yellowstone region, color-coded by depth. *Gray shaded areas represent lakes. The black dashed line is the outline of Yellowstone National Park. MT, Montana; ID, Idaho; WY, Wyoming.* (Bottom Left) *The depth distribution of the earthquakes shown on the map.* (Bottom Right) $M_L - M_C$ versus depth. *Gray circles represent the mean $M_L - M_C$ value in each depth bin. Error bars are ± 2 standard error ($\sim 95\%$ confidence interval). Depths are binned in increments of 1 km and depth is relative to 2 km above sea level, the average elevation in the region.*

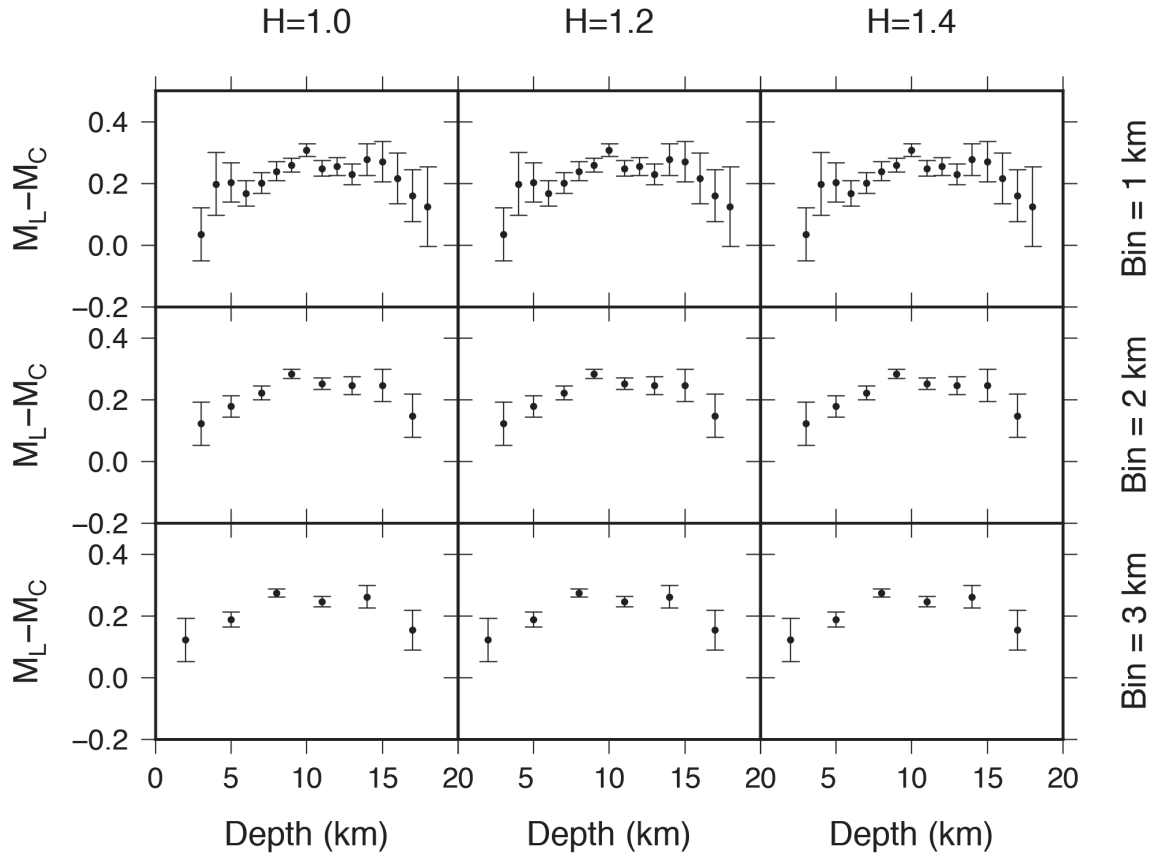


Figure 3. Robustness tests for the differential magnitude trend in the Yellowstone region (Figure 2). The circles are means and the error bars represent $\sim 95\%$ confidence intervals (± 2 standard error). The bin sizes are 1 km, 2 km, and 3 km, moving from the top to the bottom. Earthquake depths are considered well-constrained if the epicentral distance to the nearest station is either smaller than a certain multiple of the depth ($H=1.0, 1.2$, or 1.4 , varying from left to right), or smaller than the bin size (1 km, 2 km, or 3 km). All panels show evidence of decreasing $M_L - M_C$ as earthquake depth decreases.

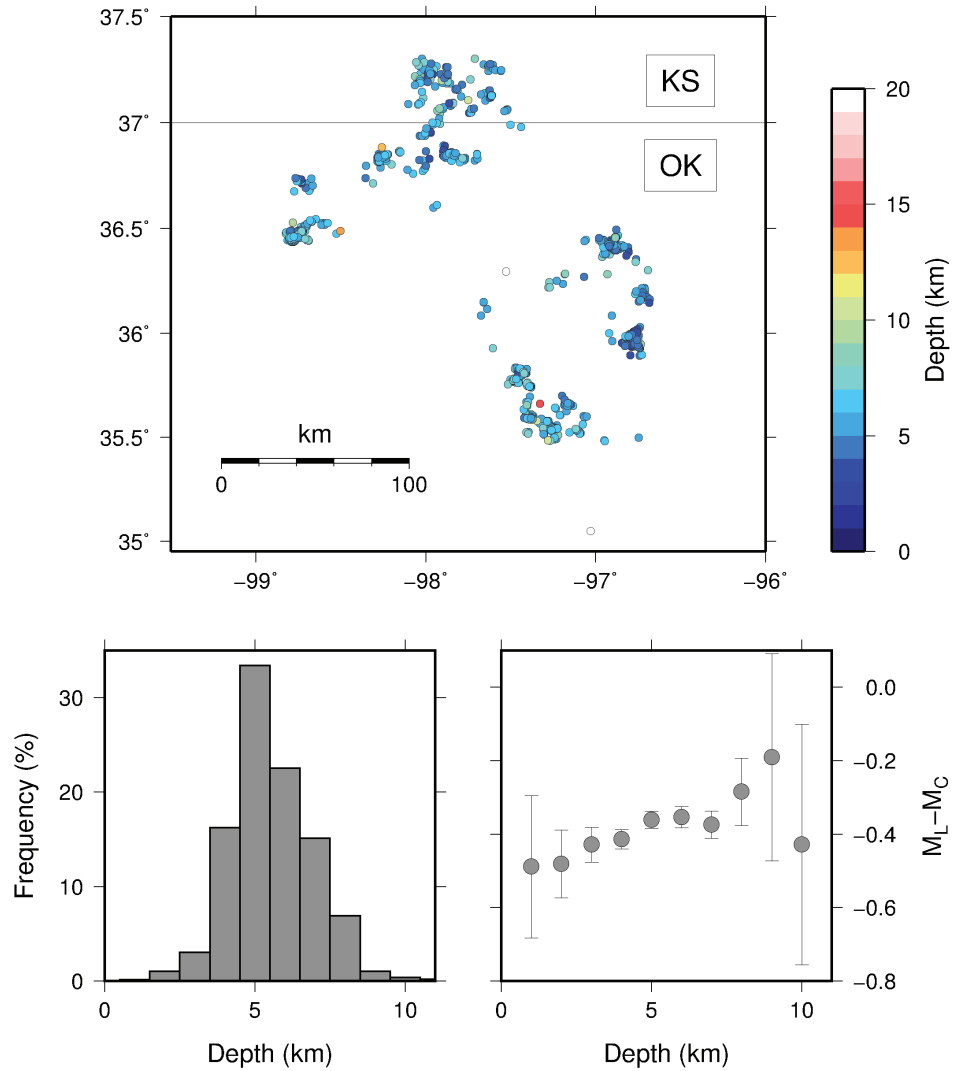


Figure 4. Similar to Figure 2, but for Oklahoma/Kansas. (Top) A map of 1,628 “good depth” earthquakes that occurred between July 2013 and August 2017 near the border of Oklahoma (OK) and Kansas (KS), color-coded by depth. (Bottom Left) The depth distribution of the earthquakes shown on the map. (Bottom Right) $M_L - M_C$ as it varies with depth. Gray circles represent the mean $M_L - M_C$ value. Error bars are ± 2 standard error (95% confidence interval). Depth bins are 1 km.

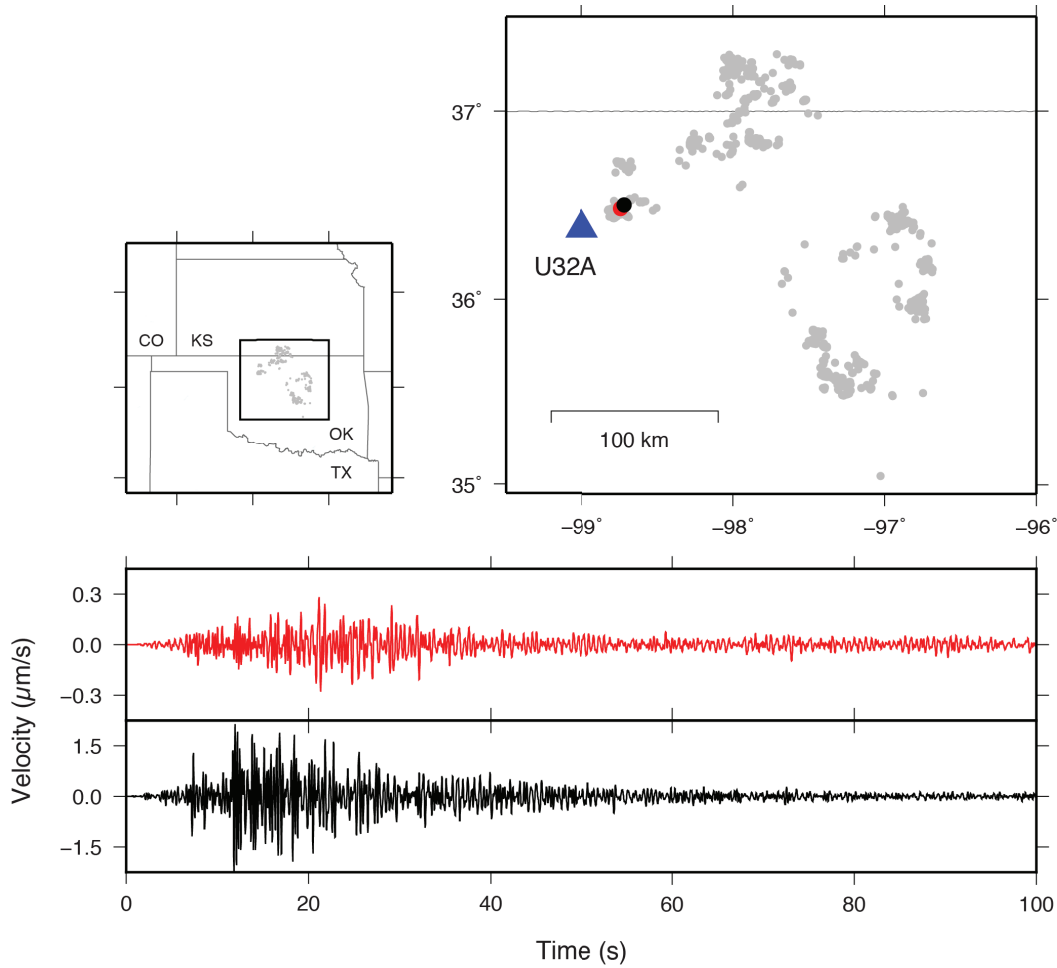


Figure 5. Similar to Figure 1, but for Oklahoma/Kansas. Comparison of co-located deeper ($M_L = 2.37$, $M_C = 2.10$, depth = 9.44 km) and shallower ($M_L = 1.31$, $M_C = 2.08$, depth = 2.45 km) wastewater injection induced earthquakes. (Top Left) A map of Oklahoma (OK), Kansas (KS), Colorado (CO), and Texas (TX) outlining the region shown in the top right. Gray circles represent earthquakes from the NEIC catalog for this region (Top Right) A map of the shallow earthquake (red circle) and deep earthquake (black circle) overlain on the NEIC catalog for this region (gray circles). Blue triangle represents the location of OK station U32A. (Bottom) The seismograms of the shallow (red) and deep (black) events as recorded on U32A BHZ filtered between 1–5 Hz. The time window is 5 s before the P-wave arrival and 95 s after the P-wave arrival for both waveforms. Note the vertical scale of the shallow earthquake is 5 times smaller than the vertical scale of the deep earthquake.

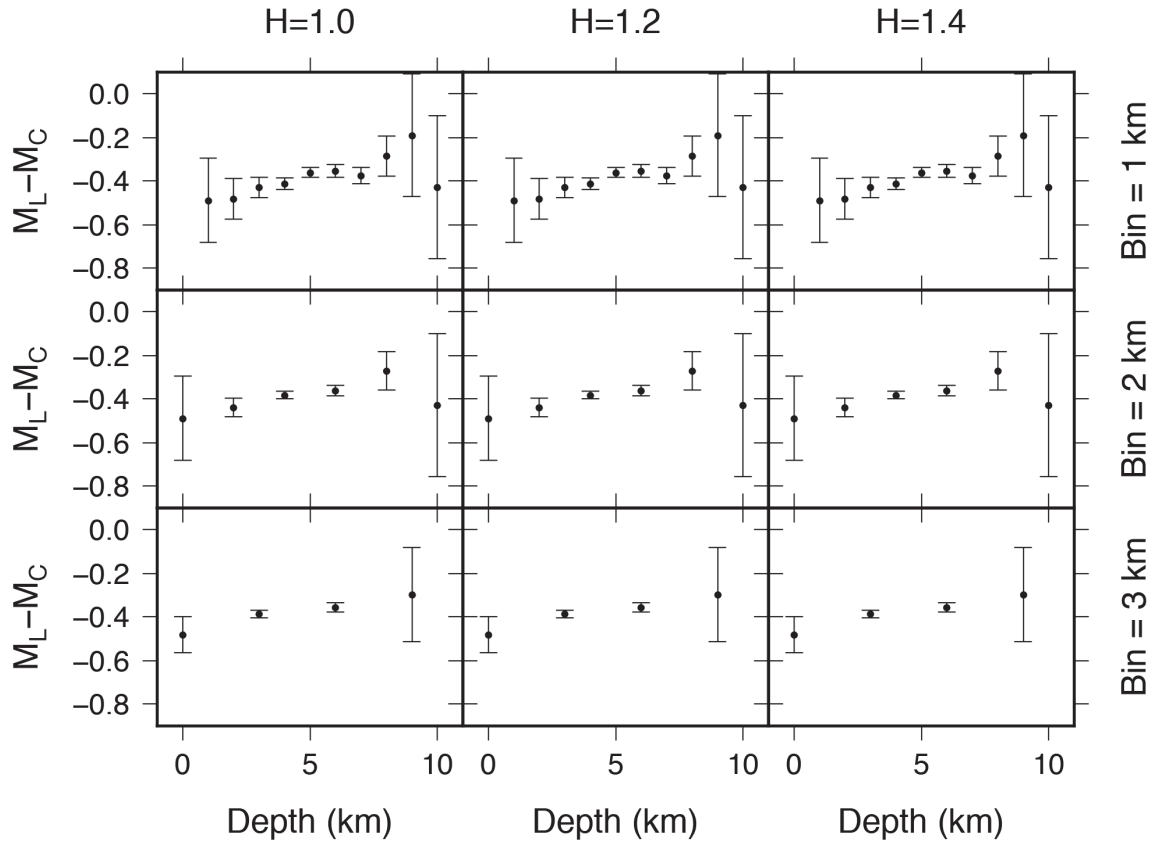


Figure 6. Similar to Figure 3, but for Oklahoma/Kansas. *Robustness tests for Figure 4.* The circles are means and the error bars are ± 2 standard error. The bin sizes are 1 km, 2 km, and 3 km, moving from the top to the bottom. Earthquake depths are considered well-constrained if the epicentral distance to the nearest station is either smaller than a certain multiple of the depth ($H=1.0, 1.2$, or 1.4 , varying from left to right), or smaller than the bin size (1 km, 2 km, or 3 km). All panels show evidence of decreasing $M_L - M_C$ as earthquake depth decreases.

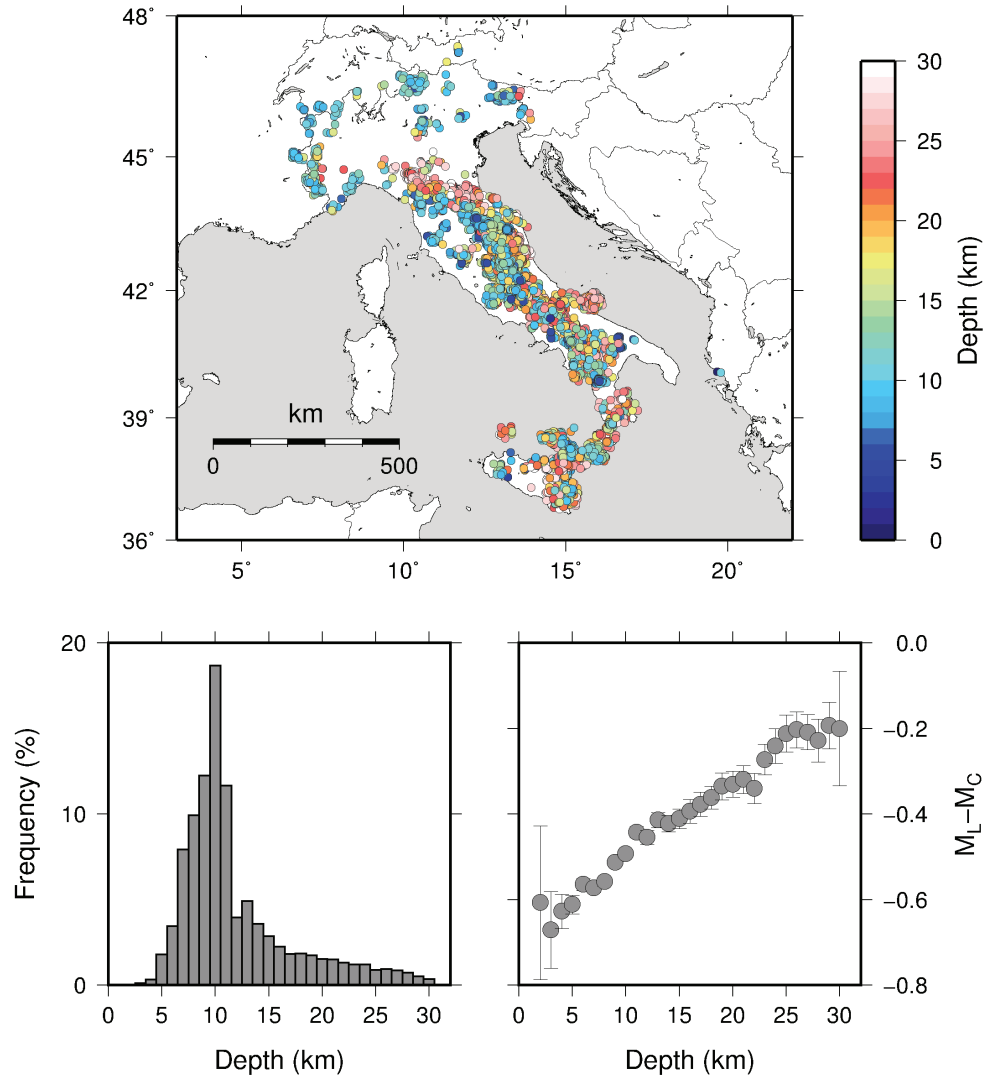


Figure 7. Similar to Figure 2, but for Italy. (Top) A map of 28,722 “good depth” earthquakes in Italy and Sicily (April 2005–April 2012), color-coded by depth. (Bottom Left) The depth distribution of the earthquakes shown on the map. (Bottom Right) $M_L - M_C$ as it varies with depth. Gray circles represent the mean $M_L - M_C$ value. Error bars are ± 2 standard error (95% confidence interval). Depth bins are 1 km.

