

RESEARCH LETTER

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Key Points:

- The difference between local (M_L) and coda/duration (M_C) magnitude separates mining-induced seismicity from tectonic seismicity in Utah
- $M_L - M_C$ acts as a depth discriminant with shallow events having more negative values
- $M_L - M_C$ or similar metrics may also be useful for discriminating small explosions from tectonic earthquakes at local distances

Supporting Information:

- Supporting Information S1

Correspondence to:

K. D. Koper,
koper@seis.utah.edu

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Magnitude-based discrimination of man-made seismic events from naturally occurring earthquakes in Utah, USA

Keith D. Koper¹, James C. Pechmann¹, Relu Burlacu¹, Kristine L. Pankow¹, Jared Stein¹, J. Mark Hale¹, Paul Roberson¹, and Michael K. McCarter²

¹Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, USA, ²Department of Mining Engineering, University of Utah, Salt Lake City, Utah, USA

Abstract We investigate using the difference between local (M_L) and coda/duration (M_C) magnitude to discriminate man-made seismic events from naturally occurring tectonic earthquakes in and around Utah. For 6846 well-located earthquakes in the Utah region, we find that $M_L - M_C$ is on average 0.44 magnitude units smaller for mining-induced seismicity (MIS) than for tectonic seismicity (TS). Our interpretation of this observation is that MIS occurs within near-surface low-velocity layers that act as a waveguide and preferentially increase coda duration relative to peak amplitude, while the vast majority of TS occurs beneath the near-surface waveguide. A second data set of 3723 confirmed or probable explosions in the Utah region also has significantly lower $M_L - M_C$ values than TS, likely for the same reason as the MIS. These observations suggest that $M_L - M_C$ is useful as a depth indicator and could discriminate small explosions and mining-induced earthquakes from deeper, naturally occurring earthquakes at local-to-regional distances.

1. Introduction

A substantial fraction of the ~1700 earthquakes located in the Utah region (Figure 1) each year by the University of Utah Seismograph Stations (UUSS) [University of Utah, 1962] are directly related to underground coal mining and are referred to as mining-induced seismicity (MIS) [Arabasz *et al.*, 1997]. In contrast to seismicity induced by the injection of high-pressure fluid into the subsurface [e.g., Ellsworth, 2013], MIS is induced by the extraction of mass (coal in the case of central Utah) from the subsurface [e.g., Gibowicz, 2009] and is distinct from the explosive sources used in some mining activities. MIS has more varied source mechanisms than naturally occurring tectonic seismicity (TS), which is dominated by double-couple sources. MIS source mechanisms can be implosional, double-couple, or a combination of both [Stickney and Sprenke, 1993; Fletcher and McGarr, 2005; Sileny and Milev, 2008; Whidden and Pankow, 2016]. Nevertheless, it can be difficult to differentiate MIS from TS because MIS is often small and very shallow, requiring extremely dense local networks to constrain the focal depths and focal mechanisms.

Discriminating MIS from TS is important for seismic hazard estimation because the predicted recurrence times of large tectonic earthquakes depend on TS background rates. In Utah, source discrimination is complicated by the fact that the coal mining district of central Utah overlaps the Intermountain Seismic Belt—a swath of TS related to Basin and Range extension that runs roughly N-S from Montana to Arizona [Smith and Arabasz, 1991]. Therefore, the location of an event within or very near mine permit boundaries is not definitive for classifying it as MIS. Focal depth is also usually not definitive because the UUSS seismic network is not dense enough to strongly constrain most focal depths by inversion of arrival times. Recently, waveform similarity clustering and P wave spectral content have been investigated as means of discriminating MIS from TS in Utah, and while both show promise, ambiguities remain [Stein, 2016].

