The Pennsylvania State Seismic Network: Report on seismic event location uncertainties

A report provided to the PA Department of Conservation and Natural Resources and the PA Department of Environmental Protection

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1.0 Introduction

The Pennsylvania State Seismic Network (PASEIS; http://paseis.geosc.psu.edu) has been operational since late 2016 and currently contains 38 broadband seismic stations. A map of the seismic stations used to locate seismic events is shown in Figure 1. Real-time event detection and preliminary event location are performed using the Earthworm software (http://www.earthwormcentral.org/). Arrival times of seismic waves from detected events are repicked by hand and used with the USGS location code HYOPINVERSE to accurately relocate the events (Klein, 2002). The relocated events are posted on the PASEIS website and entered into the PASEIS catalog. A complete description of how data from the network and other open seismic stations in Pennsylvania and surrounding states are used to detect and locate seismic events can be found at http://paseis.geosc.psu.edu/data.html. The complete seismic event catalog is available from the PASEIS website (http://paseis.geosc.psu.edu/). This report provides an assessment of the horizontal uncertainty in event locations reported in the PASEIS catalog. Uncertainties in the reported depths of the seismic events are not addressed.

From September, 2016, to the end of February, 2020, the PASEIS catalog contains 1,102 seismic events. 1,068 events are mine blasts and the remaining 34 events are probably earthquakes ("tectonic events"). The locations of the events in the catalog are shown in Figures 2 and 3. The seismic events range in magnitude from 0.7 to 3.3 (Figures 2 and 3), and were located using data from eight stations, on average, and a minimum of four stations. Using the maximum curvature technique of Wiemer and Wyss (2000) and the Gutenberg-Richter plot (Figure 4), the catalog is estimated to be complete to magnitude 2.0. That is, all events magnitude 2.0 or greater in the Commonwealth are detected and located. Many events smaller than magnitude 2.0 are also detected and located (e.g., the mean magnitude in Figure 2 is 1.4), but depending on station distribution and noise levels, some events smaller than magnitude 2.0 go undetected or are not recorded on a sufficient number of stations to obtain a location.

The slope of the linear portion of the frequency-magnitude distribution in the Gutenberg-Richter plot is termed the b-value. The b-value for the PASEIS catalog is 3.4. b-values are typically around 1.0 for earthquake catalogs, however, for catalogs dominated by blasting events b-values are typically greater than 1.5 (Weimer and Baer, 2000). The catalog's high b-value is expected given the catalog is dominated by mining-related events.

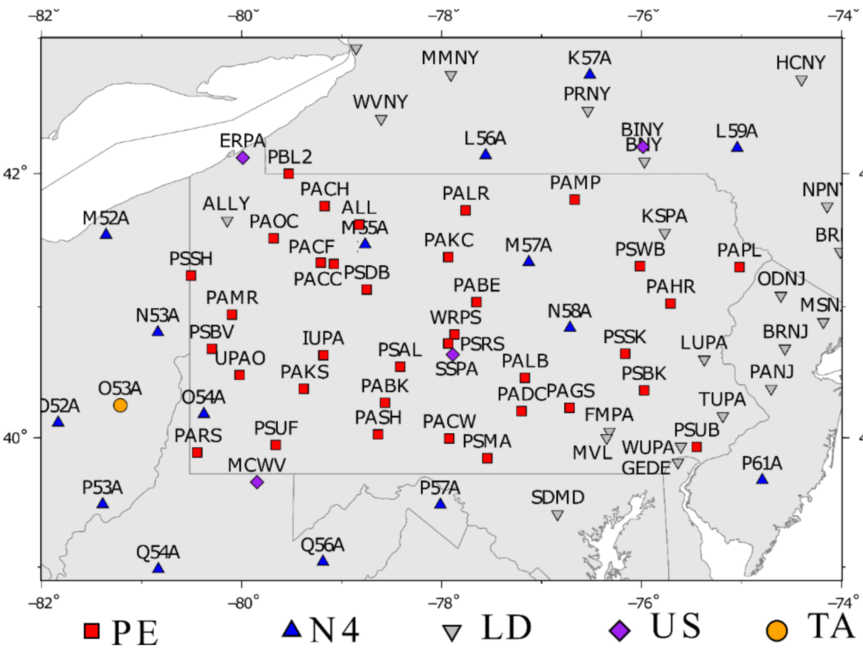

Figure 1: Stations used for seismic event detection and location. Seismic stations in several networks are used; The Pennsylvania State Seismic Network (PE, red squares), the Central and Eastern U.S. Network (N4, blue triangles), the Lamont-Doherty Cooperative Seismic Network (LD, gray inverted triangles), the United States Seismic Network (US, purple diamonds), and the Transportable Array Seismic Network (TA, orange circle).