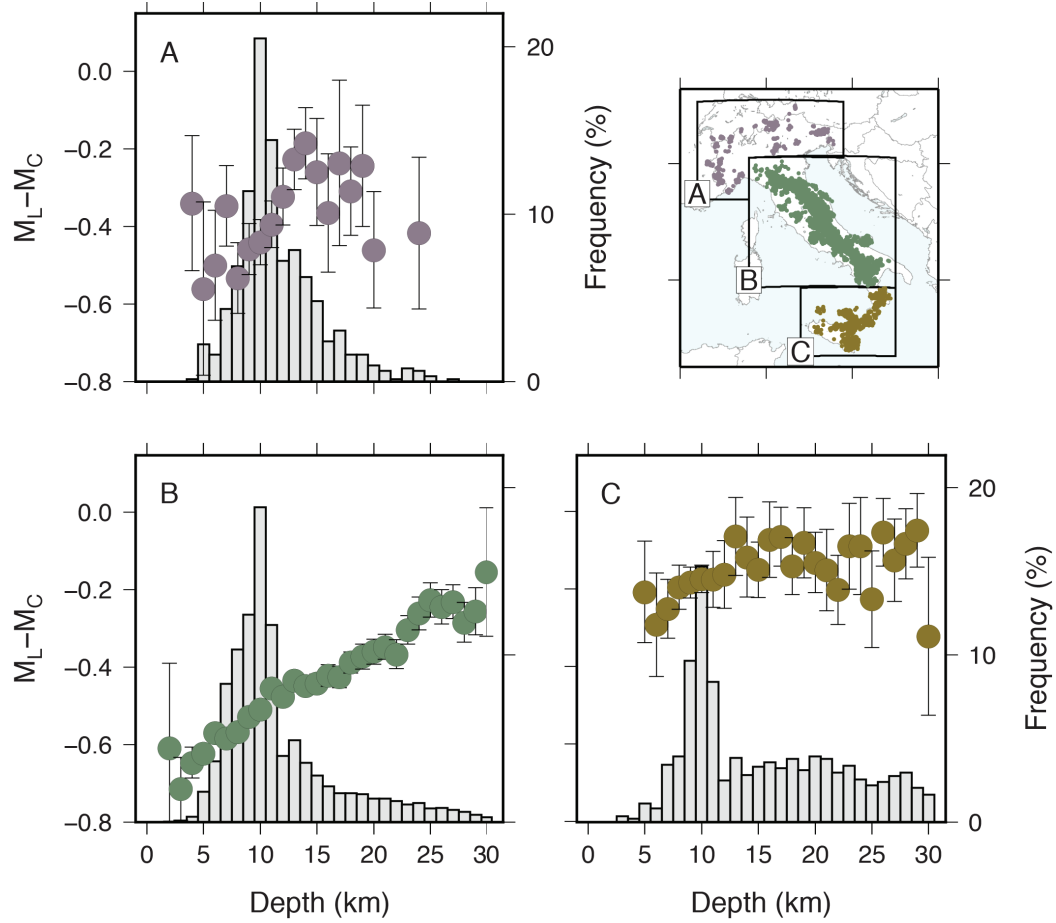


Figure 8. Regionalization of Italy. (Top Right) A map of the good-depth seismicity in Italy, color-coded by the different regions A, B, and C. (Top Left) $M_L - M_C$ for 624 earthquakes in region A. Purple circles represent mean $M_L - M_C$ values. Error bars are ± 2 standard error. Gray bars (and right, vertical axis) are the depth distribution of the earthquakes. Depth bins are 1 km. (Bottom Left) The same as the top left, but for the 26,595 earthquakes in Region B. (Bottom Right) The same as the top left, but for the 1,452 earthquakes in Region C. All regions have decreasing $M_L - M_C$ with decreasing depth.

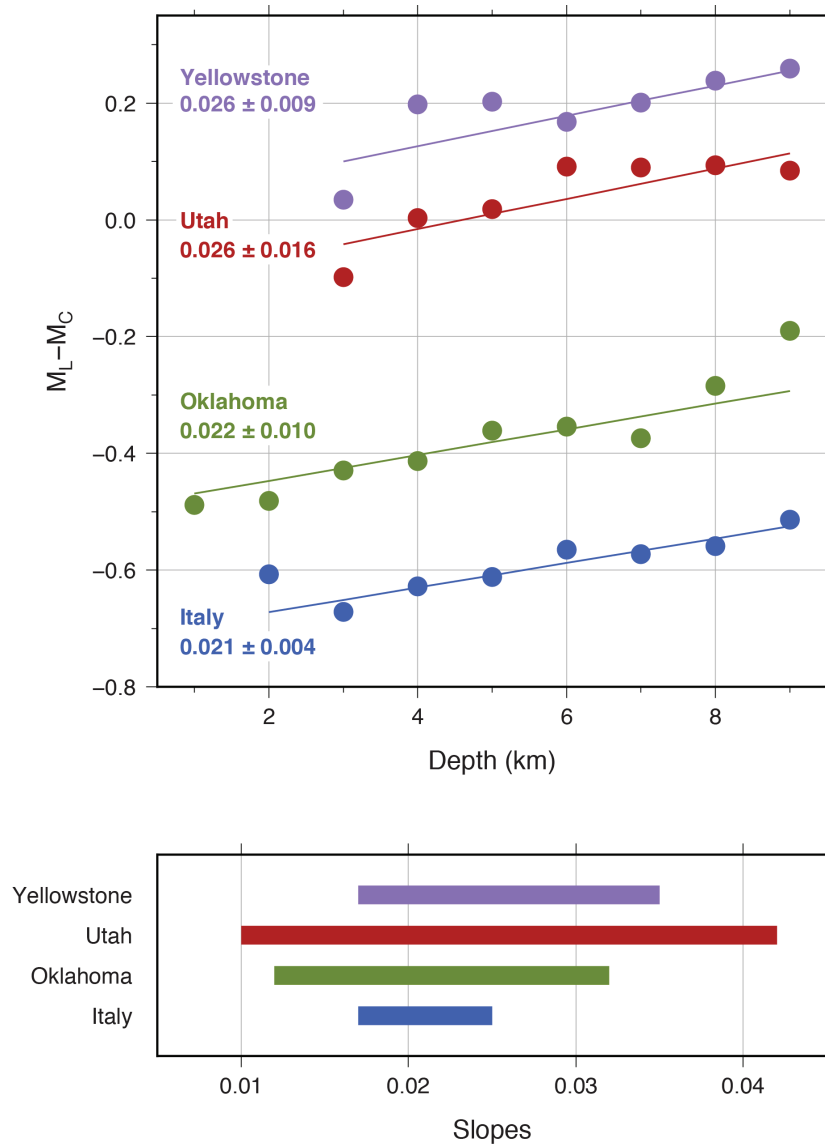


Figure 9. (Top) The $M_L - M_C$ values for each region with their reported slopes and 95% confidence intervals. *Note that all slopes in this figure are reported for a line fit to 9 km depth. The Utah data is from Koper et al. (2016).* (Bottom) The distribution of the slope values within their 95% confidence range. *Note that all slopes overlap between 0.017 and 0.025, and none overlap with 0.0.*

4. RESULTS AND DISCUSSION OF $M_L - M_C$ PORTABILITY

To explain the $M_L - M_C$ depth sensitivity observed in Utah, Koper *et al.* (2016) speculated that the existence of a shallow, low-velocity layer could act as a waveguide

for shallow sources, preferentially enhancing the signal duration and thus M_C . Such a layer occurs in some local velocity models for the Utah region that have been constrained by borehole information. The new observations presented here— M_L - M_C depth sensitivity in Yellowstone, the central U.S., and Italy—imply that a more general phenomenon may be required to explain M_L - M_C depth sensitivity because the newly studied regions have significant geologic and tectonic differences from Utah. It is also worth noting that although the simple, 1D simulations of wave propagation in a low-velocity layer by Koper *et al.* (2016) were qualitatively consistent with M_L - M_C depth sensitivity, more detailed experimentation with 1D velocity models has shown that it is relatively difficult to find models that quantitatively match the observations.

An important factor for explaining M_L - M_C depth sensitivity may be increased geological heterogeneity near the surface, a feature that is likely widespread globally. Stochastically described, small-wavelength heterogeneity is well known to extend the durations of coda waves in numerical simulations (Frankel and Clayton, 1986). It follows that shallow sources nucleating in a strongly scattering layer of the Earth generate waveforms with long-duration coda waves at local distances (e.g., Imperatori and Mai, 2015; Takemura *et al.*, 2015; Olsen *et al.*, 2018). It has also been observed that topographical scattering can generate extended, short-period, coda energy at local distances for very shallow sources (Rodgers *et al.*, 2010; Imperatori and Mai, 2015; Takemura *et al.*, 2015).

The effect of source depth on coda duration in heterogeneous Earth models was explicitly addressed by Isken and Mooney (2017). Those authors used 2D finite-difference simulations to forward model the waveforms of 13 aftershocks of the 2011 M_w

5.7 Prague, Oklahoma earthquake at local distances (< 120 km). They considered two velocity models, both with sharply decreasing velocities for depths < 2 km, which acted as a waveguide, but only one of which also contained small-scale lenses of low-velocity material representing paleo-river channels. They found that the more complicated velocity model was needed to match the complexity of the observed waveforms and, importantly, that the duration of the synthetic coda waves decreased substantially as source depth increased from 1–7 km. Isken and Mooney (2017) then used the observed coda durations to constrain the aftershocks to be in the basement at depths > 4 km. Pitarka and Ichinose (2009) simulated high-frequency wave propagation at local distances using a 3D finite-difference approach that accounted for topography as well as volumetrically distributed geologic heterogeneity. In a velocity model with strong heterogeneity limited to the upper 5 km, they found that synthetic seismograms for a source at 2 km depth had more extensive coda than those for a source depth of 10 km at frequencies of 0.1–1 Hz.

Stress drop is another possible explanation for shallow earthquakes having longer coda duration. Lower stress drops correspond to longer source durations, which in turn may lead to longer coda durations. Shallow crust may be more likely to experience lower stress drop seismic events because it is weaker and more fragmented than deeper crust. Long (2019) examined stress drop as a function of depth for natural and induced earthquakes with a focus on fluid-filled fractures in shallow, granitic crust. The author found increasing stress drop to ~ 4 km, then the stress drop values leveled off; an observation that was attributed to an increase of lithostatic pressure. Similarly, Trugman *et al.* (2017) observed a depth dependence in corner frequency and stress drop of induced

earthquakes in Kansas. Goebel *et al.* (2016) found that seismicity within the San Geronio Pass in California exhibited a sharp increase in stress drop below 10 km; however, Goebel *et al.* (2016) also analyzed seismicity in the Ventura Basin (also California) and did not observe depth-dependence in stress, leading the authors to conclude that a universal relationship between stress drop and depth is unlikely. It is possible that a combination of low-velocity surficial layers, low stress drop, crustal heterogeneities, and topography explains the changes in waveform duration with depth and each scenario needs to be comprehensively and quantitatively explored.

We emphasize that M_L - M_C is intended to be an event screening tool used to rule out tectonic earthquakes as potential nuclear explosions. As such, it must be combined with other methods of local-distance discrimination for complete characterization of small seismic events. Methods that have recently been evaluated for local-distance discrimination include $(P, R_g)/(S_g, L_g)$ amplitude ratios (Zeiler and Velasco, 2009; O'Rourke *et al.*, 2016; Kolaj, 2018; Tibi *et al.*, 2018a; Pyle and Walter, 2019), although it is still unclear if the amplitude ratios will be as effective at local distances as they are at regional distances (e.g., Bottone *et al.*, 2002). Furthermore, calibrated M_L and M_C scales may not exist in regions of monitoring interest. In these cases, new M_L and M_C scales would have to be developed. Alternatively, it might be more fruitful to use direct amplitude and duration measurements as a proxy for M_L - M_C , since M_L - M_C is directionally proportional to $\log_{10}[\text{amplitude/duration}]$.

We have shown that M_L - M_C is sensitive to source depth for tectonic, volcanic, and induced earthquakes in Yellowstone National Park, northern Oklahoma/southern Kansas, and Italy, in agreement with earlier results for Utah (Koper *et al.*, 2016). In all four cases,

M_L-M_C becomes increasingly positive as depth increases. Yellowstone M_L-M_C values increase 0.030 ± 0.007 magnitude units (m.u.) per 1 km of depth with the strictest criteria for a well-constrained depth. Oklahoma/Kansas M_L-M_C values increase 0.022 ± 0.010 m.u./km, and Italy M_L-M_C values increase 0.018 ± 0.001 m.u./km. Utah, Yellowstone, and Oklahoma/Kansas have M_L-M_C values that stop decreasing at ~ 9 km, while Italy M_L-M_C values increase up to 30 km.

There are several possible explanations for shallower events having preferentially longer coda durations than similarly sized deeper events. These explanations include (1) the presence of a near-surface, low-velocity waveguide, (2) lower stress drops for shallow events, (3) increased topographical scattering for shallow events, and (4) increased volumetric scattering for shallow events because of increased geologic heterogeneity near the surface. A comprehensive modeling study is necessary to understand the relative importance of these factors.

Nevertheless, we propose using M_L-M_C as a depth discriminant to help screen out deeper events from especially shallow seismic events ($< 4-5$ km), which may be explosions. Both local magnitude (M_L) and coda-duration magnitude (M_C) are easily measured for small seismic events, and M_L-M_C may function as a local distance analog to m_b-M_S . The Comprehensive Nuclear-Test-Ban Treaty (CTBT) is a zero-tolerance treaty that requires source discrimination for very small seismic events, which will only be well-recorded at local distances. Therefore, methods based on M_L-M_C could likely help verify the CTBT.

5. INTRODUCTION TO UTAH EXPLOSION CATALOG

An important task in regional seismic monitoring is distinguishing explosions from earthquakes. Misidentified explosions are problematic because they contaminate earthquake catalogs that are used to assess seismic hazard. Identifying small explosions at local-to-regional distances is also important for monitoring the zero-tolerance Comprehensive Nuclear-Test-Ban Treaty (Bowers and Selby, 2009). In this context, it is especially important to identify common industrial explosions, such as mine blasts, which might otherwise lead to false alarms (Richards *et al.*, 1992; National Research Council, 1998; Stump *et al.*, 2002).

Several methods have been evaluated for seismic identification of mine blasts at local-to-regional distances including P/L_g amplitude ratios (Kim *et al.*, 1993), S_g/R_g amplitude ratios (Tibi *et al.*, 2018a), R_g excitation (Goforth and Bonner, 1995), spectral modulations (Baumgardt and Ziegler, 1988; Arrowsmith *et al.*, 2006), magnitude differences (Zeiler and Velasco, 2009), and spectral deviation from an earthquake source model (Allman *et al.*, 2008). More recently, approaches based on machine learning have shown promise (Linville *et al.*, 2019). Simpler considerations such as a daytime occurrence (Wiemer and Baer, 2000), waveform similarity with previous known explosions (Gibbons and Ringdal, 2006), and location near a permitted blasting region (Astiz *et al.*, 2014) are also useful for identifying mine blasts.

In this study, we develop a new catalog of explosion source parameters in the Utah region which can be combined with the existing regional earthquake catalog to evaluate methods of source discrimination. We manually review 2,199 seismic events that occurred within or adjacent to the Utah region between 1 October 2012 and 30 June

2018. We repick the arrival times, relocate the hypocenters, and recalculate the magnitudes, resulting in revised solutions for 1,545 explosions, which are assigned to one of 26 distinct source regions. The explosions are mostly mining-related quarry blasts, but include some single-fired, above-ground explosions carried out by government agencies. We use the new catalog to examine the ability of a recently proposed (Koper *et al.*, 2016; Holt *et al.*, 2019b) depth discriminant—the difference between local magnitude (M_L) and coda duration magnitude (M_C)—to separate explosions from earthquakes in the Utah region. Previous work found a mean $M_L - M_C$ value of 0.048 ± 0.008 for 3,957 tectonic earthquakes in Utah and a mean $M_L - M_C$ value of -0.137 ± 0.008 for 3,723 likely explosions in Utah (Koper *et al.*, 2016). Their interpretation was that near surface explosions are efficient at generating extended coda waves, perhaps because of R_g excitation and scattering, leading to anomalously high M_C values.

The waveforms of the likely explosions studied in Koper *et al.* (2016) were analyzed less rigorously than those from events initially classified as earthquakes because the primary mission of the University of Utah Seismograph Stations (UUSS) is mitigating earthquake risk in the Utah region. The epicenters are generally of high-quality because they are a factor in the initial source classification process. However, for a given mine region the arrival times were picked by different analysts over a period of many years. The relative locations can be improved by using a single analyst to repick arrival times from events in a given source region at the same time—as we do here. The magnitudes of the likely explosions studied in Koper *et al.* (2016) are generally of lesser quality than those of earthquakes characterized by UUSS because magnitudes are not used in the initial source classification process. The careful waveform reanalysis we do here leads to

more accurate magnitudes and helps us identify any misclassified events, in turn leading to a more rigorous evaluation of M_L - M_C as a source classifier.

6. METHODS, ASSUMPTIONS, AND PROCEDURES FOR UTAH EXPLOSION CATALOG

The University of Utah Seismograph Stations (UUSS) operates the University of Utah Regional Seismic Network (UU; University of Utah, 1962), which, as of 30 June 2018, consisted of 39 broadband, 67 short-period, and 78 strong-motion seismometers (Figure 10). Continuous seismic data from this network are telemetered to the UUSS earthquake information center and combined with data recorded from neighboring seismic networks to detect, locate, and characterize seismic events. This process uses the ANSS Quake Management System (AQMS) software package, where ANSS is the Advanced National Seismic System. All automatically generated AQMS solutions are reviewed and refined by UUSS analysts. For AQMS solutions with magnitudes larger than $M_{2.5-3.5}$, depending on the region, a duty seismologist reviews the event within 30–60 minutes and submits refined earthquake solutions to the ANSS Comprehensive Earthquake Catalog. UUSS also publishes online reports with finalized earthquake solutions on a quarterly basis (*quake.utah.edu*).

The UUSS uses M_L and M_C to describe the magnitude of small earthquakes. M_L is calculated from the horizontal channels of broadband stations using the equation

$$M_L = \log_{10}[A] - \log_{10}[A_0] + S \quad (7)$$

where A is half of the sum of the maximum north-south channel peak-to-peak amplitude (mm) for a single cycle divided by two and the maximum east-west channel peak-to-peak amplitude (mm) for a single cycle divided by two on an emulated Wood-Anderson

seismograph, $\log_{10}[A_0]$ is an empirical distance correction, and S is an empirical station correction (Pechmann *et al.*, 2007). M_C is calculated from the vertical channel of short-period or filtered broadband stations using the equation

$$M_C = -2.25 + 2.32\log_{10}[\tau] + 0.0023\Delta \quad (8)$$

where τ is measured as the time difference in seconds from the P -wave arrival to the time that the average absolute value of the ground velocity drops below $0.01724 \mu\text{m/s}$, and Δ is the epicentral distance in km (Pechmann *et al.*, 2006).

An important task for UUSS analysts is determining whether an automatically-detected seismic event in the AQMS database is an earthquake (either local, regional, or teleseismic), a likely explosion, or a noise trigger. Because the UUSS mission focuses on reducing earthquake risk in Utah, AQMS solutions determined to be explosions are reviewed with less stringent quality criteria and excluded from the UUSS earthquake catalog. An analyst classifies a reviewed AQMS solution as a likely explosion if its epicenter is within or very near a permitted blasting region, it occurred during daylight hours (typically 13:00 – 03:00 GMT) when surface blasting is permitted in Utah, its waveforms look similar to those of previous explosions in the area, or if UUSS is given prior notification from the mine operator. In the AQMS database these events are labelled either as “qb” for quarry blast or “ex” for explosion. For convenience, in this paper we refer to all such events as “LE” for likely explosion.

There are two types of explosions that are most prominent in Utah: disposal and testing of military weapons, and quarry blasts. The most common military explosions involve the above-ground destruction of rocket motors at the Utah Test and Training Range (Stump *et al.*, 2007). A smaller number of military-related aboveground

explosions are carried out at Dugway Proving Ground (www.dugway.army.mil). Non-military surface blasts, shallow ripple-fired blasts, and shallow single-fired blasts are generally used to develop resources such as precious metals, minerals, and gravel, and are classified as quarry blasts. In 2010, a list of Utah mines with active permits for surface blasting was obtained from the Utah Division of Oil, Gas, and Mining (www.ogm.utah.gov). The list was incorporated into the AQMS system to aid UUSS analysts. If an analyst-refined event epicenter is located within either 5 km or 20 km of a permitted mine, depending on the station coverage in that area, AQMS alerts the analyst that the event might be an explosion. The AQMS-generated nearby-mine warning can bias the analyst towards an explosion label, because a nearby mine warning frequently coincides with an actual explosion. As a result, LE's are usually confined to the areas around known, active mines. An LE that does not locate near one of these mines could have an inaccurate location from analyst error or could be associated with a mine that has infrequent or small explosions.