Here we present a new method for discriminating MIS from TS in Utah that is based on the difference between local Richter magnitude (M_L) and coda/duration magnitude (M_C). We use synthetic seismograms to show that $M_L - M_C$ acts as a depth discriminant and is effective at separating MIS from TS in Utah because MIS commonly occurs at depths shallower than TS. This result suggests that $M_L - M_C$ might be an effective discriminant for other types of man-made seismicity. In particular, we propose $M_L - M_C$ as a means of discriminating small explosions from tectonic earthquakes at local distances. Local discriminants are of growing interest in forensic seismology [Douglas, 2013], in part because the Comprehensive Nuclear Test Ban Treaty (see www.ctbto.org) is a zero tolerance treaty that prohibits all nuclear explosions, no matter how

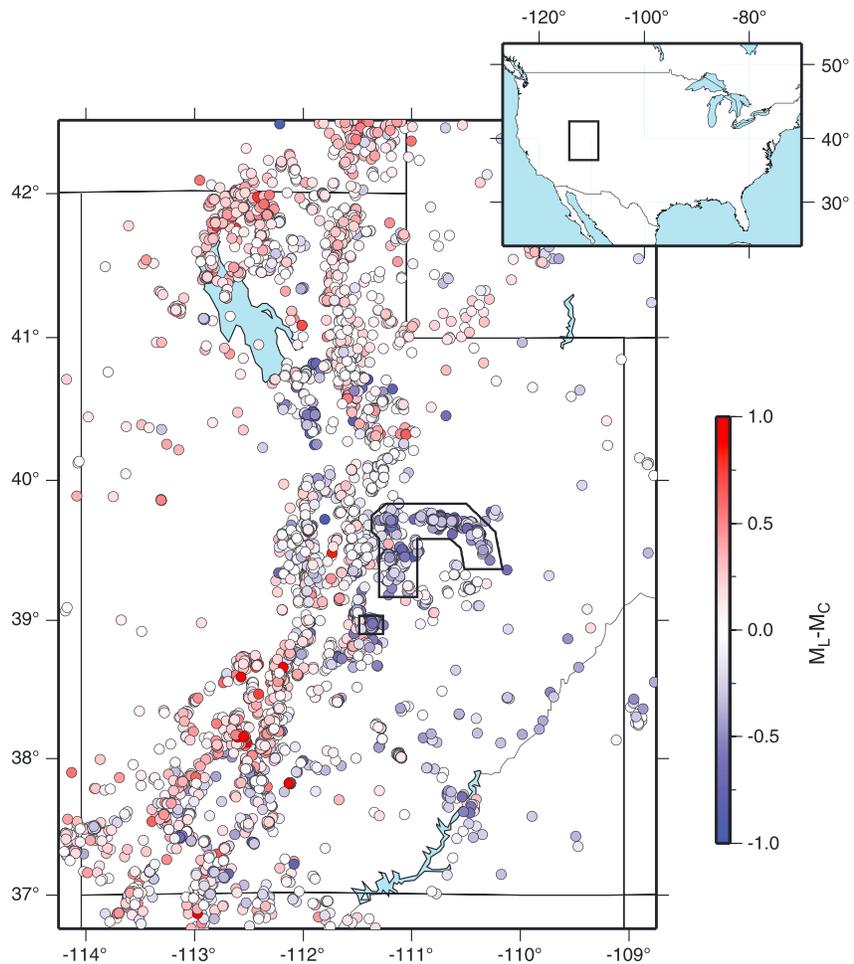


Figure 1. The epicenters of 6846 well-located earthquakes in the Utah region from 5 May 1982 to 31 March 2016 for which both M_L and M_C are reported in the UUSS catalog. The Utah region is bounded by 36.75° to the south, -114.25° to the west, 42.50° to the north, and -108.75° to the east as part of the Advanced National Seismic System (<http://earthquake.usgs.gov/monitoring/anss>), for which UUSS produces an earthquake catalog. The color of each circle indicates the value of $M_L - M_C$. The two black polygons in central Utah enclose regions of active underground coal mining.

small. If small explosions recorded only at local distances (<100–200 km) are of concern to the nuclear monitoring community [Williams, 2012], then source discrimination measures that are effective at these distances are necessary.