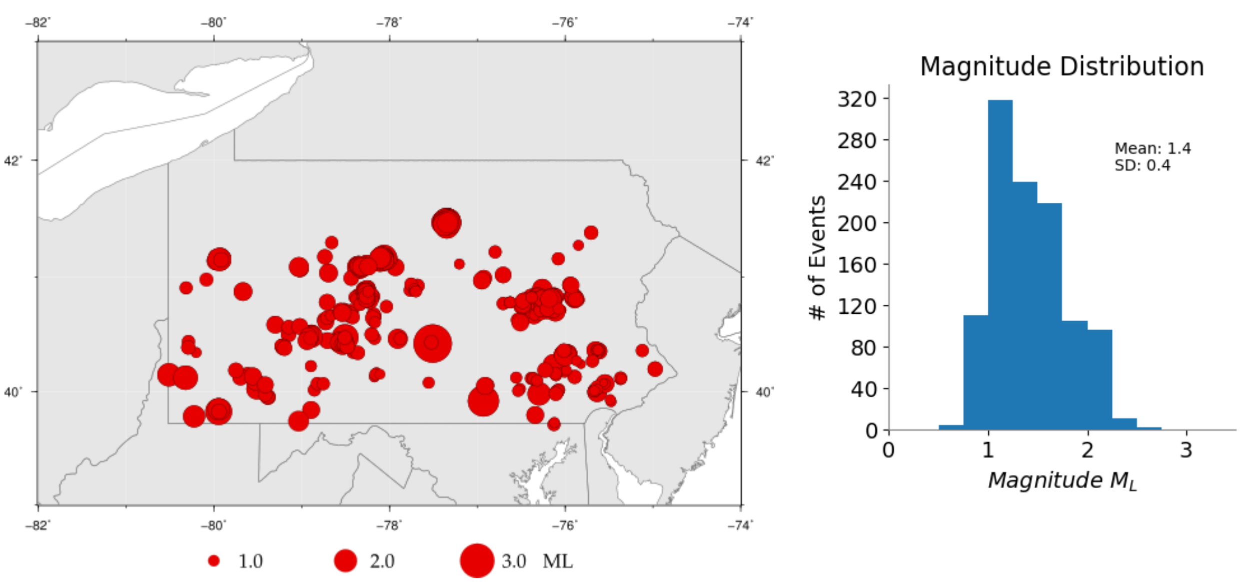

Figure 2: (Left) Map of all events in the PASEIS catalog from September 2016 through February 2020 displayed as a function of magnitude (ML). The events displayed on this map are both earthquakes and mine blasts. ML = local magnitude. (Right) Magnitude distribution for all events in the PASEIS catalog.

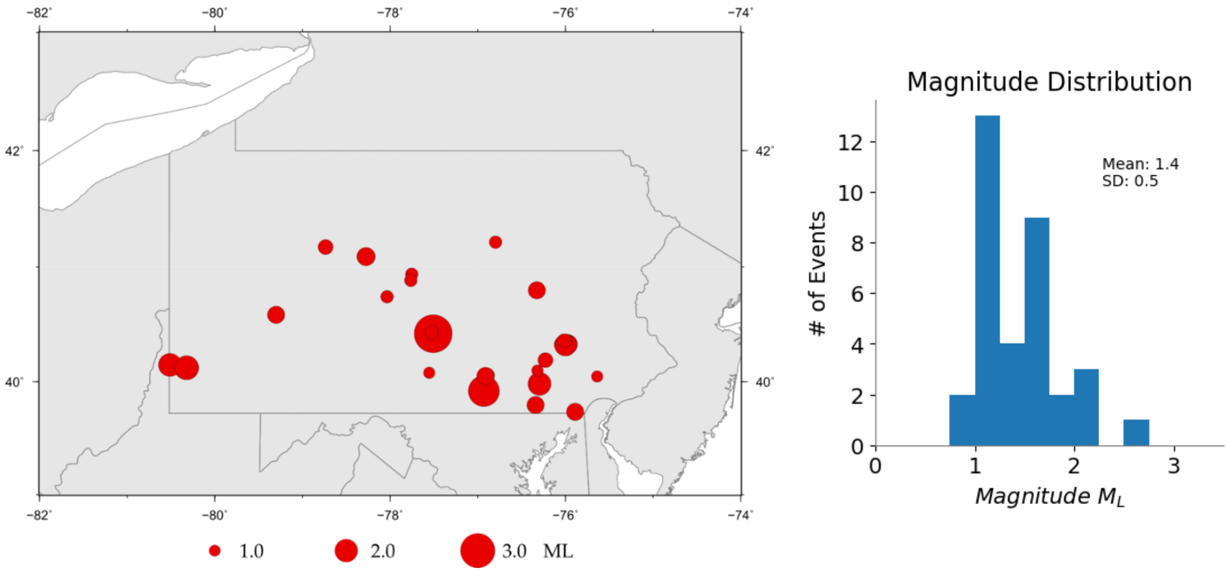

Figure 3: (Left) Map of earthquakes in the PASEIS catalog from September 2016 through February 2020 displayed as a function of magnitude (ML). ML = local magnitude. (Right) Magnitude distribution for the earthquakes in the PASEIS catalog.