Since 1 October 2012, when UUSS started using AQMS software, thousands of likely explosions have been recorded. In this study, we reanalyze these events with the goal of confirming their source type and refining their magnitudes and, when appropriate, their locations. Generally, first arrival picks on LE waveforms are made with the same standards as those for earthquake waveforms. This is because part of the initial classification process uses the proximity of the epicenter to active mines as a criterion. However, the majority of explosion magnitudes are automated AQMS solutions which are less robust. Therefore, our reanalysis was more heavily focused on improving magnitude estimations.

Because analysts work on events chronologically, as they occur, it is reasonable to reanalyze the LE's in this manner. However, reanalyzing LE's chronologically recreates the same problem the original analysts faced—the wide geographic distribution of the various sources makes event classification challenging. To mitigate this issue, and increase the accuracy of our findings, we reanalyze LE's geographically. The first step is an examination of all seismicity within a defined latitude and longitude range encompassing a known blasting region, in order to establish a qualitative understanding of the waveform differences between earthquakes and explosions in that area. This is the most valuable tool in differentiating and labelling source types correctly because earthquakes and explosions that occur in the same geologic setting generally have distinct waveforms (Figure 11). Other factors considered for source classification include: preliminary epicentral location, *P*-wave first motions, and time of day. Unlike near-surface blasting, underground blasting is not limited to daylight hours, but these blasts are typically much smaller than surface blasts and unlikely to trigger the regional network. Other classification tools include checking for acoustic arrivals on seismic stations and communicating with mine operators for ground truth information.

Reclassification results in one of five outcomes. An event that was originally classified as an earthquake, and remains classified as an earthquake upon reanalysis, is described as a true positive (TQ); if the event is reclassified as an explosion, then it is described as a false positive (FQ). An event that was originally classified as an explosion, and kept as an explosion, is described as a true negative (TX), whereas the same event reclassified as an earthquake is described as a false negative (FX). If the reclassification of an event cannot be described with this scheme, then the event is labeled as “other” (O).

Teleseismic events, noise triggers, and poorly-recorded events are examples of "other" classifications.

Once the event type is determined, we reevaluate peak-to-peak amplitude measurements for M_L determination, signal duration measurements for M_C determination, and arrival time picks for hypocenter determination. After all picks and measurements have been reviewed, we relocate the event, recalculate the associated magnitudes, and save the event to the AQMS database. Locations are calculated using HYPOINVERSE (Klein, 2002) with a set of region-specific one-dimensional velocity models. Depth control is limited for blasts because of the rarity of discernable S -waves and the low density of seismometers near blasting sites. Therefore, most explosions in our database are located with fixed depths of 2 km above sea level ($h = -2$ km) which is the approximate average elevation of permitted mines listed by the Utah Division of Oil, Gas, and Mining.

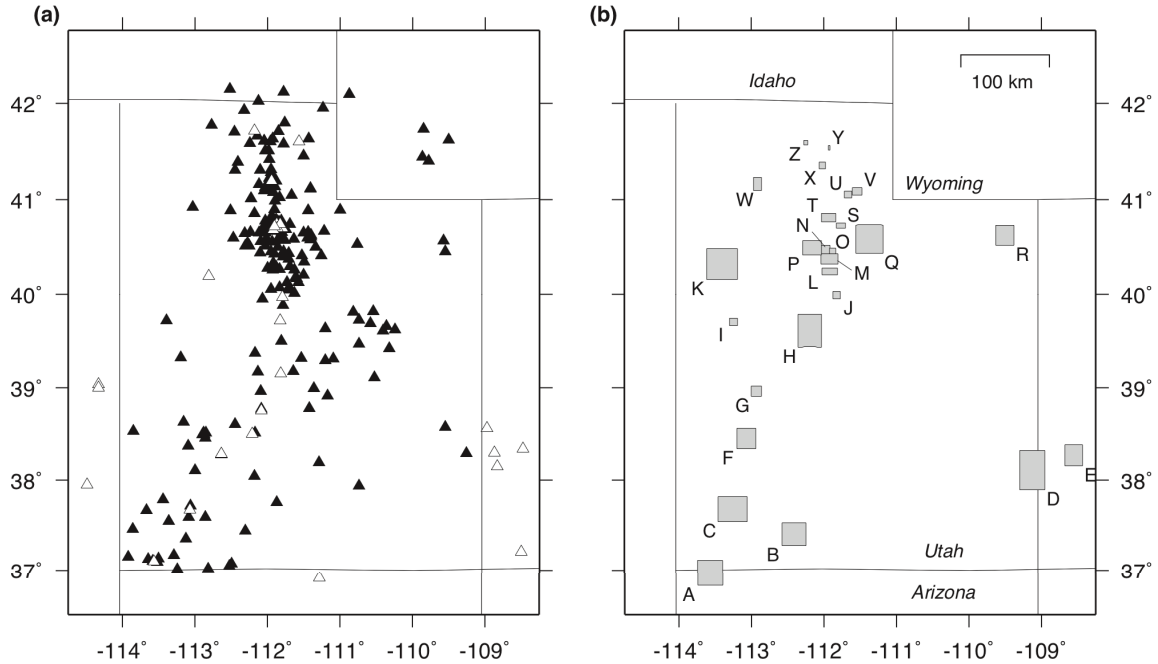


Figure 10. (a) Seismometers used by the University of Utah Seismograph Stations (UUSS) between 2012 and 2018. The UUSS maintains and operates the University of Utah Regional Network (UU; solid triangles) and records data from seismographs in allied networks (open triangles) for seismic processing. **(b)** The 26 explosion source regions, organized from south to north. The 1,545 explosions in these regions occurred between 1 October 2012 and 30 June 2018.

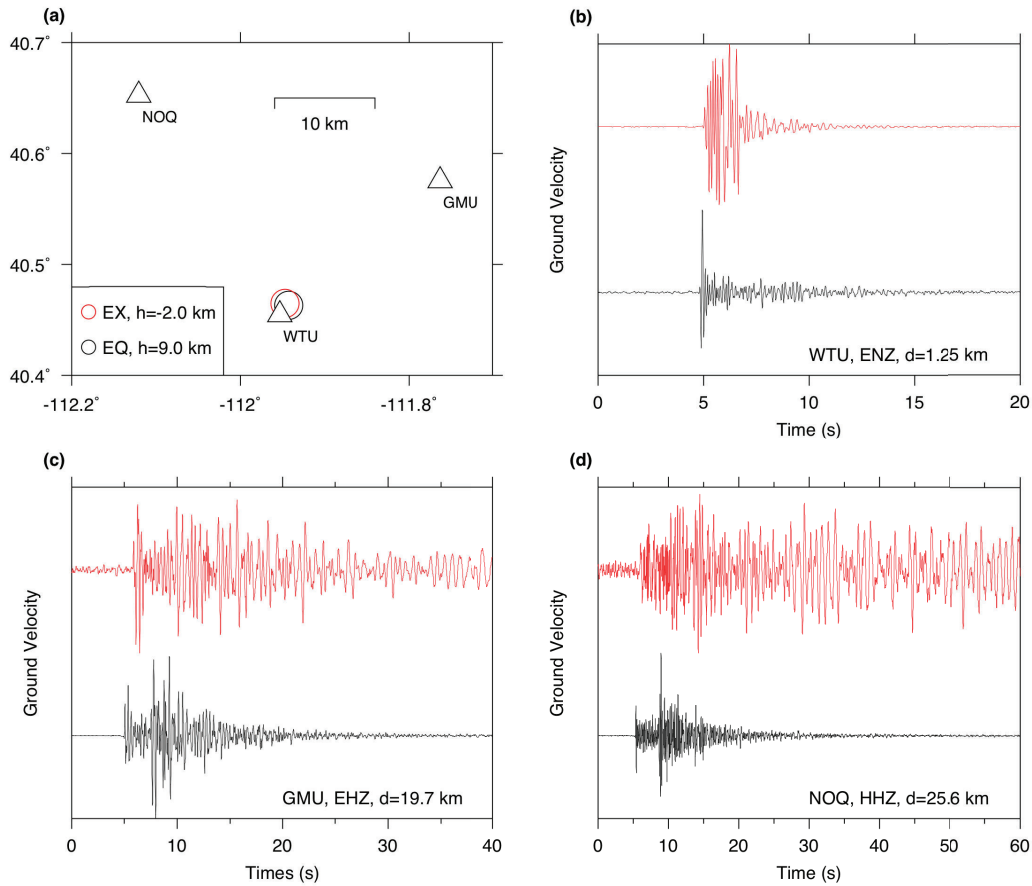


Figure 11. (a) Locations of a quarry blast (red) and naturally occurring earthquake (black) that have nearly identical epicenters. The quarry blast occurred on 2014/10/14 at 20:13:22 (UTC) with magnitudes of $1.41 M_L$ and $1.81 M_C$ and a depth of -2.0 km. The earthquake occurred on 2017/06/25 at 21:20:10 (UTC) with magnitudes of $1.95 M_L$ and $2.02 M_C$ and a depth of 9.0 km. Vertical component waveforms are shown for stations (b) UU.WTU, (c) UU.GMU, and (d) UU.NOQ. All waveforms are proportional to ground velocity and have been bandpassed at 1–10 Hz. Each trace is individually normalized in the given time window. The average epicentral distance, d , from the co-located events is reported in the bottom of each panel.

7. RESULTS AND DISCUSSION OF UTAH EXPLOSION CATALOG

In Table 1, we summarize the outcome of the reanalysis for each of the 26 geographical clusters shown in Figure 10. We report the total number of reviewed events and subtotals in each of the five classes: TQ, FQ, TX, FX, and O. We assess the quality of the original source labels using binary classification theory. Sensitivity measures the rate of true positives and is given by $TQ/(TQ+FX)$, which varies between 0 and 1. High sensitivity means that UUSS analysts missed very few actual earthquakes in their original analysis. Specificity measures the rate of true negatives and in our nomenclature is given by $TX/(TX+FQ)$, which also varies between 0 and 1. High specificity means that very few explosions were originally misclassified as earthquakes by UUSS analysts. For the 2,004 reviewed events that were not labelled O, the original analyst classifications had a sensitivity of 0.92 and a specificity of 0.96. Figure 12 illustrates the variation in sensitivity and specificity from region to region. Note that for regions with no TQ's, the sensitivity is reported as 1.00.

In Table 1 we also report the number of explosions with valid magnitude estimates for both M_L and M_C in each region. Overall, we were able to estimate both magnitudes for 1,148 of the 1,545 explosions. For explosions occurring in sparsely instrumented portions of the Utah region it was often difficult to estimate M_L because of the lack of nearby broadband stations with calibrated M_L station corrections. Very small explosions were also problematic because of the relative sparsity of broadband stations. Below we give details about each geographical cluster as defined in Figure 10.

7.1. Region A

Region A is located in the southwest corner of Utah on the border with Arizona. Station coverage is heavily biased toward the north-northeast leading to an average azimuthal gap (AAG) of 196° in the relocations. The nearest broadband station is UU.LCMT (where UU is the network code and LCMT is the station code), which is located about ~ 10 km east of the event cluster. Large amplitude, low-frequency surface wave content (R_g) is characteristic of the explosion waveforms. We reviewed 81 seismic events in this cluster, and identified 41 as explosions, 21 of which were originally identified as explosions (TX) and 20 which were originally misclassified as earthquakes (FQ). This was the highest fraction of false positives for any region. While the sensitivity of the original analyst classifications was higher than average at 0.98, the specificity was the lowest in any of the 26 regions at 0.51.

7.2. Region B

Region B is located in southern Utah about 150 km northeast of Region A. Station coverage is again biased, to the north and west, but the coverage is more uniform than in Region A and the AAG is correspondingly lower at 125° . The nearest broadband station is UU.PKCU, which is located only 5–10 km to the east of the event cluster. Emergent, spindle-shaped waveforms are again observed for the explosion waveforms. The original classifications had a perfect sensitivity of 1.00, but again a relatively low specificity of 0.71.

7.3. Region C

Region C is located in southwestern Utah with station coverage concentrated to the south and east yielding an AAG of 147° . The nearest broadband station is UU.SZCU, which is located about 20 km east of the event cluster. The original analyst classifications had lower than average sensitivity (0.74). After thorough reanalysis, including conversations with mine operators, 18 events that were originally classified as explosions were changed to earthquakes. In general, the misclassified earthquakes had emergent P waves, which made it difficult to determine first motions; however, these waveforms also tended to have impulsive S waves that were absent on the explosion waveforms. This was the only region in which M_L and M_C estimates could be made for all the verified explosions.

7.4. Region D

Region D is southwest of the Paradox Valley area in western Colorado, a region that experiences induced earthquakes from fluid injection (Figure 13; Block *et al.*, 2015; Yeck *et al.*, 2015; King *et al.*, 2016). The Bureau of Reclamation runs a small aperture network (RE) in the region to monitor the induced seismicity. The network began recording in 1985 and has recently been updated with 20 broadband three-component seismometers. Station RE.PV05 is within 1–2 km of the cluster of explosion sources, which are located about 20 km south-southwest of the injection well—where the induced earthquakes are concentrated. The nearest UUS station is UU.CRLU, which is located about 10 km to the north-northwest of the explosion cluster. It consists of three strong-motion channels and a short-period, vertical component channel.

In comparison to Regions A–C, Region D has a much lower percentage, 18% (Table 1), of total events that are earthquakes (natural and induced). A typical explosion waveform here has large amplitude surface waves and clear changes in frequency content over time—a higher frequency *P*-wave packet is followed by a lower-frequency surface wave (*R_g*) train. At greater distances, these waveforms become very emergent, which contributes to less accurate locations. The emergent nature of the first arrivals resulted in 4 events initially classified as EQ being reclassified as EX. Overall, the specificity was still quite high at 0.96, and the sensitivity was 1.00—indicating that no earthquakes were missed during the original analysis.

7.5. Region E

Similar to Region D, Region E is located in western Colorado near Paradox Valley, about 30 km east of the injection well. The nearest station, RE.PV15, is a few kilometers to the northeast of the explosions. In contrast to Region D, the waveforms from Region E have strongly impulsive first arrivals. The waveform quality, distinct geographical location, and different closest stations, are what distinguished this cluster from Region D. This region exhibits a notable lack of earthquakes (natural and induced). There were no sources in this region that were originally misclassified.

7.6. Region F

Region F is located in southwestern Utah near a region of high heat flow that is the site of a Department of Energy funded project called Frontier Observatory for Research in Geothermal Energy (FORGE, Pankow *et al.*, 2017). UUSS station coverage

is very good in this area with four new broadband stations installed within 20 km of the explosion cluster during the last several years. Several other short-period stations have long been sited within ~40 km of the cluster. Out of 17 earthquakes and 61 explosions that were reanalyzed, none were misclassified. The explosion waveforms in this region were quite distinct from earthquake waveforms.

7.7. Region G

Region G in west-central Utah is an area with infrequent natural seismicity. The closest broadband station, UU.SWUT, is located about 50 km to the north-northwest of the explosion cluster. These explosion waveforms exhibit particularly impulsive P waves, high amplitude S waves, and less distinctive R_g waves than the explosion waveforms in most other regions. The waveforms at the closest station, IMU, are very consistent leading to few misclassified events. However, the atypical R_g waves resulted in 3 FQ reclassifications, as surface wave propagation here is more similar to that of an earthquake than an explosion. Nevertheless, specificity was high at 0.96.

7.8. Region H

Region H is located in central Utah and exhibits three distinct sub-clusters of explosions. The nearest broadband station, UU.NLU, is located 20–40 km north of the seismicity. Station coverage is good, with the only gap to the southwest. The southernmost sub-cluster exhibits typical explosion waveforms with consistent frequency content. Events in the two northern clusters have waveforms with surface waves of longer

duration and lower frequency. This discrepancy contributed to 6 FX reclassifications (missed earthquakes) and a sensitivity of only 0.84. The specificity was excellent at 0.98.

7.9. Region I

Region I is located in a sparsely instrumented part of west-central Utah. The nearest broadband station, US.DUG, is located about 75 km to the northeast. A short-period vertical component station, UU.FSU is located about 5 km to the west. The explosion waveforms are very distinct from earthquake waveforms in this region. We used the *P* and *S* arrival-time moveout from the closest station, UU.FSU, to a farther station, UU.FLU, to distinguish earthquakes from explosions in Region I. The separation of the body waves at distance allows the analyst to observe the energy of *S* relative to *P*, and make a more confident choice of event type. Sensitivity and specificity were both high.

7.10. Region J

Region J is located in a densely instrumented part of central Utah. The nearest broadband station, UU.MPU, is located 5–10 km to the east, and a second broadband, UU.NLU, is located 10–15 km to the west. Perhaps because of the good station coverage, none of the 33 events were reclassified.

7.11. Region K

Region K is one of two areas in our catalog that is subject to periodic weapons testing and disposal. It is located in west-central Utah and contains the U.S. Army

Dugway Proving Ground (DPG). USS has a working relationship with DPG and has ground truth information (test confirmation and payload description) for 8 of the 9 explosions recorded in this region. USS is familiar with DPG explosive practices and the event depths in this region are fixed to -1.3 km, the elevation of the test site. Dugway explosions typically have an emergent first arrival and a highly energetic, long-duration surface wave train. These explosions are best recorded on station UU.DUG, deployed on DPG but about 20–30 km east of the seismic events. Though USS has ground truth for DPG events, high-accuracy seismic locations can be difficult to determine because of station gaps to the north and west. No events were misclassified in this region.

7.12. Region L

Region L is in an area of central-northern Utah with dense station coverage but infrequent natural seismicity. The nearest broadband station, UU.MPU, is located about 15 km southeast of the cluster, and 5 other stations are located at shorter distances. Natural earthquakes are infrequent in this area and only 1 of the 31 events reviewed here was an earthquake. None of the events were misclassified.

7.13. Region M

Similar to Region L, Region M is located in an area of central Utah with infrequent natural seismicity (3 EQ versus 70 EX). The relocated epicenters cluster tightly, but with some northwest-southeast scatter. Two broadband stations, UU.NLU and UU.MPU, are located within 40 km of the event cluster. There are 7 type-O events here, which are poorly recorded, small-magnitude LE's. The EX waveforms are consistent

from event to event and with other mines (emergent arrivals, frequency content, and decay rate). The low rate of natural seismicity and the consistency of the waveforms contributed to there being no misclassifications.

7.14. Region N

Region N is located in north-central Utah in a densely instrumented part of the network. The nearest broadband, UU.NOQ, is about 15 km northwest of the seismicity, but nearly 10 other seismograph stations are located at similar or closer distances. This region encompasses a mine as well as an earthquake swarm that occurred in June 2017 leading to a perfect balance of source types (41 EQ and 41 EX). There were no misclassifications in this region.

7.15. Region O

Region O is nearby Regions M and N and is an area of dense station coverage. This coverage outweighs the low magnitude of the explosions which allows for 90% of the events to have calculable M_L and M_C values. The first arrivals at station UU.WTU are emergent, leading to relatively dispersed epicenters for this region. UU.WTU is used in tandem with UU.GMU for discrimination based on phase moveout. Even with a low rate of seismicity, there are 3 FX reclassifications, giving a sensitivity of 0.25, the lowest in any region. The P wave frequency content and S wave frequency content for some of the blasts in this region looked similar to that of an earthquake, but these events were correctly classified after finding subtle similarities in waveform characteristics between the events when all were simultaneously compared.

7.16. Region P

Region P is located in the Oquirrh mountain range in north central Utah (Figure 14). The nearest broadband station, UU.NOQ, is 5–10 km to the north of the clustered seismicity. Region P contains one of the largest open pit mines in the world, which is a source of frequent explosions. A variety of blasting practices are used to mine primarily porphyry copper and other precious metals such as gold and molybdenum. Dense station coverage and the relatively large magnitude of these events result in well constrained locations. There is only 1 FQ (specificity ~ 1.0) because UUSS analysts are very familiar with this mine. In contrast, there are a significant number of FXs (6), leading to a relatively low sensitivity of 0.79. This is likely due to the 70:1 ratio of LE's to earthquakes in this region.