2. Magnitudes in the Utah Earthquake Catalog

The Utah region seismicity catalog produced by UUSS (Figure 1) contains only earthquake information—explosion sources are routinely and consistently removed—therefore we also refer to it as an earthquake catalog. The preferred measure of event size in the Utah earthquake catalog is a local Richter magnitude denoted by M_L :

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

where A is one half of the arithmetic average of the maximum peak-to-peak amplitudes (in mm) on the horizontal components of an actual or simulated Wood-Anderson seismogram, A_0 is a distance correction [Richter, 1958], and S is a station correction [Pechmann et al., 2007]. In practice, the peak-to-peak amplitudes often represent the amplitude of the S_g wave packet at a period near 0.8 s, the free period of the Wood-Anderson instrument. Until broadband seismometers were added to the UUSS network beginning in the late 1990s, only a few percent of the events in the catalog were large enough or near enough to Wood-Anderson seismometers for direct M_L calculation. By 2002 the fraction of events with M_L s rose to about 30%, and since

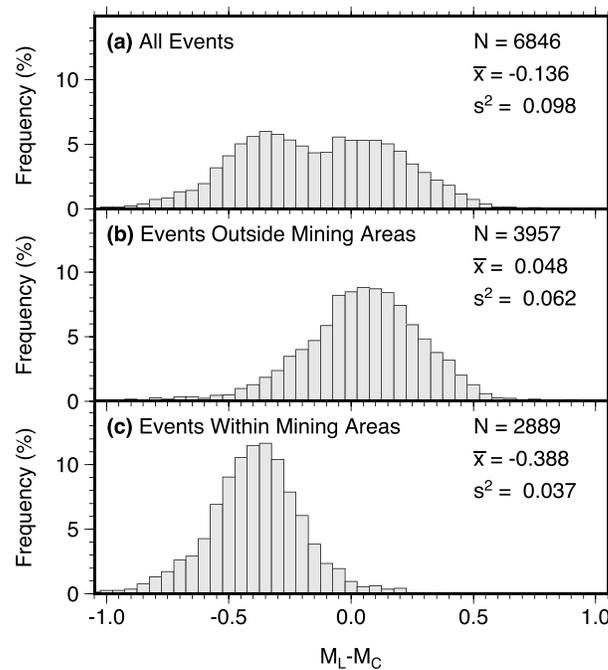


Figure 2. Histograms of $M_L - M_C$ for the earthquakes shown in Figure 1 for (a) all events, (b) events outside of the mining districts, and (c) events inside of the mining districts. Sample means are denoted by \bar{x} , and sample variances are denoted by s^2 . The bin width is 0.05 m.u.

is the epicentral distance in kilometers [Pechmann et al., 2006]. By defining the coda end relative to a fixed value of ground velocity (instead of the more traditional pre-event noise level), we obtain duration measurements that are insensitive to changes in instrument gains, variations in noise levels, and the codas of any preceding seismic events. Coda shapes are fit to the average absolute value of the trace amplitudes in overlapping 2 s time windows (shifted in 1 s increments). The constants in equation (2) were derived by orthogonal regression of 9037 ($\log_{10}[\tau]$, Δ) observations from 923 earthquakes in the Utah region for which a direct M_L determination was available. In this sense, M_C is explicitly calibrated to agree with M_L and can be used as an indirect M_L estimate for earthquakes lacking a direct M_L determination when, for example, calculating seismicity rates.

Figure 1 shows $M_L - M_C$ for 6846 events in the Utah region that occurred between 24 May 1982 and 31 March 2016 for which a direct M_L and an independent M_C measurement were made and reported in the UUSS catalog. Known and probable explosions are routinely removed from the UUSS catalog so the events shown in Figure 1 are overwhelmingly earthquakes. As expected from the M_L -based calibration of M_C , the magnitude differences are small, and nearly all the variation is within ± 1 magnitude unit (m.u.). There is coherent geographical variation in $M_L - M_C$. The most noteworthy feature is a strongly negative patch of $M_L - M_C$ values in the active coal mining regions, which are outlined with black polygons (Figure 1). A geographically binned version of this figure is available in the supporting information (Figure S2).

A histogram of the $M_L - M_C$ values shown in Figure 1 is presented in Figure 2a. The mean is small, -0.136 m.u., but the distribution is clearly non-Gaussian with strong peaks near -0.35 m.u. and 0.0 m.u. The bimodality implies that the events are selected from two distinct populations. Figures 2b and 2c present histograms of events from outside and inside of the permitted mining regions, respectively. Each of these histograms is noticeably more symmetric than the combined distribution shown in Figure 2a, and both appear Gaussian. The sample means of the two groups are quite different. The mean of the sample drawn from outside the mining regions, presumably dominated by TS, is 0.048 m.u. The mean of the sample drawn from inside the mining regions, presumably dominated by MIS, is -0.388 m.u. This value is nearly the same as the mean $M_L - M_C$ value of -0.44 m.u. reported for 74 MIS events near the Crandall Canyon, Utah, coal mine [Pechmann et al., 2008]. The corresponding sample variances are 0.062 m.u.² for TS and 0.037 m.u.² for MIS.

2013 it has been about 50% (Figure S1 in the supporting information). M_L s in the Utah region agree reasonably well with moment magnitudes (M_W) in the range of M_W 3.5–5.5 [Pechmann et al., 2007; Whidden and Pankow, 2012] although the slope of the best fitting linear $M_L - M_W$ relation is less than one [Arabasz et al., 2016].

Nearly all of the events in the UUSS catalog are assigned a magnitude based on total signal duration, which has long been recognized as a useful proxy for event size [Lee et al., 1972; Real and Teng, 1973; Herrmann, 1975]. The UUSS coda/duration magnitude scale is denoted by M_C (equivalently M_d or M_r), and in the Utah region it is defined as

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

where τ is the time in seconds between the onset of the P wave and the time at which the coda on a short-period, vertical component seismogram falls below a ground velocity of $0.01724 \mu\text{m/s}$; Δ is

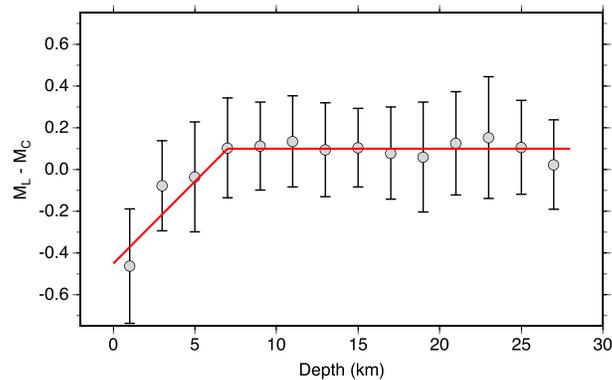


Figure 3. $M_L - M_C$ for the 795 earthquakes outside of the coal mining districts that have well-constrained depths, as described in the text. The circles are $M_L - M_C$ means within 2 km wide depth bins, and the vertical bars are ± 1 standard deviation. Standard errors of the mean are generally smaller than the circle size, except for the shallowest and deepest bins. The red line illustrates the interpreted reduction in $M_L - M_C$ for depths shallower than ~ 6 km.

(TP—declaring TS when the event is in the TS population) varies against the probability of a false positive (FP—declaring TS when the event is in the MIS population) as the $M_L - M_C$ threshold is varied from 1.0 to -1.0 . A threshold of -0.19 , corresponding to a TP probability of 0.83 and an FP probability of 0.15, gives the performance closest to an ideal discriminator (TP = 1.0, FP = 0.0) when using a Cartesian measure of distance in FP-TP space.

3. $M_L - M_C$ as a Depth Discriminant

There have been several experiments in Utah in which seismometers were temporarily deployed near active coal mines in order to obtain high-resolution MIS hypocenters. From October 2000 to April 2001, an array of 12 seismometers was installed over the Trail Mountain Mine and used to locate approximately 1900 seismic events coincident with longwall mining operations [Arabas *et al.*, 2005; Boltz *et al.*, 2014]. Following the 6 August 2007 Crandall Canyon mine collapse, five seismometers were temporarily installed above and next to the mine, resulting in ~ 1000 well-located aftershocks after application of waveform cross-correlation techniques [Kubacki *et al.*, 2014]. These and other studies have shown that MIS in Utah occurs very close to mine level, at depths of < 2 km below the surface.