The 2,817 LE's in Region P required a different analysis strategy than the other regions. We chose to evaluate every tenth explosion in chronological order for efficiency. Through selecting a subset chronologically, we believed we would get a representative sample of epicenters, magnitudes, blasting practices, and times of day for the LE's. In this region, three stations are used to verify that an event is from this mine. UU.MID is normally the closest station to an event and UU.CWU and UU.NOQ, while farther away, also have clear waveforms.

Although only a tenth of all Region P LE's were carefully analyzed, every remaining event was briefly checked for duplication and time of day. Duplication of events occurs in other mining regions, but was most commonly observed in Region P. Occasionally, an event is large enough to trigger the AQMS automatic procedure and this

automatic solution is not reviewed by an analyst. The analyst may then process a separate trigger with the same event and two solutions will exist in the database. This occurred for 25 events in Region P.

7.17 Region Q

Region Q is in north-central Utah about 50 km east of Region P, but still within the densest portion of the UUSS regional network. The broadband station UU.JLU is within the LE cluster, which is relatively dispersed compared to the tight epicentral clustering observed in other regions. Region Q events are processed as having three, indistinct sub-clusters of seismic activity: two east-west lineations (sub-clusters I and II) and a southern group of events (sub-cluster III). Sub-cluster I is the northernmost subset of events within this region and its seismicity is best recorded on UU.RCJ. The explosion waveforms typically have high-amplitude, low-frequency, impulsively-arriving, and quickly-decaying surface waves. Events within sub-cluster II can be described as more emergent and smaller amplitude than sub-cluster I. These events are often well-recorded on UU.KLJ and UU.JLU. Sub-cluster III events demonstrate clear frequency changes upon the arrival of *S* waves. Station UU.HEB records the highest quality waveforms for these LE's. Both sensitivity (0.98) and specificity (0.93) are high in this region.

7.18. Region R

Region R is in the northeastern corner of Utah where station density is low, leading to an AAG of 200 (Figure 15). Broadband station UU.RDMU, however, is located adjacent to the southern edge of the LE cluster. Region R contains an active

phosphate mine. Natural earthquakes are infrequent in this region and all the events were correctly classified. Additionally, 99% of events had both an M_L and M_C measurement, making Region R among the top 2 mines with both M_L and M_C values. This is mainly owing to the large size of the events here.

This mine sets off explosives in double shots, an uncommon practice in Utah. The majority of shots have an eight second delay, plus or minus a few seconds. Only station UU.RDMU was close enough to consistently record the double shots clearly, though they are occasionally visible at UU.VNL. We limit our reanalysis to 67 of the 185 LE's in Region R: single blasts (very infrequent), double blasts with enough delay (~ 10 s) to distinguish the two shots, and double blasts that essentially overlap, but have a larger second shot. The goal is to avoid double shots that are indistinguishable since they would yield an artificially high M_C . Events with an unclear number of shots, or unrecorded on UU.RDMU, or both, are not analyzed. Double shots from this mine can look similar to earthquakes; the P wave of the second shot can look like the S wave of the first shot. The analyst looks for the number of phases as distance increases. An earthquake recorded at local distances will have two distinct body wave phases (P and S), whereas a double blast would yield four phases (P and S for each blast).

7.19. Region S

Region S is located in north-central Utah where station density is highest. The nearest broadband station, UU.CTU, is within a few kilometers of the LE cluster. Good station coverage (65% of events have M_L and M_C estimates) and extremely clear, consistent, and blast-like waveforms at UU.CTU contribute towards making confident

classifications (specificity of 1.00). There were no natural earthquakes in Region S during the time period covered in this study.

7.20. Region T

Region T is nearby Region S and includes one of the quarries that UUSS analysts are very familiar with (Figure 16). This familiarity results in no event reclassifications in this region. UU.HRU, the closest station to most of the event epicenters, and UU.RBU are used in tandem for classification. Along with region N, region T also encompasses an earthquake swarm, which included 7 events located southwest of the LE cluster in March 2012. Over 90% of the 200 events have both M_L and M_C . In general, the strong overall station coverage outweighs the small size of the events and results in well-constrained epicenters and magnitudes.

7.21. Region U

Region U is also in the high-density portion of the UUSS regional network about 20 km northeast of Region T. The nearest broadband station, UU.CTU, is about 10 km to the east of the LE cluster, and the strong-motion station UU.MOR is essentially collocated with the LE's. Region U has slightly more earthquakes than the neighboring regions to the south (4 EQ versus 22 EX) and the LE's are quite small. These factors lead to 3 FQ classifications and a relatively low specificity of 0.86. None of the four earthquakes were previously misclassified, giving a sensitivity of 1.00. Both M_L and M_C estimates were available for only 9 of the 22 LE's because of their small size.

7.22. Region V

Region V borders Region U to the east, and shares the same good station coverage. The waveforms from the 8 earthquakes in this region are distinct from the waveforms of the 14 explosions, and none of the events were reclassified. Typical explosion waveforms with large-amplitude surface waves are best observed at broadband station UU.TCU, which is a few kilometers to the east. The earthquakes in the region have impulsive *S* waves at UU.TCU.

7.23. Region W

Region W is just west of the Great Salt Lake in northern Utah. It is on the western edge of the high-density portion of the UUSS seismic network and the nearest broadband station, UU.SPU, is about 40 km to the northeast. Region W is home to the Hill Air Force Base's Utah Test and Training Range (UTTR). The UTTR is a Major Range and Test Facility run by the Department of Defense which is remote enough to evaluate weapons that could be too impactful to test elsewhere (Hedlin *et al.*, 2012). In addition to the 178 analyzed explosions at UTTR, Region W has a distinct cluster of events about 8 km north of the main UTTR blasting platform (Figure 17). UTTR explosions from the main platform have waveforms with impulsive *P* waves, slightly less impulsive *S* waves at larger distances, and well-defined frequency changes between the two. The cluster to the north has emergent first arrivals.

The aboveground nature of these explosions means that surface waves (*Rg*) are not as effectively produced and discrimination is more difficult. We used stations UU.BGU, UU.SNUT, and UU.SPU for discrimination. UU.SPU records the least number

of events, but is the most useful in discrimination because the *S* wave is most prominent. Station coverage is poor in Region W, with an AAG of 170. Most of the UTTR explosions occur at certain times of the day during certain months of the year. Though there are 8 FQ's in this region, the consistency in blasting origin time, high frequency of testing, and low rate of natural seismicity make discrimination straightforward. The availability of ground truth information regarding UTTR explosions allowed us to fix the depths at -1.5 km.

7.24. Region X

Region X is located in a densely instrumented part of northern Utah. The nearest broadband station, UU.SPU, is about 20 km to the west. Three other stations, UU.GZU, UU.PCL, and UU.BES, are located within a few kilometers of the explosion cluster. Like Region N, Region X encompasses an earthquake swarm as well as the explosion cluster. The earthquake swarm was clearly recognized by analysts, so there are no reclassifications in this region. 70% of the events in this region have an M_L and M_C measurement which is likely a result of the relatively large size of the explosions.

7.25. Region Y

Region Y is about 20 km north of Region X and is likewise densely instrumented. The closest station to the events in region Y (UU.BCU) is close to the average epicentral centroid; however, this station is usually too noisy to contribute to discrimination. Instead, we primarily relied on UU.WVUT, UU.LTU, and UU.HONU. The LE's in this

area have dominant surface waves that make explosion sources obvious. The sensitivity was 1.00 and the specificity was 0.91.

7.26. Region Z

Region Z is located about 20 km west of Region Y in northern Utah. The explosion cluster is about 40 km northeast of broadband station UU.SPU. Short-period station UU.LTU is essentially collocated with the LE's but event locations are hard to constrain because first arrivals are emergent and only propagate to a few nearby stations. The three FQ reclassifications (specificity of 0.77) are likely a consequence of clear *S* waves in the LE waveforms.

7.27. Regional Summary

We present the original and revised M_L - M_C distributions for the same group of 1,007 reanalyzed explosions in Figure 18. The revised distribution is more asymmetrical and less biased than the original distribution. The shift in M_L - M_C that occurred during reanalysis reflects larger revisions to M_C than to M_L (Figures 13–17), likely because peak-to-peak amplitude picks are simpler to make than choosing coda duration windows. The changes in M_C values are mostly due to the redetermination of the signal duration, as the human-reviewed duration is often very different than the automatic-solution since the automatic-solution was calibrated for earthquakes, not explosions. M_C values are also changed through relocation, as relocation changes the epicentral distance, but these changes are minimal relative to the change in M_C from reevaluated signal duration measurements. During reanalysis the number of explosions with both M_L and M_C grew to

1,148, with a mean of -0.196 ± 0.017 (95% confidence interval). Previous work in Utah found a mean M_L-M_C value of -0.137 ± 0.008 for likely explosions and a mean value of 0.048 ± 0.008 for naturally occurring tectonic earthquakes, which dominantly occur at depths of 5–15 km (Koper *et al.*, 2016). Hence, the work presented here corroborates the usefulness of M_L-M_C as a crustal depth discriminant in Utah, helping to distinguish extremely shallow seismic events from deeper, naturally occurring earthquakes.

It is interesting to consider how M_L-M_C varies regionally since there is a range of source types, propagation paths, and site effects across the Utah region. In Figure 19, we present M_L-M_C mean values and 95% confidence intervals for each region with at least 5 M_L-M_C observations. Of the 22 regions that meet this requirement, 19 have M_L-M_C means that are more negative than the overall earthquake mean at confidence levels above 95%. Two regions (F and U) have M_L-M_C 95% confidence intervals that include the earthquake range. Only Region G has an M_L-M_C 95% confidence interval that is more positive than the earthquake range.

M_L-M_C has a stronger dependence on M_L than M_C (Figure 19). Events with larger M_L tend to have larger, more earthquake-like values of M_L-M_C . We attribute this to UUSS/AQMS network processing techniques. All of the individual station M_C values are averaged to calculate the event M_C . Any station M_C value is discarded from the calculation of the event M_C if it differs by more than 0.8 magnitude units from the event M_C . This leads to a distance dependence of M_C . Small events are only recorded by nearby stations, and those seismograms tend to have anomalously long durations relative to typical peak-to-peak amplitudes because R_g energy, which is strong at close distances, extends duration more than it increases amplitude (M_C is increased relative to M_L). Large

events are mostly recorded at farther stations where R_g is less observable, so waveforms tend to have more typical durations and M_C and M_L are in agreement. In other words, the distance dependence of the UUSS M_C formula is too weak to account for the true distance-dependent change in coda energy from explosions. If these anomalously large station M_C values were not eliminated from the event averages, many regions (such as P) would have more negative M_L-M_C values. The relatively high values of M_L-M_C in Regions F, U, and G noted earlier corroborate this network processing explanation. Other source-specific factors also play a role in the regional variation of M_L-M_C . For instance, Regions K and W have 95% confidence intervals for M_L-M_C that are only slightly below the earthquake range. These are the two regions that contain above ground explosions. The weak coupling to the solid Earth leads to less efficient R_g excitation, which in turn leads to shorter codas and more positive M_L-M_C values.

The clearest example of source-related M_L-M_C variation comes from a comparison between Regions S and T (Figure 20). These two regions are separated by only ~ 15 km and produce similarly sized quarry blasts with 26 events in Region S having a mean M_L of 1.24 ± 0.052 , and 180 events in Region T having a mean M_L of 1.21 ± 0.036 . Yet, Region S has a mean M_L-M_C of -0.098 ± 0.046 , while Region T has a mean M_L-M_C of -0.512 ± 0.333 . Waveform differences from the two regions occur over a range of distances and azimuths (Figure 2.20), implying that the difference is not caused by geologic variations along source-to-receiver paths, but rather by variations in the source region.

There are two likely source-related explanations for the waveform variations observed in Regions S and T. The first explanation is that the mine in Region T may use

more shot holes on average than the mine in Region S. Increasing the number of shot holes increases the source-time function without affecting the maximum amplitude of the explosion. As the duration of the source-time function approaches the dominant period of R_g (0.5–2 s), R_g is increasingly excited leading to longer duration waveforms (Kim *et al.*, 1993). The second explanation involves near source geology. Region T is geologically heterogeneous, with deformed Mississippian limestones overlain by extensive conglomerates. It lies within the mature Wasatch Fault damage zone, along the boundary between the Salt Lake City sedimentary basin to the southwest and the Wasatch Mountains to the northeast. Such near-source sediment is thought to enhance *P*-to-*S* conversion (Kim *et al.*, 1993), leading to longer coda duration. Region S, in contrast, is on the axis of the ductilely deformed Parley’s Canyon Syncline, a structure composed of competent, laterally homogeneous Jurassic limestones, more distant from the basin. Determining the relative balance of these two effects requires obtaining detailed blasting patterns from the mines and performing high-frequency waveform simulation in realistic Earth models, which we leave for future work.

We manually refined the locations and magnitudes of 1,545 explosions that occurred in the Utah region between 1 October 2012 and 30 June 2018. M_L values vary from 0.65 to 2.90 with a median of 1.58, and M_C values vary from 0.35 to 3.15 with a median of 1.68. Most of the explosions are delay-fired, near-surface mine blasts, although some single-fired, above-ground blasts related to military activities are also included. The new catalog is intended to be used by researchers in verification seismology working on methods of low-yield nuclear monitoring. While methods of classifying moderate-sized (M_3 –5) seismic events recorded at regional distances (~200–2000 km) are well-

established (National Research Council, 2012), it is unclear whether the same methods are effective for small seismic events (M_0-2) recorded at local distances (<200 km), or whether new discriminants need to be developed.

We used the new catalog to confirm the effectiveness of M_L-M_C as a depth discriminant in the Utah region. A total of 1,148 explosions in the new catalog were well recorded enough to have both M_C and M_L calculated. The mean M_L-M_C value for the explosions is -0.196 ± 0.017 (95% confidence interval), significantly more negative than the M_L-M_C value of 0.048 ± 0.008 previously observed for naturally occurring earthquakes in Utah (Koper *et al.*, 2016). We attribute the negative M_L-M_C values of explosions to their shallow depth, which preferentially excites local surface waves (R_g) that scatter and disperse within the low-velocity, strongly heterogeneous, shallow crust, thus generating abnormally long-duration coda waves.

We observed significant variation in M_L-M_C among 26 distinct explosion source regions in and around Utah. The most negative value of -0.634 ± 0.204 was observed for 9 explosions from a quarry in north central Utah, and the most positive value of 0.218 ± 0.314 was observed for 13 explosions from a quarry in southwestern Utah. However, even nearby source regions could have significantly different values because of different blasting practices or geologic setting. Two explosion source regions near Salt Lake City that are separated by just 15 km had mean M_L-M_C values that differed by 0.414 ± 0.336 . To achieve the best discrimination results, M_L-M_C observations should be combined with other, preferably non-correlated, local discriminants in a mathematically rigorous manner, perhaps similar to the methodology used to combine regional-to-teleseismic discriminants (Anderson *et al.*, 2007).

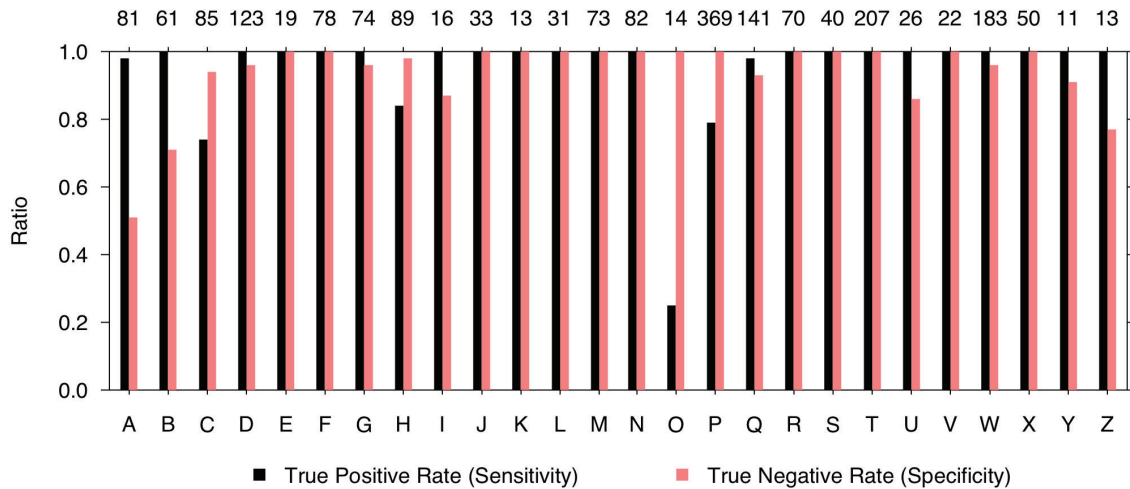


Figure 12. Variation in sensitivity and specificity of the original UUSS analyst classification of source type. For sensitivity, a ratio of 1.0 means that no earthquakes were originally misclassified as explosions. For specificity, a ratio of 1.0 means that no explosions were originally misclassified as earthquakes. The total number of earthquakes and explosions reviewed in each region are listed across the top x axis.

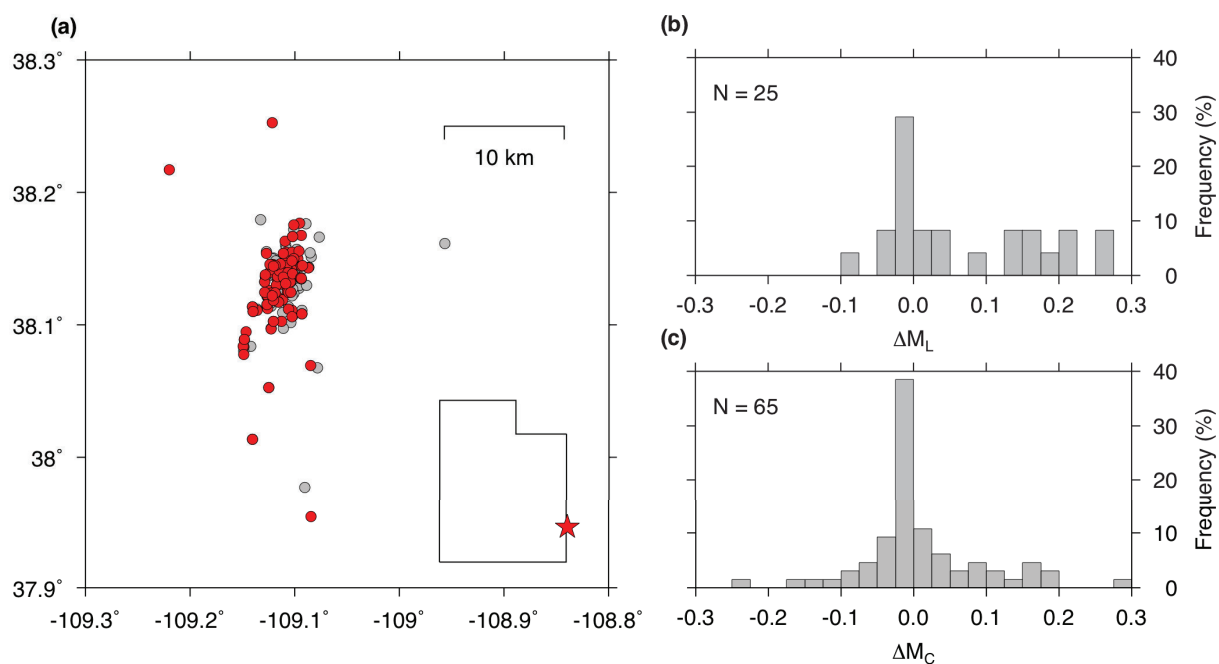


Figure 13. (a) Map of Region D with explosions plotted to reflect their epicenters before (gray) and after (red) reanalysis. The location of Region D within the Utah region is indicated by the red star on the inset image of the state. Changes in (b) M_L and (c) M_C during reanalysis.