The TS events in the Utah earthquake catalog generally have larger depths than the MIS events. The nominal median depth for the 3957 earthquakes that occurred outside of the mining districts in Figure 1 is 5.1 km, which is relative to a datum of 1.5 km above sea level. In the majority of cases though, the event depths are weakly constrained because of the sparseness of the UUSS regional seismic network. But approximately 20% of these events can be considered to have well-constrained depths because they meet the following criteria: the formal standard error in depth is less than 2 km, and the epicentral distance to the nearest station is either smaller than 1.4 times the focal depth [Gomberg *et al.*, 1990] or smaller than 2 km. For these events the median depth is 11 km. This median is likely deeper than that of the overall TS population because the deeper an event is, the more likely that a station exists within the critical distance range. Nevertheless, there is a reasonably wide distribution of focal depths within the “well-located” subset. Mean $M_L - M_C$ for this subset of events is plotted in 2 km depth bins in Figure 3, which shows a clear decrease in $M_L - M_C$ as depth becomes less than about 6 km. This trend is robust with respect to bin size and the distance criterion used to categorize a focal depth as well constrained (Figure S4). The robustness tests are important since not all nearest stations include *S* arrival times and in these cases, when only a *P* arrival time is picked, a maximum epicentral distance approximately equal to the focal depth is required for a well-constrained depth [Gomberg *et al.*, 1990].

The depth-dependent trend in $M_L - M_C$ for TS (Figures 3 and S4) suggests that the separation of MIS and TS by $M_L - M_C$ (Figures 2 and S3) is related to the difference in depth between the shallower MIS and the deeper TS.

Using Welch’s *t* test for cases in which the population variances are not necessarily equal, the mean $M_L - M_C$ values for the MIS- and TS-dominated populations are significantly different above the 99.99% confidence level.

The ability of $M_L - M_C$ to act as a binary classifier between TS and MIS is illustrated in Figure S3 of the supporting information with a receiver operating characteristic (ROC) curve. In this example, $M_L - M_C$ is used to declare an event as TS when the observed value of $M_L - M_C$ is above some threshold value. Using Gaussian probability distribution functions to describe the TS and MIS populations (as suggested by Figures 2b and 2c), the ROC curve shows how the probability of a true positive