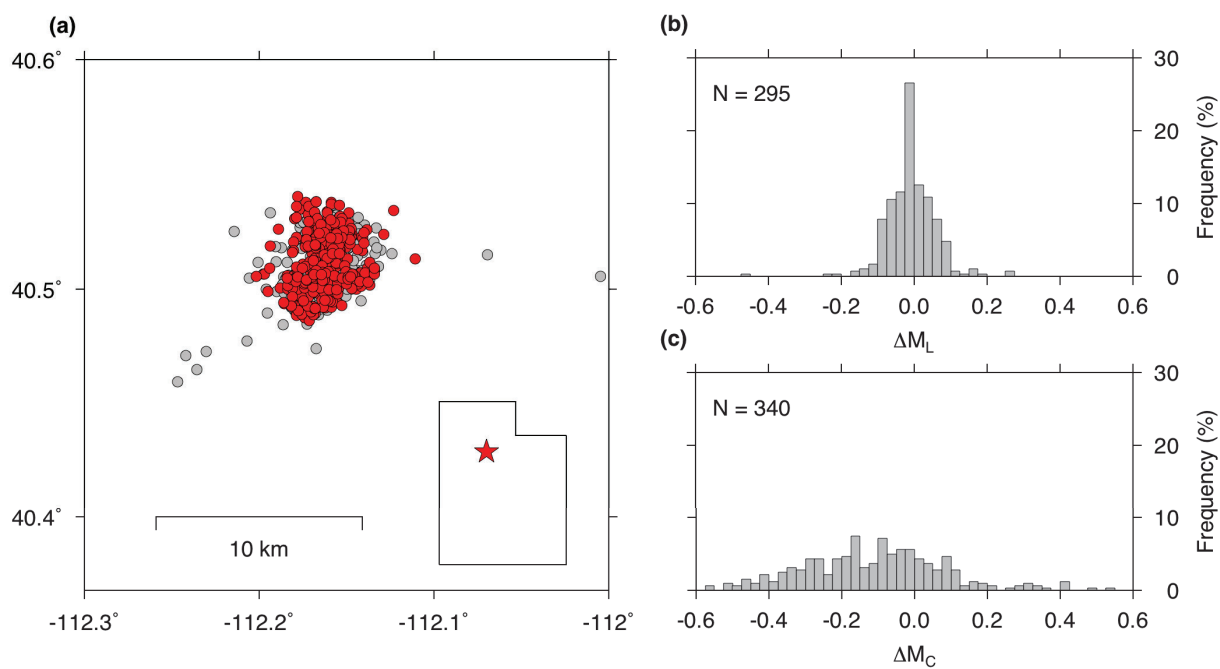


Figure 14. (a) Map of Region P with explosions plotted to reflect their epicenters before (gray) and after (red) reanalysis. *The location of Region P within the Utah region is indicated by the red star on the inset image of the state.* Changes in (b) M_L and (c) M_C during reanalysis.

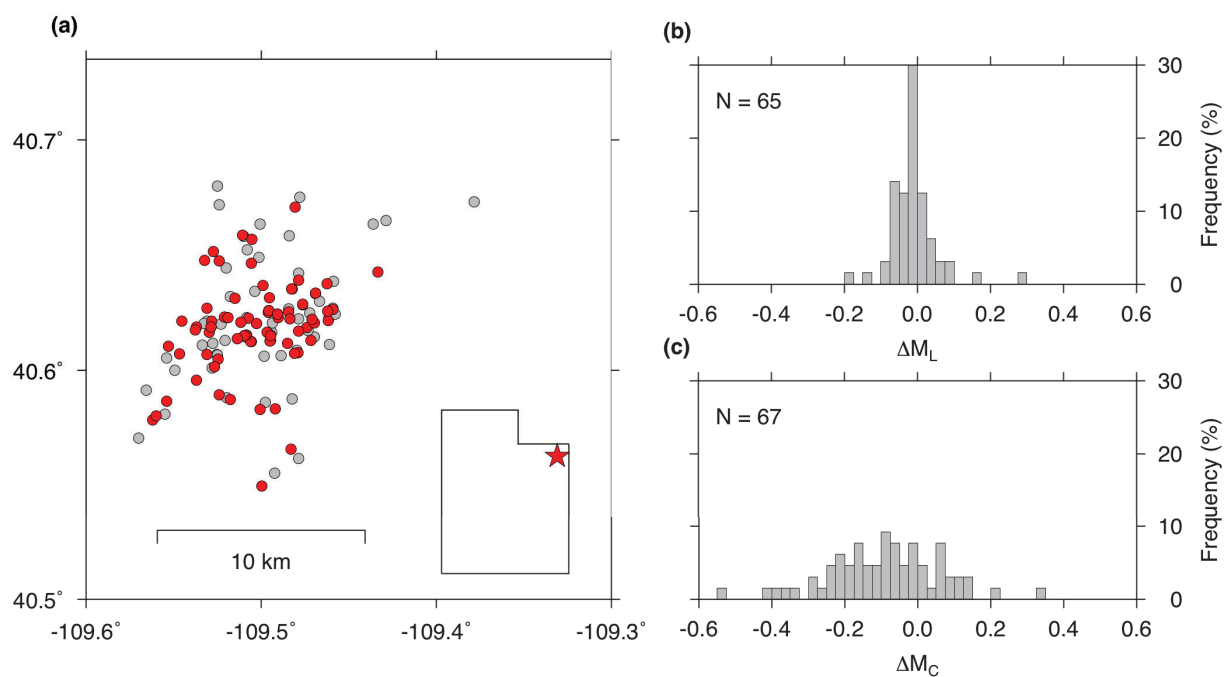


Figure 15. (a) Map of Region R with explosions plotted to reflect their epicenters before (gray) and after (red) reanalysis. The location of Region R within the Utah region is indicated by the red star on the inset image of the state. Changes in (b) M_L and (c) M_C during reanalysis.

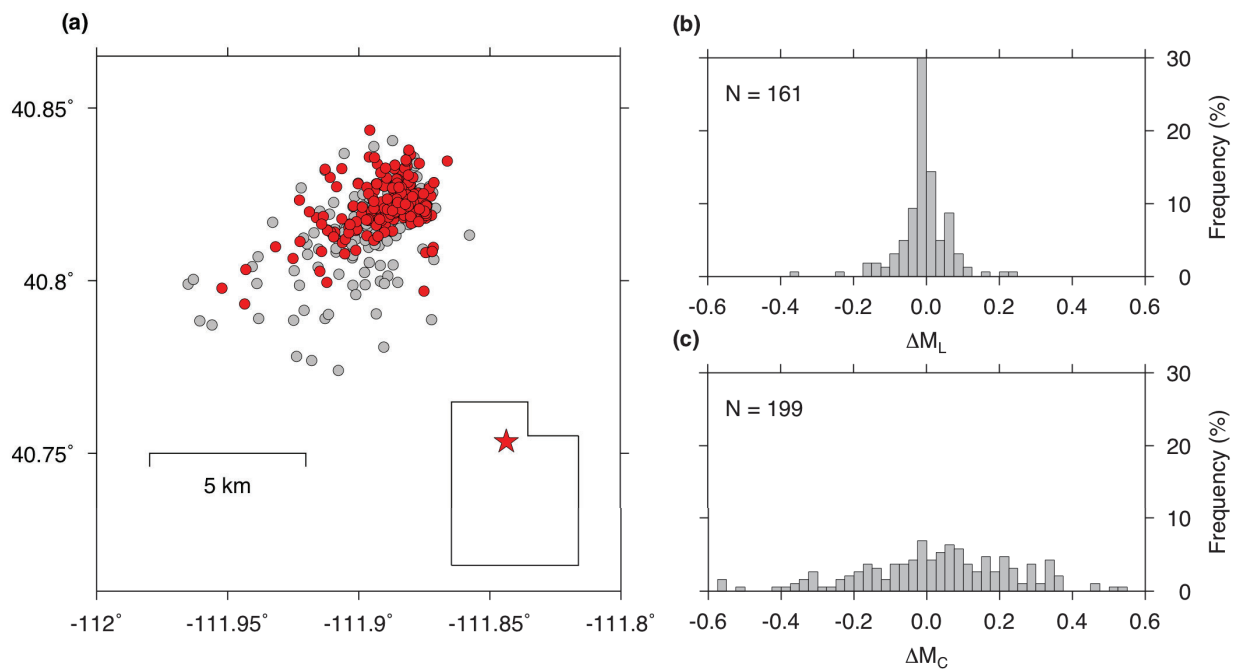


Figure 16. (a) Map of Region T with explosions plotted to reflect their epicenters before (gray) and after (red) reanalysis. The location of Region T within the Utah region is indicated by the red star on the inset image of the state. Changes in (b) M_L and (c) M_C during reanalysis.

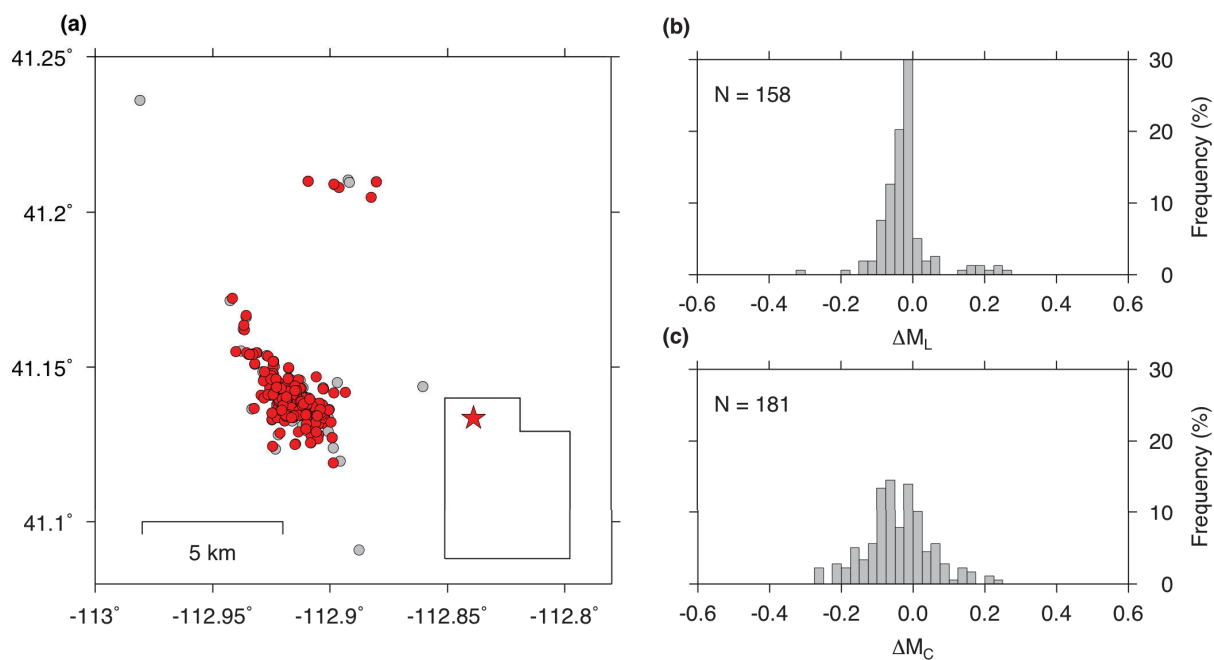


Figure 17. (a) Map of Region W with explosions plotted to reflect their epicenters before (gray) and after (red) reanalysis. *The location of Region W within the Utah region is indicated by the red star on the inset image of the state.* Changes in **(b)** M_L and **(c)** M_C during reanalysis.

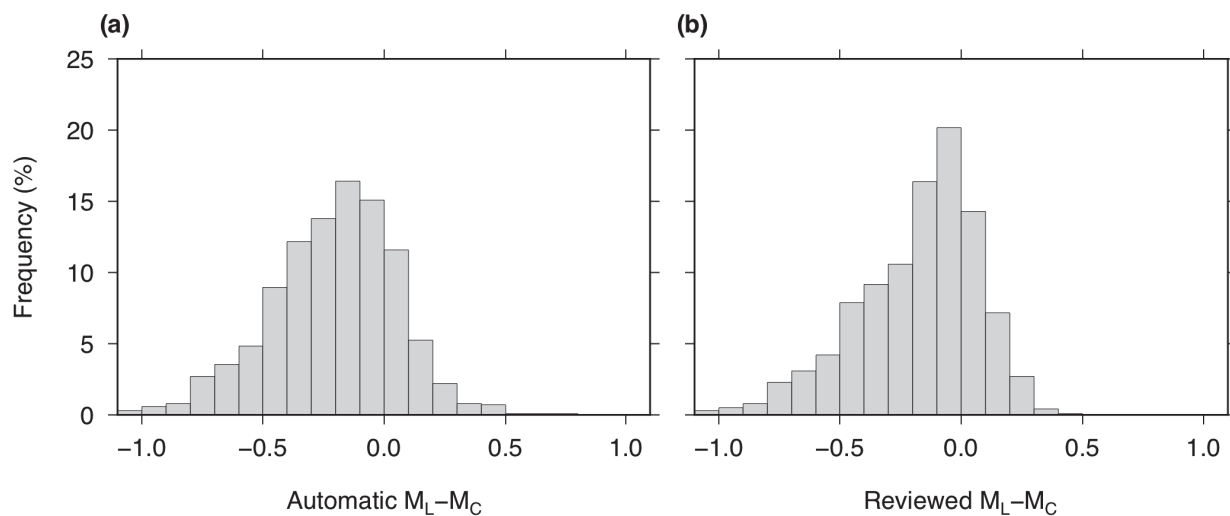


Figure 18. Histograms of $M_L - M_C$ values for the same 1,007 explosions in the Utah region (a) before reanalysis and (b) after reanalysis.

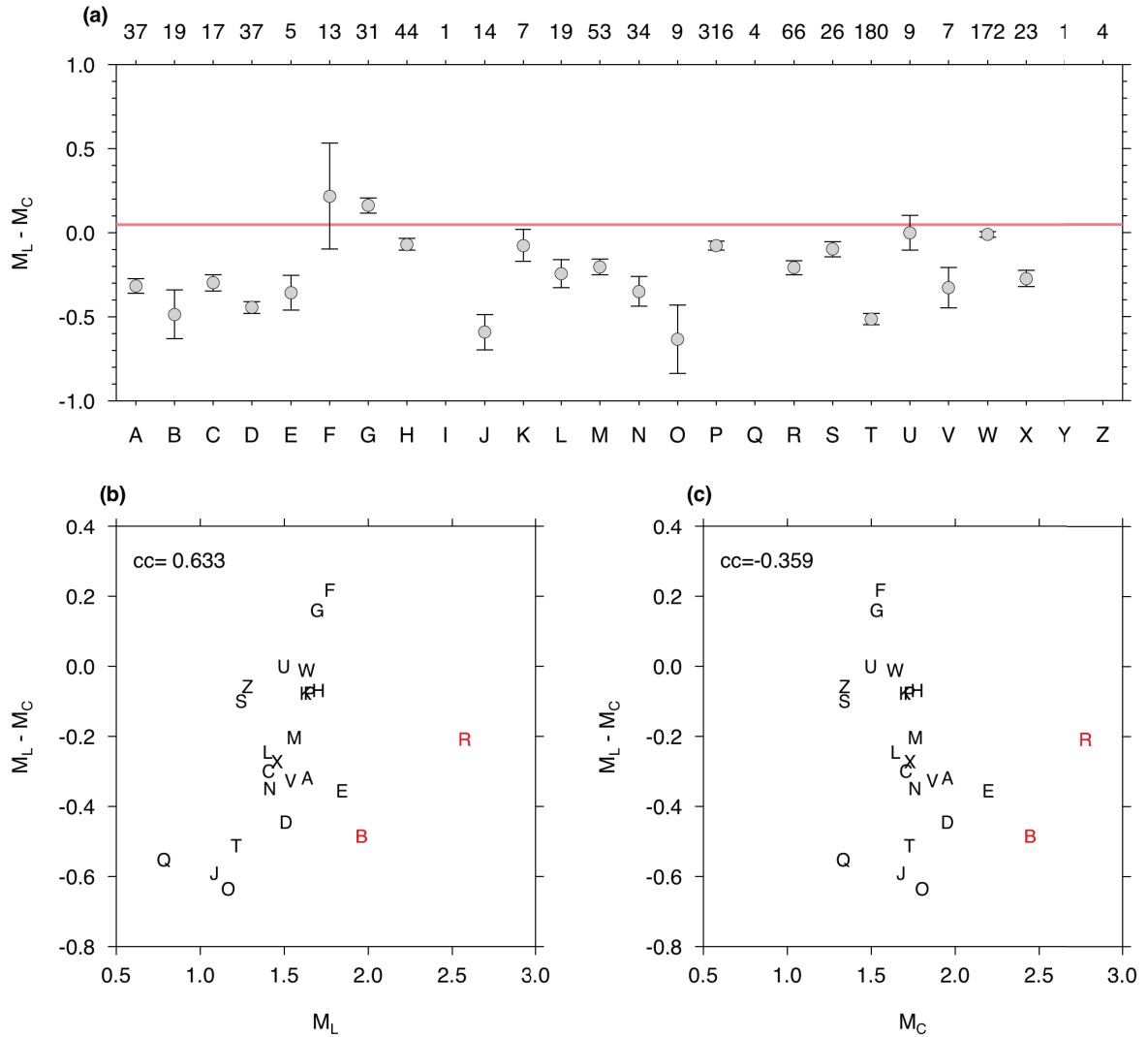


Figure 19. (a) Average $M_L - M_C$ values for analyst reviewed explosions in the Utah region. The letters across the bottom correspond to boxed regions in Figure 10, and the numbers across the top indicate the number of explosions in each region. The error bars represent 95% confidence intervals. The red line is the 95% confidence interval for naturally occurring earthquakes in the Utah region. Average $M_L - M_C$ plotted against average (b) M_L and (c) M_C for the 22 regions with $N > 4$ observations. In both cases, regions R and B (red font) were omitted from the correlation coefficient (cc) calculation.

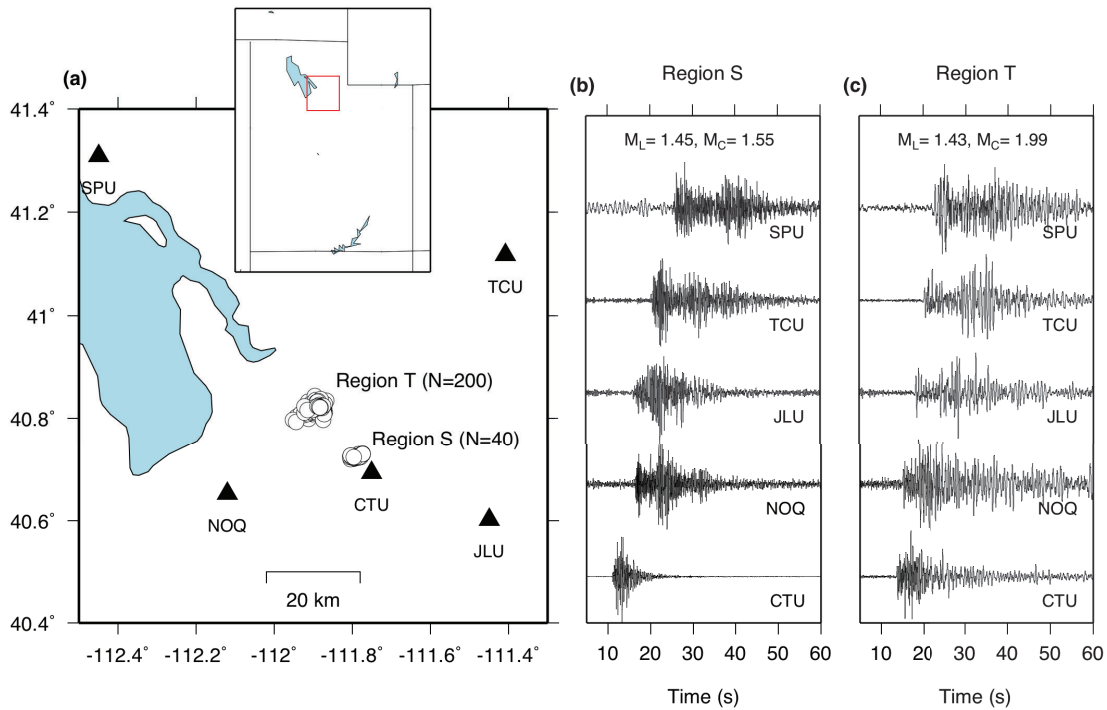


Figure 20. (a) Comparison of typical explosion waveforms from two nearby quarries in north central Utah. The (b) Region S explosion occurred on 2012/11/03 13:49:23 (UTC) and the (c) Region T explosion occurred on 2012/11/27 14:55:04 (UTC). Events from Region T generally have anomalously large M_C values, while those from Region S have more earthquake-like M_L - M_C values. All traces are proportional to vertical-component ground velocity in a 1–10 Hz passband.

Table 1. Reclassification of Explosion Clusters in the Utah Region.

Source Region	No. of Reviewed Events	EQs kept as EQs (TQ)	EQs changed to EXs (FQ)	EXs kept as EXs (TX)	EXs changed to EQs (FX)	Sensitivity TQ/(TQ+FX)	Specificity TX/(FQ+TX)	Other* (O)	EXs with M _L & M _C
A	81	39	20	21	1	0.98	0.51	0	37
B	61	40	6	15	0	1.00	0.71	0	19
C	92	50	1	16	18	0.74	0.94	7	17
D	130	23	4	96	0	1.00	0.96	7	37
E	19	0	0	19	0	1.00	1.00	0	5
F	79	17	0	61	0	1.00	1.00	1	13
G	74	0	3	71	0	1.00	0.96	0	31
H	90	32	1	50	6	0.84	0.98	1	44
I	18	1	2	13	0	1.00	0.87	2	1
J	33	15	0	18	0	1.00	1.00	0	14
K	13	4	0	9	0	1.00	1.00	0	7
L	31	1	0	30	0	1.00	1.00	0	19
M	80	3	0	70	0	1.00	1.00	7	53
N	85	41	0	41	0	1.00	1.00	3	34
O	14	1	0	10	3	0.25	1.00	0	9
P	409	22	1	340	6	0.79	1.00	40	316
Q	144	95	3	41	2	0.98	0.93	3	4
R	188	3	0	67	0	1.00	1.00	118	66
S	41	0	0	40	0	1.00	1.00	1	26
T	209	7	0	200	0	1.00	1.00	2	180
U	27	4	3	19	0	1.00	0.86	1	9
V	23	8	0	14	0	1.00	1.00	1	7
W	183	0	8	175	0	1.00	0.96	0	172
X	50	17	0	33	0	1.00	1.00	0	23
Y	12	0	1	10	0	1.00	0.91	1	1
Z	13	0	3	10	0	1.00	0.77	0	4
Totals	2199	423	56	1489	36	0.92	0.96	195	1148

*This category includes regional, teleseismic, and unknown events, either correctly or incorrectly initially classified, in addition to duplicate events in the database, or events with data quality too poor to analyze.

8. INTRODUCTION TO M_L - M_C FOR CHEMICAL EXPLOSIONS

Underground nuclear explosions can be detected, located, identified, and characterized using seismic data (e.g., Douglas, 2013). Source constraints derived from seismic analysis can be important for verifying nuclear test-ban treaties such as the Comprehensive Nuclear-Test-Ban Treaty (e.g., Bowers and Selby, 2009). For large seismic events ($M > 4$) well-recorded at regional-to-teleseismic distances (> 150 km) there are several useful seismic methods for identifying explosions from the much larger population of earthquakes. Nuclear explosions tend to have relatively high body wave magnitudes (m_b) compared to surface wave magnitudes (M_S) (e.g., Stevens and Day, 1985), relatively high ratios of high-frequency P/S energy (e.g., Walter *et al.*, 1995; Kim and Richards, 2007), and relatively large isotropic moments (e.g., Ford *et al.*, 2009; Alvizuri and Tape, 2018; Chiang *et al.*, 2018).

Smaller explosions ($M < 3$) that are well-recorded only at local distances (< 150 km) can be more difficult to identify. m_b and M_S are classically defined at teleseismic distances, and although they have been extended to regional distances (e.g., Russell, 2006; Bonner *et al.*, 2006), it is challenging to extend their viability to local distances. High-frequency P/S amplitude ratios tend to show higher variability at local distances compared to regional distances (O'Rourke *et al.*, 2016a; Pyle and Walter, 2019), presumably because of stronger path effects. And it is difficult to infer the moment tensors of seismic events with magnitude below 3–3.5 because of low signal-to-noise ratios at periods (> 10 s) for which acceptable Green's functions can easily be synthesized (e.g., Herrmann *et al.*, 2011). Because of these factors, there is strong interest in developing new or improved seismic methods of low-yield discrimination. For example,

it has been debated whether or not the Democratic People's Republic of Korea detonated a low-yield (~ 3 tons TNT equivalent) nuclear explosion on 12 May 2010 (e.g., Zhang and Wen, 2015; Kim *et al.*, 2017).

Recent work has found that comparisons of the two most commonly assigned magnitudes for small seismic events, local magnitude (M_L) and coda duration magnitude (M_C), may be useful for discriminating explosions from earthquakes at local distances (Koper *et al.*, 2016). Extremely shallow seismic events tend to have relatively large M_C compared to M_L because of anomalously strong or long coda waves, and buried explosions are generally much shallower than naturally occurring tectonic earthquakes. Hence, at local distances $M_L:M_C$ comparisons may be useful in identifying especially shallow seismic events that deserve detailed analysis as potential explosions, similar to how $m_b:M_S$ comparisons are used as an explosion screening tool at regional-to-teleseismic distances (Selby *et al.*, 2012; Ford and Walter, 2014).

Earlier studies observed enhanced M_C for mining induced earthquakes in Utah, mine blasts in Utah, very shallow earthquakes induced by wastewater injection in the Oklahoma region, and very shallow tectonic earthquakes in Utah, the region around Yellowstone National Park, and Italy (Koper *et al.*, 2016; Holt *et al.*, 2019b; Voyles *et al.*, 2020). However, these source types have important differences from underground nuclear explosions. Mine blasts are typically composed of a series of smaller explosions distributed across space and time that generate waveforms systematically different than those generated by single-fired explosions (e.g., Kim *et al.*, 1993; Stump *et al.*, 2002). And earthquakes tend to be well-described by double-couple source models, whereas single-fired explosions are better described by a combination of isotropic and

compensated linear vector dipole source models (e.g., Alvizuri *et al.*, 2018).

In this study, we assign M_L and M_C to events occurring during three seismic experiments that recorded buried single-fired explosions as well as nearby tectonic earthquakes: the 2009–2010 Bighorn Arch Seismic Experiment (BASE) in the Bighorn Mountains of northern Wyoming (O'Rourke *et al.*, 2014; Worthington *et al.*, 2016), the 2014–2016 imaging Magma Under St. Helens (iMUSH) experiment near Mount St. Helens (Kiser *et al.*, 2016; Ulberg *et al.*, 2020), and Phase I of the Source Physics Experiment (SPE), which occurred at the Nevada National Security Site (NNSS) during 2011–2016 (Snelson *et al.*, 2013; Pyle and Walter, 2019). For each experiment, we compare M_L and M_C values of the explosions to those of nearby earthquakes and quantify the ability of M_L - M_C to separate the two source populations. Because buried, single-fired chemical explosions are good seismic analogs for underground nuclear explosions (Stump *et al.*, 1999), our results are directly relevant to assessing whether M_L - M_C is likely to be effective at discriminating small nuclear explosions from earthquakes at local distances.

9. METHODS, ASSUMPTIONS, AND PROCEDURES FOR M_L - M_C FOR CHEMICAL EXPLOSIONS

Our procedure for assigning M_L follows the approach currently used by the University of Utah Seismograph Stations (UUSS; Pechmann *et al.*, 2007), which is based on the original formulation by Richter (1958). We measure amplitudes from the horizontal components of high-gain, broadband channels (BH and HH) that have been processed to have the instrument response of a Wood-Anderson seismometer, which has peak sensitivity at a period near 0.8 s (IASPEI, 2013). The amplitude on a single

component is defined as one-half of the largest peak-to-peak value in a 30-s window beginning at the theoretical S wave arrival time. The station amplitude is defined as the square root of the product of the two horizontal component amplitudes. A station amplitude is accepted for use in assigning a station M_L if it is larger than twice the value of the noise amplitude, which is defined as the average absolute value in a 10-s window beginning 12 s before the theoretical P wave arrival time. We define the station M_L as the $\log_{10}$ of the station amplitude plus a distance correction. The distance corrections vary from 1.5 at 10 km to 4.9 at 600 km (Richter, 1958). An event M_L is defined by taking the median of three or more station M_L values. We do not use station corrections.

Our procedure for assigning M_C is related to the approach currently used by UUSS (Pechmann *et al.*, 2006), which is based on earlier work that used M_d or M_τ to indicate duration magnitude (Lee *et al.*, 1972; Real and Teng, 1973; Herrmann, 1975). We measure durations from the vertical components of high-gain channels (BH, EH, HH, and SH) that have been instrument-corrected to ground velocity in units of m/s and filtered with a 4-pole Butterworth bandpass between 1 and 10 Hz. We take the envelope of the seismogram (defined as $(x^2(t) + H^2[(x(t))])^{1/2}$ where H indicates the Hilbert transform and $x(t)$ is the original seismogram) to create a strictly positive function representing instantaneous amplitude. We take the $\log_{10}$ of the envelope and fit a least-squares line to the data in a post-S time window. The beginning of the post-S time window is defined as $t_1 + 0.25(t_2 - t_1)$ where t_1 is the time of the maximum amplitude in a 30-s window starting at the theoretical S arrival time (t_S), and t_2 is the time at which the amplitude drops below twice the pre-P noise level, which is defined as the average value in a 10-s window starting 12 s before the theoretical P wave arrival time (t_P). The end of the post-S time

window is defined as t_2 . The station duration (τ) is defined as the time, in units of seconds, when the best-fitting line from the post-S time window falls below a value of 1.724×10^{-8} m/s (t_3) minus t_P (Figure 21). Defining τ relative to a fixed cut-off value, instead of relative to the pre-P noise level, increases consistency during swarm sequences when the P-wave of an event often arrives during the coda of a previous event. It also mitigates the influence of diurnal changes in ambient seismic noise. The particular cut-off value used here was selected in part to make M_C values consistent with M_L values in the Utah region. A station duration is accepted for use in assigning a station M_C if the sample correlation coefficient of the line fit in the post-S window is less than -0.2, in which case the station M_C is defined using the UUSS formula for seismic events in the Utah region,

$$M_C = -2.25 + 2.32\log_{10}[\tau] + 0.0023\Delta \quad (9)$$

where Δ is the source-receiver distance in kilometers. An event M_C is defined by taking the median of three or more station M_C values. No station corrections are used.

These definitions of M_L and M_C are optimized for the Utah region and since we do not attempt to recalibrate the magnitude scales for the other regions studied here, we also consider alternate magnitude scale definitions to test the robustness and transportability of our results, as discussed below.

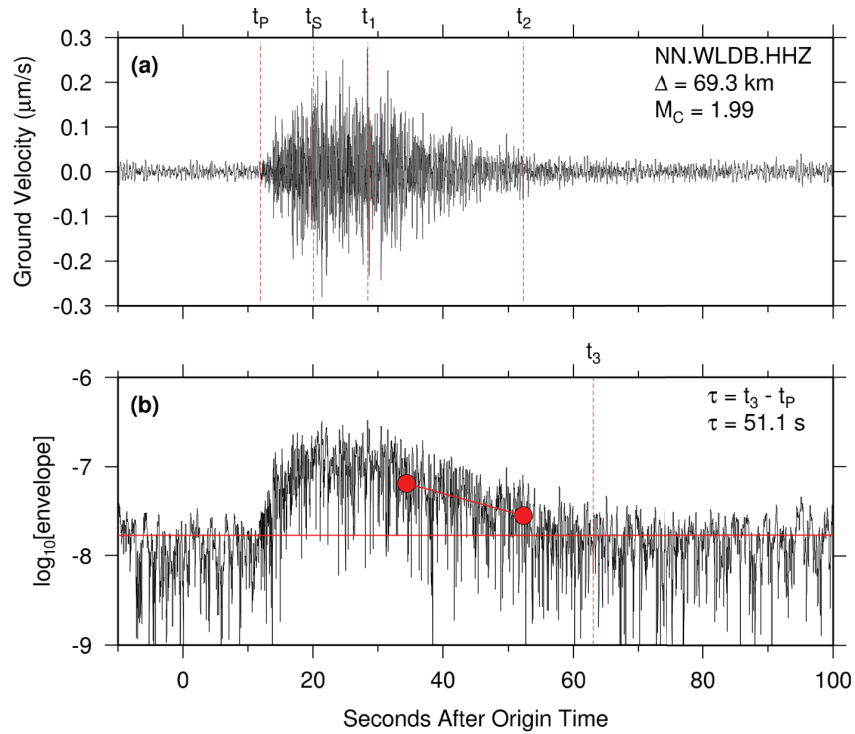


Figure 21. Example coda duration measurement. **(a)** Ground velocity from the SPE-6 explosion filtered between 1 and 10 Hz. The dashed red lines indicate the theoretical P arrival time (t_P), the theoretical S arrival time (t_S), the time of maximum amplitude in the S time window (t_1), and the time at which the signal reaches twice the pre-event noise level (t_2). **(b)** The $\log_{10}$ of the envelope of the ground velocity record in m/s. The horizontal red line indicates the cut-off level and the sloping red line between the two circles shows the best-fitting line to the coda (correlation coefficient of -0.35). The dashed red line indicates the time of intersection between the two (extrapolated) solid red lines (t_3). The duration, τ , is given by $t_3 - t_P$.

10. RESULTS AND DISCUSSION FOR M_L - M_C FOR CHEMICAL EXPLOSIONS

10.1 Analysis of Data from the Bighorn Experiment

The Bighorn Arch Seismic Experiment (BASE) was a two-year deployment of broadband and short-period seismometers in northern Wyoming and southern Montana (Figure 22; O'Rourke *et al.*, 2014; Yeck *et al.*, 2014; Worthington *et al.*, 2016). BASE included an active-source component and was sited in a seismically active region, making it suitable for studies of small-magnitude source discrimination. A large number of blasts from coal mining operations in the nearby Powder River Basin were also recorded during BASE, providing a third source type for local-distance discrimination studies. O'Rourke *et al.* (2016a) used BASE data to test P/S amplitude ratio discrimination, O'Rourke and Baker (2017) used BASE data to develop a spectrogram-based method of R_g detection, and Kintner *et al.* (2020) used BASE data to test the ability of R_g/S_g amplitude ratios to act as a depth discriminant.

Here we evaluate the efficacy of M_L - M_C as a source discriminant using local-distance waveforms of seismic sources cataloged in O'Rourke *et al.* (2016a): 22 local earthquakes, 24 borehole shots, and 37 mine blasts (Figure 22). The earthquakes were detected, located, and characterized using BASE data (O'Rourke *et al.*, 2016b). The depths vary between 6.1 and 39.0 km and the magnitudes (M_L) vary between 0.44 and 2.42. The borehole shots were all single-fired at shallow depths with charge size varying from 113 to 907 kg. Detailed information about the mine blasts is lacking, but they were most likely delay-fired blasts at or near the surface with total charge sizes on the order of

tens of thousands of kilograms (O'Rourke *et al.*, 2016a).

For each of the 83 sources, we downloaded all available seismic data from stations within 150 km, with the exception of strong-motion channels (channels beginning with HN and EN) and data from the Texan 4.5 Hz geophones (channel EHZ with station code ZI). In total, we collected data for 282 high-gain stations from 11 permanent or temporary regional seismic networks (Figure 22). Using the procedures described previously, we were able to assign both M_L and M_C to 14 of 22 earthquakes, 19 of 24 borehole shots, and 37 of 37 mine blasts (Figure 23). The median number of stations used in assigning M_L/M_C values was 9/57 for earthquakes, 10/95 for borehole shots, and 23/52 for mine blasts. More stations were used to assign M_C values because of the relatively large number of short-period, vertical component sensors deployed during BASE. Our M_L values tracked the catalog M_L values for the earthquakes very well, with a correlation coefficient of 0.98 and a mean difference of 0.04. There were no catalog M_L values for the borehole shots or mine blasts, and no catalog M_C values for any of the sources. Our M_L and M_C values were positively correlated for all three source types with correlation coefficients of 0.97 for earthquakes, 0.88 for borehole shots, and 0.97 for mine blasts.

The mine blasts were uniformly bigger than the borehole shots, however the M_L - M_C distributions were very similar with means of -0.483 ± 0.066 (borehole) and -0.492 ± 0.056 (mine blasts), where the quoted uncertainties represent $\sim 95\%$ confidence intervals for the population means. The $\sim 95\%$ confidence intervals are defined as plus or minus twice the standard error, not the larger standard deviation, and we maintain this convention for the remainder of the study. Combining the explosions into a single

population gives a mean M_L-M_C of -0.489 ± 0.044 . The earthquake M_L-M_C distribution was significantly more positive than the explosion distributions with a mean of -0.171 ± 0.102 . The separation between the explosion and earthquake populations can be quantified with the Hellinger distance (H) (e.g., Gibbs and Su, 2002), a general measure of similarity between two discrete probability distributions, p_i and q_i , defined as

$$H = \frac{1}{\sqrt{2}} \left[\sum_{i=1}^n (\sqrt{p_i} - \sqrt{q_i})^2 \right]^{\frac{1}{2}} \quad (10)$$

where n is the number of probability bins. It varies from 0 for identical distributions to 1 for non-overlapping distributions. Using a bin size equal to the precision of our magnitude estimates (0.01), gives an H of 0.96 between the earthquake and borehole M_L-M_C distributions. This value is biased high because at this scale there are many empty bins in between non-empty bins. If we instead approximate the two distributions as continuous and Gaussian, and perform the integration of the corresponding Gaussian functions with the trapezoid rule in small step sizes from $(\mu - 3\sigma)_{\text{explosion}}$ to $(\mu + 3\sigma)_{\text{earthquake}}$ (-0.91 to 0.41), we find $H=0.60$. We use the second approach for the remainder of the study.

The separation between populations can also be quantified using concepts from binary classification theory (James et al., 2013), which is being increasingly used in seismology because of the growth in machine learning applications (Bergen et al., 2019; Kong et al., 2019). We define a cut-off M_L-M_C value, M_{cut} , such that sources with $M_L-M_C < M_{\text{cut}}$ are classified as explosions, otherwise they are classified as earthquakes. As M_{cut} is systematically varied, in this case from -1.5 to 0.5 in steps of 0.01, the false positive rate (FPR) and true positive rate (TPR) vary from 0.0 to 1.0, tracing out a receiver operating characteristic (ROC) curve (Figure 24). Here the TPR is the number of explosions with

$M_L - M_C < M_{\text{cut}}$ divided by the total number of explosions, and the FPR is the number of earthquakes with $M_L - M_C < M_{\text{cut}}$ divided by the total number of earthquakes. The point on the ROC closest to the ideal classifier (TPR=1, FPR=0) gives the optimal value of M_{cut} . More importantly, the area under the ROC curve (AUC) is a measure of how similar the two populations are. It varies from 0.5 for a random classifier to 1.0 for an ideal classifier. We find AUC=0.92 when comparing the earthquake and borehole $M_L - M_C$ distributions.

Finally, we test the robustness of the $M_L - M_C$ separation between earthquakes and borehole explosions by considering alternate definitions of M_L and M_C . For a second M_L definition, we use the IASPEI (2013) formula

$$M_L = \log_{10}[A] + 1.11\log_{10}[\Delta] + 0.00189\Delta - 2.09 \quad (11)$$

where A is amplitude in nm and Δ is distance in km. For a second M_C definition, we use the UUS formula for seismic events in the Yellowstone region,

$$M_C = -2.60 + 2.44\log_{10}[\tau] + 0.0040\Delta \quad (12)$$

where τ is duration in seconds and Δ is distance in km. We measure A and τ in the same manner as before, and again use the median of three or more station magnitude estimates to define an event magnitude. Considering the four possibilities resulting from combining the two M_L definitions with the two M_C definitions, we find Hellinger distances of 0.49–0.60 and AUC values of 0.86–0.92, indicating that the clear distinction between earthquake and explosion $M_L - M_C$ distributions in this region is a robust result.

10.2 Analysis of Data from the iMUSH PASSCAL Experiment near Mount St. Helens

The 2014–2016 iMUSH experiment was a collaborative project aiming to image

the structure of the crust and upper mantle magma plumbing system underlying Mount St. Helens. The active-source component of iMUSH consisted of 23 borehole explosions (Figure 25) with charge weights of 450–900 kg that were detonated 24 July 2014 – 1 August 2014 and recorded by thousands of vertical component 4.5 and 10 Hz geophones (Kiser *et al.*, 2019). The shots were also recorded by 71 broadband stations that were part of iMUSH (Mann *et al.*, 2019; Ulberg *et al.*, 2020), as well as an additional ~190 broadband and short-period seismometers—from other, mostly permanent, seismic networks—that were within 150 km of the source region (Figure 25). We did not use waveforms from the vertical-component geophones deployed during the 10-day active source experiment because they provide few opportunities for comparison of earthquakes and explosions with similar magnitudes (Hansen and Schmandt, 2015). The explosions were assigned magnitudes of 0.9–2.3 by the Pacific Northwest Seismic Network (PNSN). The PNSN also located 91 crustal earthquakes with magnitudes of at least 1.5 in the explosion source region between 28 November 2014 and 22 August 2016 (Figure 25). The earthquake depths varied from -1.4 to 23.2 km relative to sea level, with a median value of 11.2 km. Wang and Schmandt (2019) used this dataset to evaluate P/S amplitude ratios as a source discriminant at local distances.