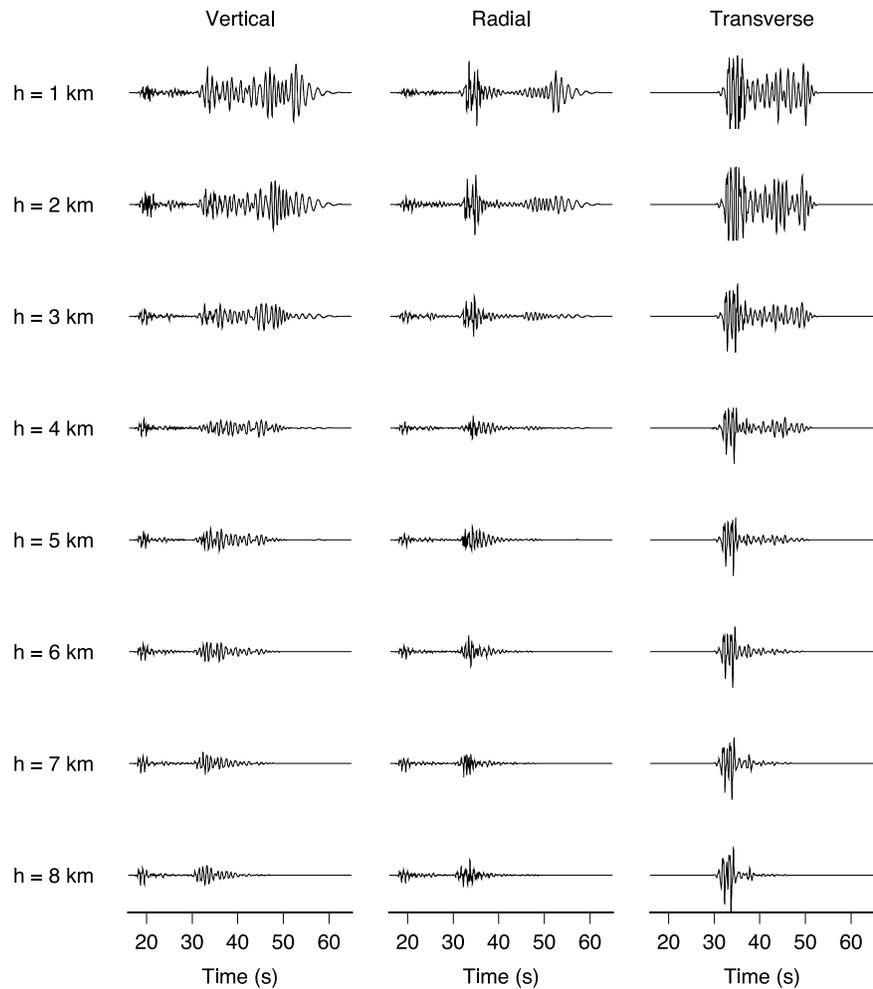


Figure 4. Synthetic ground velocity seismograms for a double-couple source (strike = 355°, dip = 80°, and rake = -70°) in the Trail Mountain Mine Basin and Range velocity model [Pechmann *et al.*, 2002; Boltz *et al.*, 2014] at a distance of 100 km for source depths of 1–8 km. The traces have been bandpass filtered at 1–5 Hz. Uniform scaling is used for all 24 traces, and the $h = 1,2$ km traces on the transverse components are intentionally clipped. Note the extra signal duration in the seismograms computed at the shallowest depths.

To explore this idea, we computed synthetic seismograms using a 1-D velocity model (Figure S5) derived for the Trail Mountain Mine in central Utah [Pechmann *et al.*, 2002; Boltz *et al.*, 2014]. The model contains a series of low-velocity layers in the upper 4.1 km that are based on a stratigraphic column from the mine and average P wave formation velocities generalized from four nearby sonic logs. The P/S velocity ratios in the model were derived from a station-pair analysis of local earthquake P and S arrival times. We assigned a Q_S of 25 in the upper 0.36 km, a Q_S of 100 in next 3.74 km, and a Q_S of 500 in the deeper layers, and set $Q_P = 2Q_S$. The synthetics were computed at a series of depths for a double-couple source using Green’s functions calculated with an $f-k$ technique [Zhu and Rivera, 2002]. Seismograms at a distance of 100 km for source depths of 1–8 km clearly show how shallow focal depth leads to extended waveform duration because of energy trapped in the low-velocity layers near the surface (Figure 4). The relative size and duration of this energy is strongly dependent on Q in the low-velocity layers, which is poorly known. Equivalent synthetics calculated with the IASP91 reference model [Kennett and Engdahl, 1990], which has a simple two-layer crust, have much shorter duration (Figure S6).

It is important to note that as the source becomes deeper, the peak amplitude of the S_g wave packet, which is generally used to calculate M_L , is less diminished than the amplitude and duration of the guided energy, which is used to calculate M_C . Therefore, shallow depths preferentially enhance M_C relative to M_L . This