We were able to assign M_C to 22 of the 23 borehole explosions. The number of stations used in the assignments varied from 46 to 127 with a median of 90, and the M_C values varied from 1.09 to 2.22 with a median of 1.47. We assigned M_L to all 23 explosions. The number of stations varied from 22 to 82 with a median of 48, and the M_L values varied from 1.03 to 2.23 with a median of 1.57. These values were similar to PNSN catalog M_L values with a mean difference of -0.10 and a correlation coefficient of

0.81. Our explosion M_C and M_L values were strongly correlated, with a correlation coefficient of 0.89 (Figure 26). The mean of the M_L - M_C differences was 0.065 ± 0.068 .

We were able to assign M_C to all 91 of the crustal earthquakes. The number of stations used in the assignments varied from 5 to 147 with a median of 95, and the M_C values varied from 1.00 to 2.66 with a median of 1.54. We assigned M_L to 90 of 91 crustal earthquakes. The number of stations varied from 3 to 97 with a median of 51, and the M_L values varied from 1.09 to 3.42 with a median of 1.92. These values were similar to PNSN catalog M_L values with a mean difference of -0.09 and a correlation coefficient of 0.94. Our earthquake M_C and M_L values were strongly correlated, with a correlation coefficient of 0.91 (Figure 26). The mean of the M_L - M_C differences was 0.364 ± 0.042 , about 0.3 units more positive than the corresponding explosion value. The Hellinger distance between the earthquake and explosion distributions was 0.55 and the AUC value was 0.90. The population separation remained robust with respect to M_L and M_C definitions, with H varying from 0.42 to 0.55, and AUC varying from 0.84 to 0.90.

Because of the extraordinarily high density of seismometers available during iMUSH, we can evaluate the effect of source-receiver distance on the ability of M_L - M_C to separate source populations. We consider four different distance ranges, 10–150 km, 10–50 km, 50–100 km, and 100–150 km, and compare the separation to the base case of 0–150 km. We exclude stations closer than 10 km because at these distances the hypocentral distance is often significantly different than the epicentral distance and amplitudes can have high variance. For each distance range we recalculate event magnitudes using only those station magnitudes that meet the distance criterion. For distance ranges of 10–150 km and 10–50 km we find little difference with respect to the

base case, with Hellinger distances of 0.58 and 0.57, respectively, compared to the base value of 0.55; however, Hellinger distance decreases to 0.34 for 50–100 km, and to 0.40 for 100–150 km (Figure 27). At the two farther distance ranges the variances of the explosion M_L - M_C distributions become large, due in part to a lower number of stations, and the means of all four M_L - M_C distributions increase significantly. The shift in mean M_L - M_C values with distance could probably be resolved by developing calibrated magnitude scales for this region, however it is unclear if the Hellinger distances would increase. It could be that M_L - M_C based source discrimination is inherently more effective at the smallest distances (0–50 km).

10.3 Analysis of Data from Phase I of the Source Physics Experiment

The Source Physics Experiment (SPE) is an ongoing project that aims to improve capabilities for seismic monitoring of nuclear weapon tests by recording and modeling data from a series of chemical explosion analogs to historic nuclear explosions (Snelson *et al.*, 2013). Here we use data from Phase I of SPE, which consisted of 6 explosions at the Nevada National Security Site (NNSS) between 3 May 2011 and 12 October 2016. The single-fired explosions were detonated in the same borehole, in granite, at depths of 31.4–87.2 m with yields of 89–5025 kg TNT equivalent (Pyle and Walter, 2019). The fourth shot misfired on the first attempt (SPE-4) and the successful second attempt was named SPE-4'. We compare magnitudes from the SPE Phase I explosions to those from the Pyle and Walter (2019) catalog of 265 earthquakes that occurred near NNSS during 2000–2018 (Figure 26). The nominal depths of the earthquakes vary from 0.0 to 18.9 km, although they are poorly resolved in most cases. Magnitudes in the earthquake catalog

were assigned by various agencies and vary from 0.81 to 4.2 for M_L and from 1.07 to 4.32 for M_w . For each of the 271 seismic sources we downloaded all available seismic data from high-gain stations within 150 km. This resulted in a total of 146 stations from 10 temporary and permanent regional networks (Figure 28). We did not download geophone data from the large-N component of SPE (e.g., Mellors *et al.*, 2018).

We were able to assign M_C for each shot except SPE-1, which had waveforms that were partially corrupted by a nearly simultaneous regional earthquake. For SPE-2 through SPE-6 the number of stations used in assigning M_C were 4, 15, 8, 39, and 29. The M_C values varied from 0.98 to 2.33 and were strongly correlated with $\log_{10}[\text{yield}]$, having a correlation coefficient of 0.98 (Figure 28). The only anomaly involved an M_C of 1.53 for SPE-2, which had a yield of 997 kg, while SPE-3 had a larger M_C of 1.75 for a smaller yield of 905 kg. We were able to assign M_L for shots SPE-3, SPE-5, SPE-6, using amplitudes from 3, 28, and 20 stations, respectively. SPE-2 had a valid amplitude measurement at only 1 of 7 available broadband stations (US.TPNV), while SPE-4' was so small that it had no valid measurements from 18 available broadband stations. The three M_L values (1.38, 2.06, and 1.65) were strongly correlated with $\log_{10}[\text{yield}]$, having a correlation coefficient of 0.99 (Figure 29). The mean M_L - M_C value for the three shots assigned both magnitudes was -0.327 ± 0.058 (Figure 30).

We were able to assign M_C to 187 of the earthquakes. The number of stations used in the assignments varied from 3 to 45 with a median of 15, and our M_C values varied from 0.83 to 3.45 with a median of 2.20. There were no catalog M_C values to use for comparison. We were able to assign M_L to 149 of the earthquakes. The number of stations used in the assignments varied from 3 to 20 with a median of 8, and our M_L

values varied from 1.38 to 4.36 with a median of 2.34. Our M_L values were positively correlated with the catalog M_L values, with a correlation coefficient of 0.83, and a mean difference of only 0.01 units. For the 149 earthquakes we assigned both M_C and M_L , the two magnitudes were strongly correlated with a correlation coefficient of 0.90. The mean M_L-M_C value was 0.109 ± 0.032 , over 0.4 units larger than the corresponding value for the three explosions (Figure 21). With only three explosions the distance measurements between the explosion and earthquake M_L-M_C probability distributions are less meaningful than in the previous two cases; however, we report them here for completeness, finding $H=0.88$ and $AUC=0.99$. The high separation is maintained under the alternative M_L and M_C definitions, with H varying from 0.86 to 0.90, and AUC varying from 0.96 to 0.99. The difference in M_L-M_C population means also remains robust, varying from 0.369 to 0.431 units in the four scenarios.

10.4. Summary

A summary of M_L-M_C distributions for earthquakes and buried, single-fired explosions is presented in Figure 31. The M_L-M_C distributions for a given source type vary substantially from region to region. For instance, the mean M_L-M_C value for earthquakes varies by nearly 0.5 units, from -0.171 in BASE, to 0.109 in SPE, to 0.300 in iMUSH. This should not necessarily be surprising though, because our magnitude scales were not calibrated for any of the three study regions. Substantial effort is usually involved in designing an M_L scale that properly accounts for regional variation of amplitude with distance and site effects (e.g., Savage and Anderson, 1995; Miao and Langston, 2007; Pechmann *et al.*, 2007; Sheen *et al.*, 2018; Holt *et al.*, 2019a). Likewise, regional calibration is needed for developing a coda duration magnitude scale (e.g., Lee

et al., 1972; Pechmann *et al.*, 2006). Nevertheless, the separation of single-fired explosions and earthquakes in M_L - M_C space is robust from region to region. The separation is also independent of the precise rule used to assign M_L and M_C . This suggests that a fundamental difference in the source properties of buried, single-fired explosions and earthquakes is strongly encoded in M_L - M_C values computed at local distances (<150 km).

The source property with the biggest impact on M_L - M_C values is likely the depth since crustal earthquakes are observed to have increasingly negative M_L - M_C values as the focal depth approaches the surface (Koper *et al.*, 2016; Holt *et al.*, 2019b). Enhanced coda for several extremely shallow events in the western U.S. was also observed by Mayeda and Walter (1996), and Murphy *et al.* (2009) suggested that coda-derived source spectra could be used as a depth discriminant. Initial work simulating the high-frequency wavefield at local distances in realistic Earth models supports this interpretation. Voyles *et al.* (2019) used a 3D finite-difference method to simulate the wavefield for frequencies up to 5 Hz and distances up to 150 km. They compared synthetics for isotropic and double-couple sources at depths of 1–10 km in a suite of velocity models that contained deterministic 3D heterogeneity in the form of basins, stochastic 3D heterogeneity in the form of volumetric scatterers, and surface topography. The same explosion source modeled near the surface and at depth produced contrasting coda durations, whereas explosion and earthquake sources modeled at the same depth yielded comparable coda durations. Voyles *et al.* (2019) found 3D volumetric heterogeneity (scattering) to be the most important factor in creating synthetics that matched the character of the observations. Simple 1D reference velocity models (e.g., IASP91; Kennett and Engdahl,

1991) without topography were not able to reproduce the observations.

Source discrimination or screening based on M_L - M_C is likely comparable to methods based on R_g/S_g amplitude ratios, another metric that is known to be very sensitive to source depth for small events recorded at local distances (Ma and Motazedian, 2012; Kolaj, 2018; Tibi *et al.*, 2018a; Kintner *et al.*, 2020), but methods based on $M_L:M_C$ comparisons may be simpler to implement. R_g/S_g observations require regionally-dependent group velocity windows, and possibly frequency bands, whereas the same generic definitions of M_L and M_C —with theoretical travel times predicted by IASP91—were effective in the three regions studied here. Furthermore, R_g is known to attenuate rapidly in some regions (e.g., Myers *et al.*, 1999) and in these cases the R_g time window may become dominated by S coda. $M_L:M_C$ methods do not require phase identification, the existence of R_g , or customized velocity models for predicting body wave (P_g and S_g) arrival times.

Because M_L - M_C source discrimination is primarily a depth discriminant, it needs to be combined with other evidence or discriminants to definitively separate very shallow earthquakes from buried explosions. The most obvious partner for M_L - M_C is high-frequency P/S ratios. An excellent discriminant at regional distances, P/S ratios are relatively poorly studied with mixed results for small explosions recorded at local distances. O'Rourke *et al.* (2016a) found that single-station P/S ratios were able to distinguish between earthquake and explosion populations in Wyoming, but that discrimination failed more often at distances smaller than 50 km, while Pyle and Walter (2019) found that P/S discrimination for events in Nevada was inconsistent at individual seismic stations. Both studies observed that network averaging generally improved

discrimination performance above ~ 6 Hz. One reason for the inconsistent P/S performance is large scatter in the earthquake populations at local distances compared to regional distances, which is likely a function of both source radiation effects and path effects that are mitigated at longer distances by scattering and attenuation. Another factor is that the generation of shear waves from the explosions may be strongly azimuthally dependent (Pitarka *et al.*, 2015). M_L-M_C requires at least 3 stations, so it also takes advantage of network averaging, and is therefore less sensitive to source radiation effects than single-station P/S ratios.

There is empirical evidence that combining seismic discriminants can generate significant gains in source classification at local distances. Tibi *et al.* (2018b) combined R_g/S_g ratios with P_g/S_g ratios in a multivariate quadratic discriminant function framework, and found that the addition of R_g/S_g observations improved source misclassification by 4–14% compared to P_g/S_g ratios on their own. We expect combining M_L-M_C with P_g/S_g ratios would lead to even bigger gains because of its greater independence from P_g/S_g . M_L-M_C is completely insensitive to P_g amplitude and is sensitive to S_g amplitude in a frequency band around 1 Hz, whereas local-distance P_g/S_g ratios strongly depend on P_g and S_g amplitudes at frequencies >5 –6 Hz. It is also possible that M_L-M_C and P_g/S_g have a complementary dependence on distance, with M_L-M_C being more effective at distances <50 km and P_g/S_g being more effective at distances of 50–150 km, although more work is needed to confirm this.

We observe that the difference between local magnitude (M_L) and coda duration magnitude (M_C) effectively separates earthquakes from buried, single-fired explosions in Washington, northern Wyoming, and southern Nevada. We assigned magnitudes using

generic, uncalibrated formulas on seismic data assembled from a mix of networks and instrument types. The discrimination performance of M_L - M_C reported here could likely be improved by carefully calibrating both magnitude scales for regional wave propagation and site effects, however its success in this study implies that it would add value in the real-world case of identifying a small underground explosion occurring in an area which lacks a dense, permanent regional network. In that case, an uncalibrated pseudo-network must be created dynamically by assimilating all available nearby seismic data. It is also likely that the discrimination performance of M_L : M_C comparisons could be improved by considering functionals more complicated than M_L - M_C , such as the linear relationships between m_b and M_s that are used in screening large seismic events recorded teleseismically (e.g., Selby *et al.*, 2012; Ford and Walter, 2014).

M_L - M_C acts primarily as a local-distance depth discriminant, separating extremely shallow seismic sources (<2–3 km) from earthquakes occurring deeper in the crust. It is similar to using R_g identification (e.g., Kafka, 1990; Saikia, 1992) or R_g/S_g amplitude ratios (e.g., Zeiler and Velasco, 2009; Ma and Motazedian, 2012) as indicators of shallow depth, but it may be easier to implement since it does not rely on phase identification and seems less sensitive to the details of wave propagation in a given area. We recommend combining M_L : M_C comparisons with network averaged high-frequency P/S amplitude ratios to confidently identify underground explosions from other very shallow seismic sources, perhaps using a formalism similar to the event classification matrix method developed for combining teleseismic discriminants (Anderson *et al.*, 2007). The two metrics have complementary sensitivities and their combination could significantly enhance the classification of small seismic sources recorded at local distances.

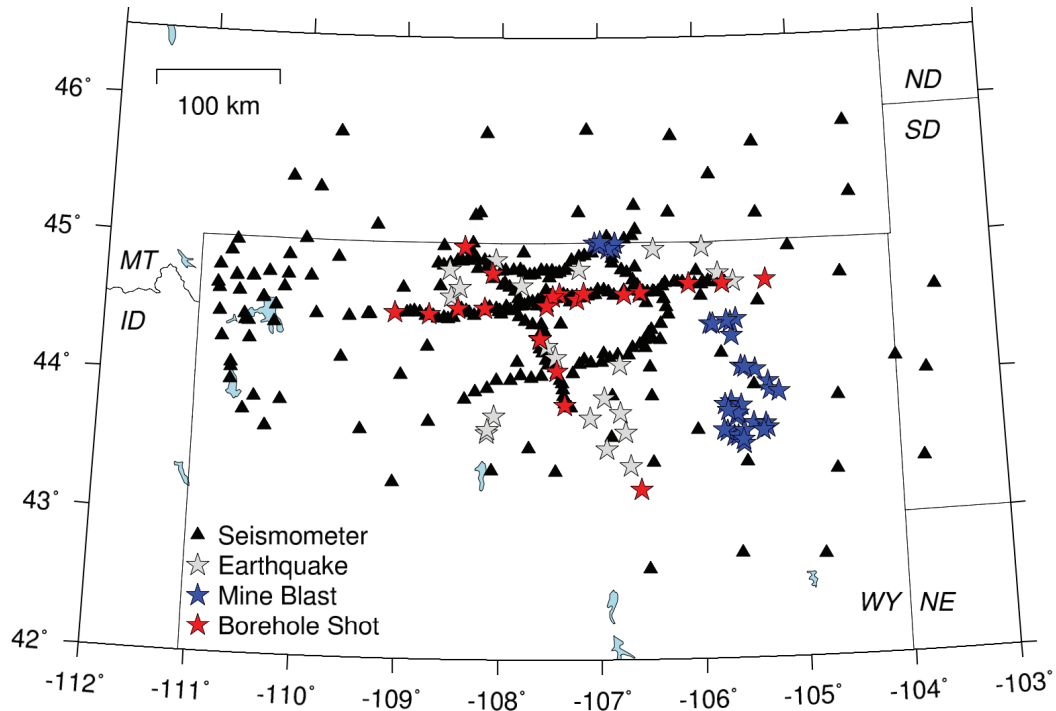


Figure 22. Locations of high-gain seismometers that were within 150 km of a local seismic source (stars) during the 2009–2010 BASE experiment. *The 288 stations come from 11 temporary and permanent seismic networks: IU (1), IW (1), MB (3), PB (6), RE (6), TA (35), US (2), WY (17), XV (38), Z2 (7), ZH (172), where the numeral after each network code indicates the number of seismometers from that network. We do not include data from ~1,000 Texan 4.5 Hz geophones deployed during BASE with the network code ZI. Locations of the seismic sources are taken from O'Rourke et al. (2016b).*

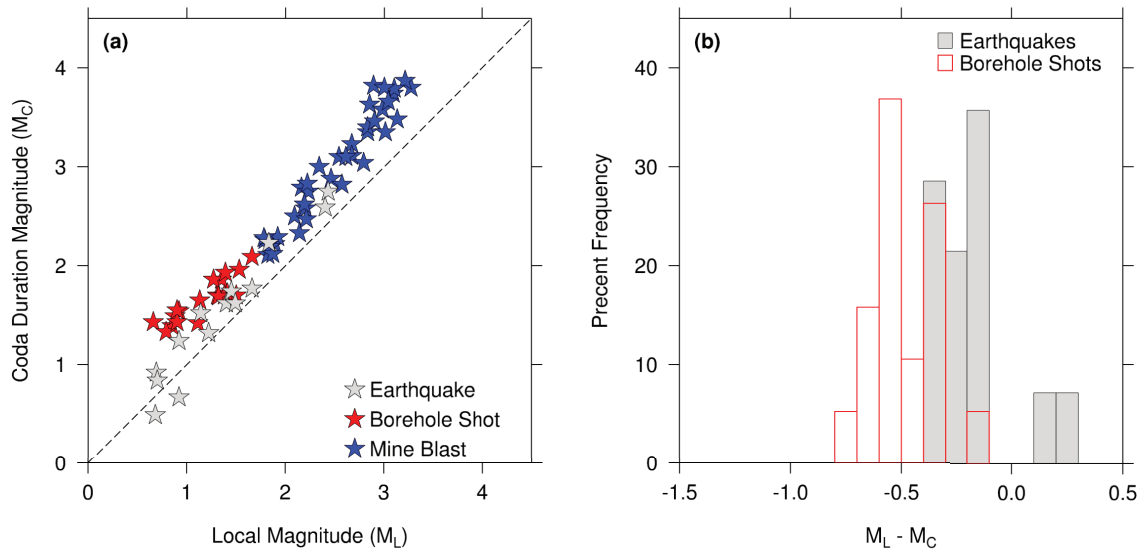


Figure 23. (a) Relationship between M_L and M_C for sources recorded during BASE. The dashed line has a slope of 1. **(b)** $M_L - M_C$ histograms in units of 0.1 for the borehole shots and earthquakes. The mine blast histogram is not shown.