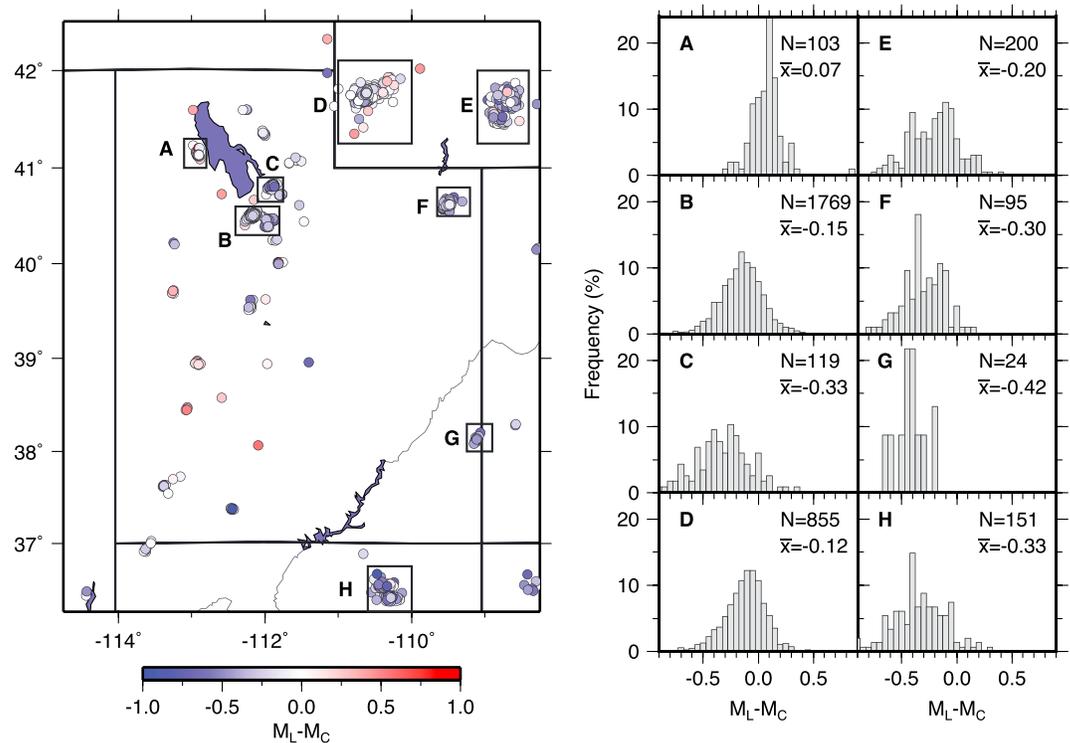


Figure 5. $M_L - M_C$ for 3723 likely explosions that occurred between 1 October 2012 and 25 June 2016. The events are organized in geographical clusters (A to H), and the corresponding $M_L - M_C$ distributions are presented in subpanels on the right. Clusters E and H fall just outside of the Utah region shown in Figure 1 but are included here for completeness.

phenomenon is consistent with earlier observations that the existence or amplitude of a short period Rayleigh wave (R_g) can be used as an indicator of shallow focal depth because its amplitude is much more sensitive to focal depth than the amplitudes of regional distance body waves such as P_g and S_g [Båth, 1975; Kafka, 1990; Ma and Motazedian, 2012]. However, short-period R_g is strongly attenuated with distance and can be difficult to observe beyond 150 km [Bowers and Selby, 2009], limiting its usefulness as a depth discriminant. $M_L - M_C$ may be better suited as a depth discriminant, particularly since R_g energy lost to elastic scattering [e.g., Myers et al., 1999] will contribute to the amplitude and duration of the coda, and thus to M_C . Anomalously long coda durations for shallow events in the western U.S. were previously identified by Mayeda and Walter [1996], who suggested that spectral peaks in the coda were created by scattered R_g energy.

4. $M_L - M_C$ for Explosions in the Utah Region

The dependence of $M_L - M_C$ on source depth implies that other shallow seismic sources, in addition to MIS, might be distinguished from deeper, naturally occurring earthquakes based on $M_L - M_C$. We test this hypothesis in the Utah region using a data set of 3723 confirmed or likely explosions that were recorded in 2012–2016 and for which M_L and M_C have been independently estimated (Figure 5). The likely explosions are identified as such because their automatic locations are near known blasting areas and they occurred during the daytime, when blasting is permitted. Such events are excluded from the UUSS earthquake catalog, and their automatic magnitudes and locations are not refined by an analyst as thoroughly and rigorously as for earthquakes.

As shown in Figure 5, we selected eight geographical clusters of likely explosions and computed $M_L - M_C$ statistics for each one. The number of events in a cluster varied from 24 (cluster G) to 1769 (cluster B), with a median of 135. Seven of the eight clusters had negative means (−0.42 to −0.12 m.u., with a median of −0.30 m.u.) that are significantly smaller than the TS value of 0.048 m.u. at confidence levels above 99%. The only cluster with a positive $M_L - M_C$ mean is cluster A, with a mean of 0.07 m.u.; however, this

cluster represents a series of ground surface explosions at the Utah Test and Training Range in which solid-propellant rocket motors are destroyed [Stump *et al.*, 2007]. Seismic efficiency for such sources is known to be low, and it is likely that not enough seismic energy is trapped by the shallow low-velocity layers when the source is located above the waveguide for M_C to be enhanced. Analogous reasoning explains why in Figure 3 M_L-M_C becomes flat for tectonic earthquakes deeper than 6–7 km—the source moves below the waveguide.