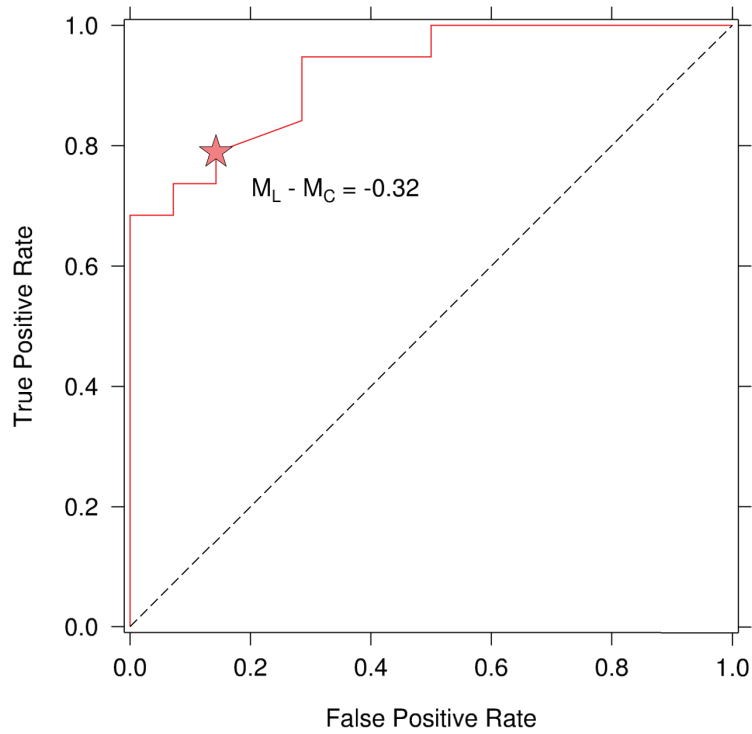


Figure 24. Receiver operating characteristic (ROC) curve (red line) for using the quantity $M_L - M_C$ as a binary classifier between borehole explosions and earthquakes recorded during BASE. The false positive rate is the probability of classifying an earthquake as an explosion, and the true positive rate is the probability of classifying an explosion as an explosion. Each point on the ROC curve corresponds to a specific $M_L - M_C$ value (M_{cut}) used for classification. The dashed line represents a random classifier, while an ideal classifier would plot in the upper left corner. The point on the ROC curve closest (in the sense of Euclidean distance) to an ideal classifier occurs at $M_L - M_C = -0.32$.

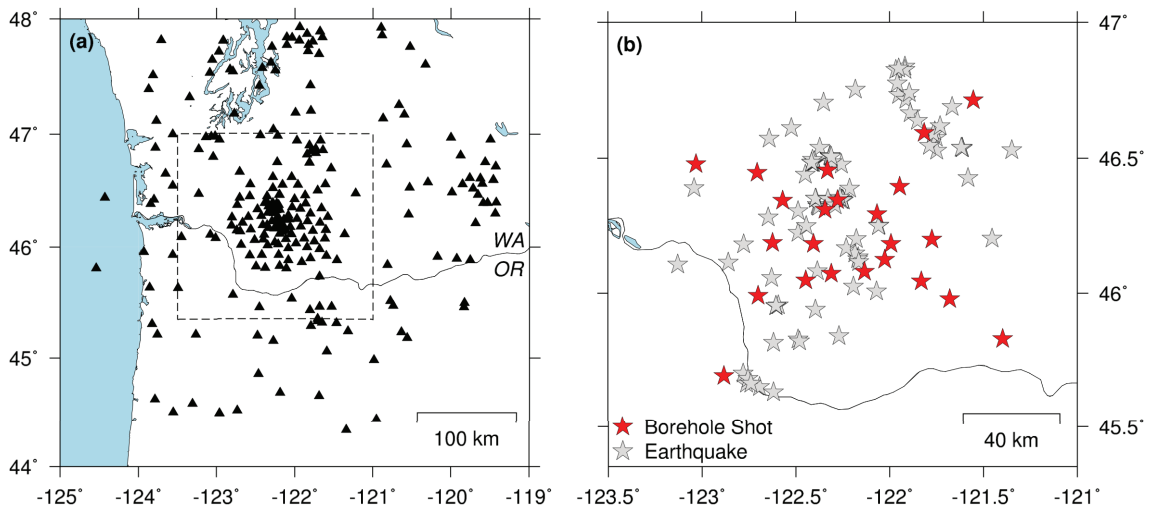


Figure 25. (a) Locations of the 262 high-gain seismometers that were within 150 km of the borehole shots or nearby earthquakes during the 2014–2016 iMUSH experiment. *The seismometers come from ten temporary and permanent seismic networks: 7D (2), CC (12), IU (1), PB (18), TA (10), US (2), UW (114), X4 (12), XD (71), YH (20), where the numeral after each network code indicates the number of seismometers from that network. The dashed box encloses the iMUSH experimental region shown in the adjacent panel. (b)* Epicenters of 23 borehole shots and 91 earthquakes recorded during iMUSH.

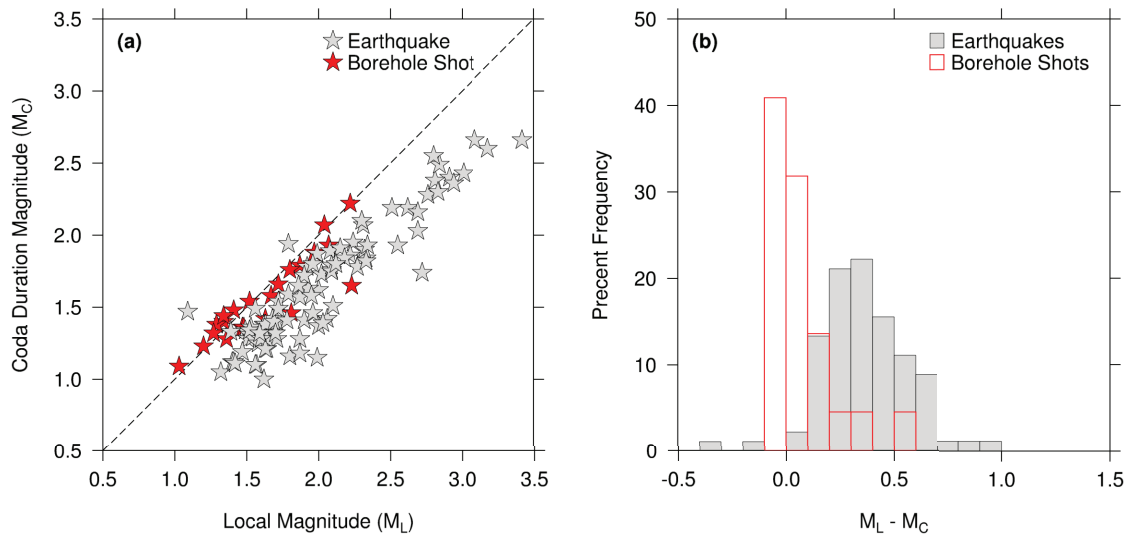


Figure 26. (a) Relationship between M_L and M_C for sources recorded during iMUSH. **(b)** $M_L - M_C$ histograms in units of 0.1 for the borehole shots (red) and earthquakes (gray).

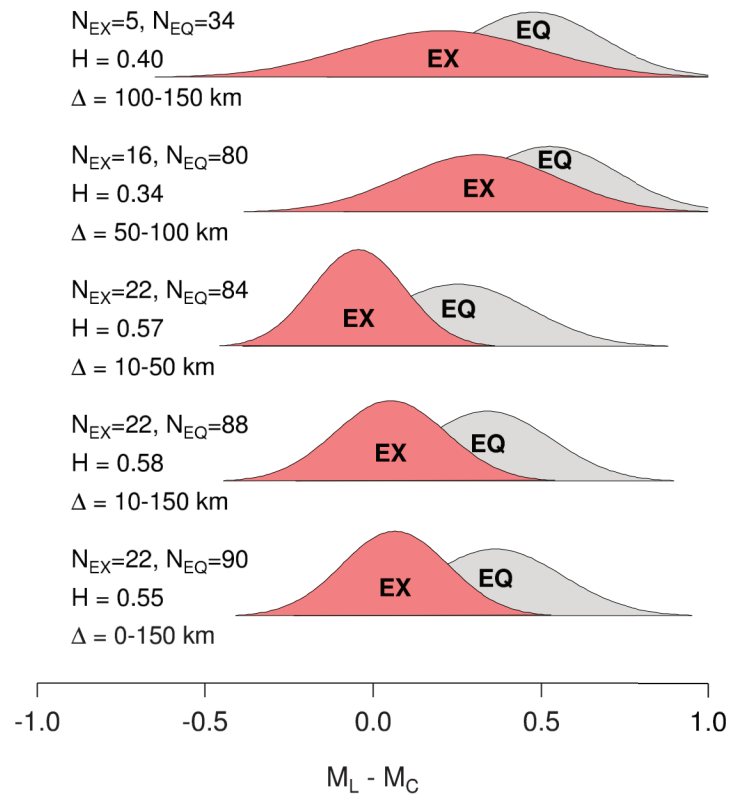


Figure 27. Separation of $M_L - M_C$ distributions for earthquakes (EQ) and explosions (EX) when both magnitudes are calculated with data from restricted distance ranges during the iMUSH experiment.

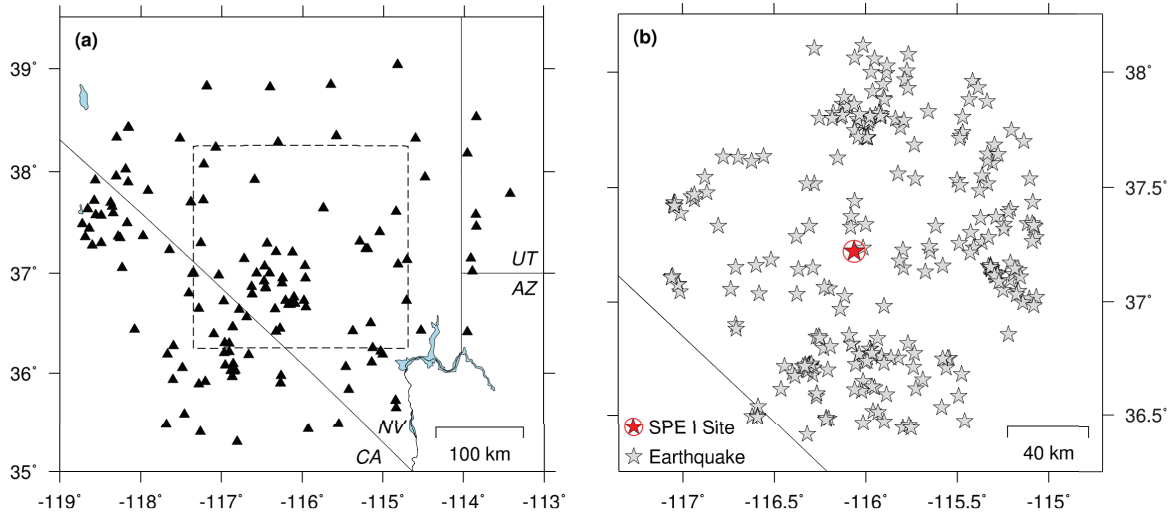


Figure 28. (a) Locations of the 146 high-gain seismometers that were within 150 km of the SPE Phase I borehole during 2011–2016 or nearby earthquakes during 2000–2018. *The seismometers come from 10 temporary and permanent seismic networks: CI (13), IM (3), LB (2), NN (45), PB (4), SN (31), TA (25), US (2), UU (4), and XE (17), where the numeral after each network code indicates the number of seismometers from that network. The dashed box encloses the source region shown in the adjacent panel. (b)* Epicenters of 265 earthquakes (gray stars) that occurred between 17 January 2000 and 8 April 2018 within ~150 km of the SPE Phase I test site (Pyle and Walter, 2019), which is indicated with the red star.

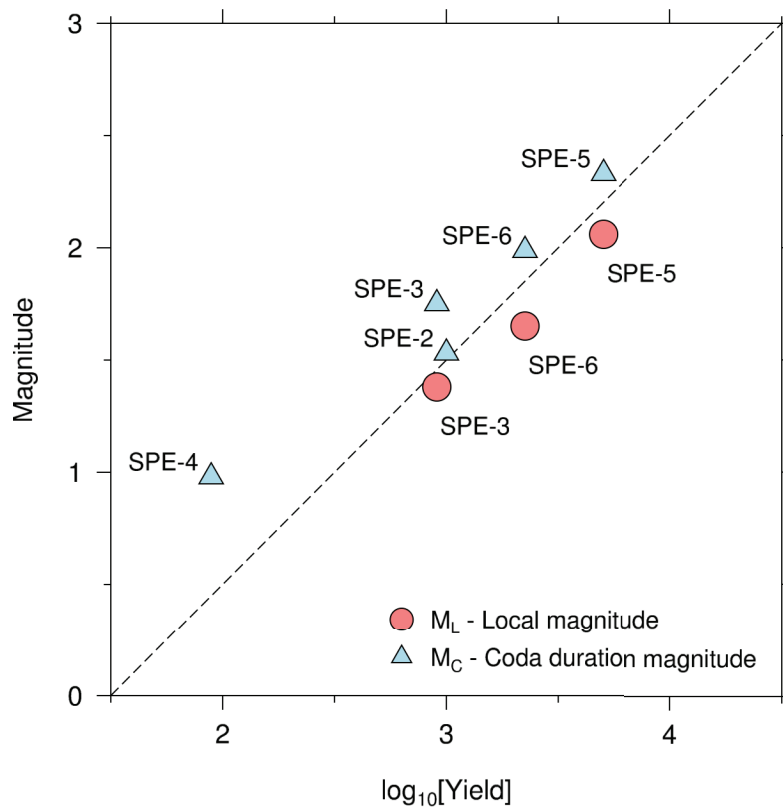


Figure 29. Magnitude estimates for the explosions from SPE Phase I. The dashed line has a slope of 1. Yield is in units of *kg equivalent TNT*.

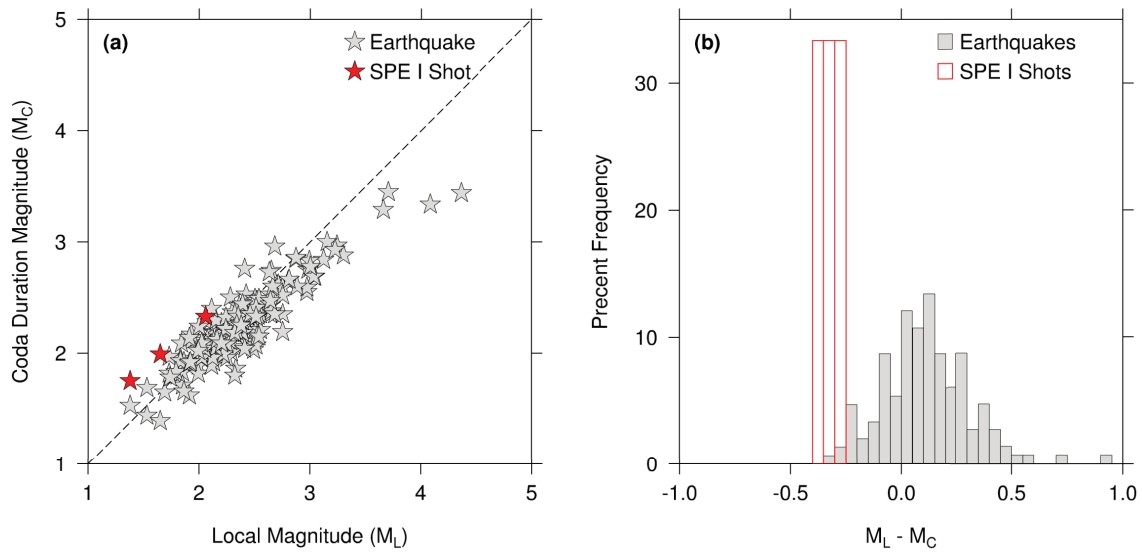


Figure 30. (a) Relationship between M_L and M_C for SPE Phase I explosions and nearby earthquakes. *The dashed line has a slope of 1.* **(b)** $M_L - M_C$ histograms in units of 0.05 for the explosions (red) and earthquakes (gray).

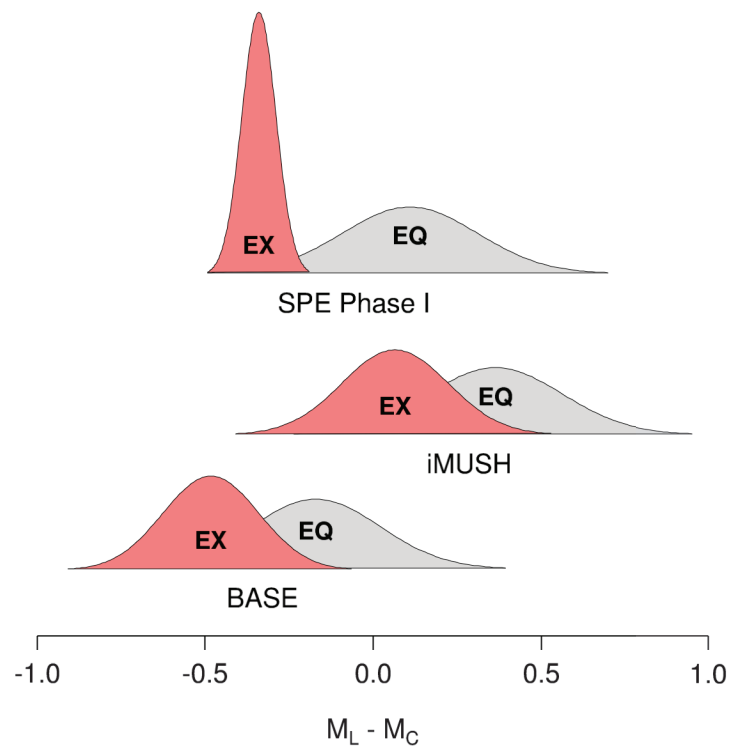


Figure 31. Summary of M_L - M_C distributions for earthquakes (EQ) and single-fired chemical explosions (EX) using data recorded at local distances (<150 km). *All distributions are approximated with Gaussians and plotted $\pm 3\sigma$ around the mean. From top to bottom the Hellinger distances (H) are 0.88, 0.55, and 0.60.*

11. CONCLUSIONS AND RECOMMENDATIONS

The results from this contract support the idea that comparisons between local magnitude (M_L) and coda duration magnitude (M_C) are useful as an indicator of especially shallow focal depth for small seismic events recorded at local distances (< 150 km). The quantity $M_L - M_C$ was found to be anomalously negative for naturally occurring shallow earthquakes in Utah, the Yellowstone region, and Italy; shallow mining induced earthquakes in Utah; shallow hydrologically induced earthquakes in Oklahoma and Kansas; mining or weapons testing and disposal explosions in Utah; and buried, single-fired chemical explosions in Nevada, Washington, and Wyoming. However, significantly more work needs to be done to establish the viability of $M_L - M_C$ as a complement to high-frequency P/S ratios in identifying low yield nuclear explosions. We recommend the following tasks for future work:

- (1) Continued evaluation of $M_L - M_C$ depth sensitivity with new, diverse datasets. Possible datasets include: historic recordings of underground nuclear explosions in Nevada; well-located earthquakes and single-fired explosions in southern California; any local or near-local data available in areas of special interest.
- (2) Continued evaluation of simple functional forms of amplitude and duration that might outperform $M_L - M_C$, with emphasis on evaluating how much improvement can be gained from regional calibration.

(3) Synthesis of seismograms in realistic (3D) Earth models to better understand the relative contributions to local distance coda generation from topographic scattering, shallow waveguide effects, and stochastically described volumetric heterogeneity.

(4) Quantification of the potential increase in source classification capability when M_L - M_C observations and high-frequency P/S amplitude ratios are combined for the same datasets.

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(*directly related to work performed during this contract: 4 journal papers, 8 meeting presentations)

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List of Symbols, Abbreviations, and Acronyms

AAG	Average Azimuthal Gap
AFRL	Air Force Research Laboratory
ANSS	Advanced National Seismic System
AQMS	ANSS Quake Management System
AUC	Area under the ROC curve
BASE	2009–2010 Bighorn Arch Seismic Experiment
CTBT	Comprehensive Nuclear-Test-Ban Treaty
DPG	Dugway Proving Ground
EQ	Earthquake
EX	Explosion
FPR	False positive rate
FQ	False positive
FX	False negative
H	Ratio of distance to nearest station over focal depth; also Hellinger distance
IDC	International Data Center
IASPEI	International Association of Seismology & Physics of the Earth's Interior
iMUSH	2014–2016 imaging Magma Under St. Helens experiment
INGV	National Institute of Geophysics and Volcanology
m_b	Body wave magnitude
M_C	Coda duration magnitude
M_L	Local magnitude
M_S	Surface wave magnitude
M_w	Moment magnitude
LE	Likely explosion
NEIC	National Earthquake Information Center
NNSS	Nevada National Security Site
PNSN	Pacific Northwest Seismic Network
ROC	Receiver operating characteristic

SPE	Source physics experiment
TPR	True positive rate
TQ	True positive
TX	True negative
UTTR	Utah Test and Training Range
UUSS	University of Utah Seismograph Stations

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