Similarly, the low seismic efficiency of some blasting practices may explain why certain geographical clusters in Figure 5 have M_L-M_C means that, while negative, are significantly higher than the MIS mean of -0.388 m.u. Upgoing energy from an uncontained explosion is likely to be lost to the atmosphere while for a contained explosion much of the initially upgoing energy is reflected by the surface back into the shallow waveguide, where it would act to increase M_C . Downgoing energy from uncontained and contained explosions, which contribute to S_g amplitudes and are manifested in M_L , should be less sensitive to source containment. Cluster D in southwestern Wyoming, with a mean of -0.12 m.u., is an area known for open pit coal mining in which near-surface, uncontained cast-blasts are often used [Chambers *et al.*, 2015]. Similarly, region B, with a mean of -0.15 m.u., contains a major open pit copper mine (Bingham Canyon) that often conducts loosely contained, near-surface blasts. Cluster F, on the other hand, has a mean of -0.30 m.u. and results from a mining operation in which deeper, well-contained blasts are used as part of the excavation process.

5. Conclusions

Shallow seismic sources in Utah have enhanced values of coda/duration magnitude (M_C) relative to local magnitude (M_L). The mean M_L-M_C value for 2889 predominantly mining-induced earthquakes is 0.44 m.u. smaller than that for 3957 naturally occurring tectonic earthquakes. Mean M_L-M_C for seven of eight blasting areas in the Utah region (totaling 3213 explosions) are 0.17 – 0.47 m.u. smaller than the mean of the naturally occurring earthquake population. The differences in M_L-M_C between shallow man-made seismic sources (explosions and MIS) and the generally deeper tectonic earthquakes are statistically significant at confidence levels above 99%.

We propose that M_L-M_C can be used to help discriminate shallow (<2 – 3 km) seismic sources from deeper (>4 – 5 km) earthquakes when an event is not recorded by a seismometer near enough to have its depth resolved from inversion of body wave arrival times. M_L and M_C can be determined for small events with relatively few observations; hence, an M_L-M_C discriminant can be effective in cases where moment tensor inversion is not possible because of low data quality or poorly known Green's functions. Furthermore, an M_L-M_C discriminant does not rely on the existence of the fast attenuating R_g phase at regional distances. M_L-M_C may provide a local-to-regional distance analog of the m_b-M_S discriminant that has traditionally been effective at identifying large nuclear explosions with teleseismic data but has been less successful with recent, smaller-magnitude nuclear tests in North Korea [Bowers and Selby, 2009; Murphy *et al.*, 2013]; however, for the Utah data set presented here, the M_L/M_C separation is not distinct enough for an M_L-M_C discriminant to be used in isolation. Rather, an M_L-M_C discriminant would be most effective as one component of a multi-discriminant scheme [Anderson *et al.*, 2007].

Our explanation for why M_L-M_C works as a depth discriminant in Utah is that shallow (<2 – 3 km) seismic sources occur within a low-velocity waveguide that traps energy and lengthens the duration of the seismogram (increasing M_C) without significantly enhancing the peak S_g amplitude—which is commonly used for calculating M_L . Presumably, shallow low-velocity layers are widespread in the Utah region, whether from accumulated sediment or fractured and weathered bedrock. Our simulations of this phenomenon (Figure 4) are done with a 1-D velocity model that neglects the influence of geological heterogeneities and topography, which are known to scatter energy out of short-period surface waves and extend the duration of seismic codas [e.g., Myers *et al.*, 1999; He *et al.*, 2008], and they probably underestimate the waveguide effect in reducing M_L-M_C for shallow seismic sources. Future work should simulate regional distance wave propagation in more realistic Earth models and examine if other measures of signal duration versus peak amplitude are effective in separating very shallow sources from deeper crustal sources at local-to-regional distances. It will also be important to investigate the effectiveness of M_L-M_C as a depth discriminant in regions that lack strong shallow waveguides.

Acknowledgments

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