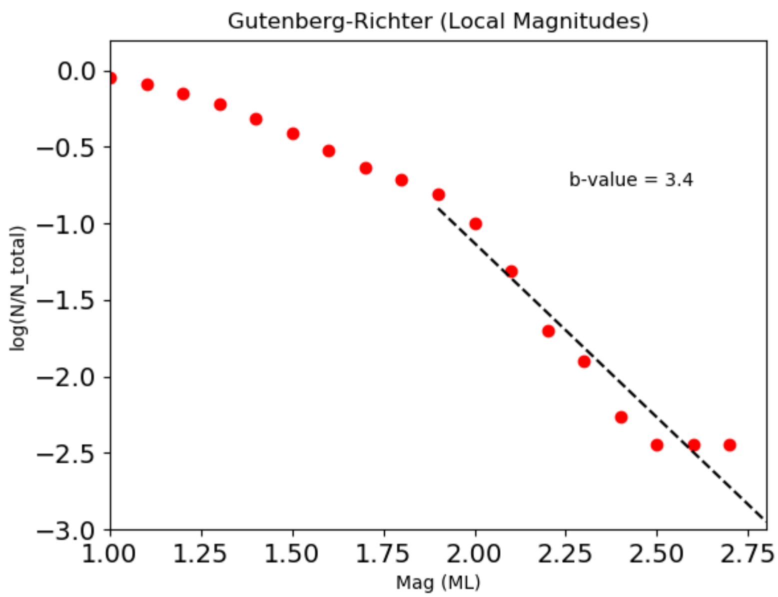

Figure 4: Gutenberg-Richter plot showing the b-value for the PASEIS catalog. The magnitude of completeness for the catalog is 2.0.

2.0 Methodology

For this report, we have analyzed the horizontal uncertainty in event locations using two methods. First, formal uncertainty estimates from the location code HYPOINVERSE are investigated. HYPOINVERSE uses an iterative least-squares method to determine hypocenter location. Formal (i.e., mathematical) uncertainty in HYPOINVERSE is determined by using the square root of the eigenvalues of the covariance matrix to compute the major axes of the joint hypocentral error ellipsoid. The formal uncertainty estimate is based on an assumption that measurement errors in seismic travel times follow a Gaussian distribution. Another assumption is that the travel time equations are locally linear near the hypocenter location. Because these may not necessarily be valid assumptions, the formal uncertainties may misrepresent the true (unknown) location uncertainties (Flynn, 1965; Buland, 1986). The investigation of formal uncertainties was performed for the catalog as a whole, and, additionally, the catalog was separated into several regions across the state to determine if there are regional differences in formal uncertainty.

In order to circumvent the assumptions made in the formal uncertainty calculation used in the HYPOINVERSE code, we also investigated the horizontal uncertainties in the PASEIS catalog using the empirical "ground truth" approach (Bondar and McLaughlin, 2009). In this approach, the ground truth derived uncertainty is defined as the distance between a known (i.e., ground truth) location of the seismic event, such as a mine blast, and the event location obtained from the location code. To implement this approach, we grouped together events in the PASEIS catalog from four mines, and then calculated the ground truth uncertainty for each event with respect to the mine location, where the known or ground truth event location is assumed to be the center of the mine. The four mines were chosen based on quantity of mining related events and the ability to associate the events with a particular mine. Other mine regions were investigated, however, they either contained too few events or we were unable to associate blasts with a specific mine.

3.0 Results

Events in the PASEIS catalog are located using a single 1D velocity model that is broadly representative of the geology of Pennsylvania. Because the geology of Pennsylvania is not uniform, event locations obtained using a single 1D velocity model could possibly lead to geographic variability in event location uncertainty, particularly if the average 1D velocity structure in a region deviates considerably from the 1D model used to locate events. Therefore, in presenting the results for formal horizontal uncertainty, we report them in aggregate as well as separately for seven regions across the Commonwealth.

3.1 Formal Horizontal Uncertainty

The average (mean) formal uncertainty in the horizontal locations for events in the PASEIS catalog is 1.2 km, with a standard deviation of 0.59 km, a range from 0 to 4.2 km, and a mode of 0.5 to 1 km (Figure 5).

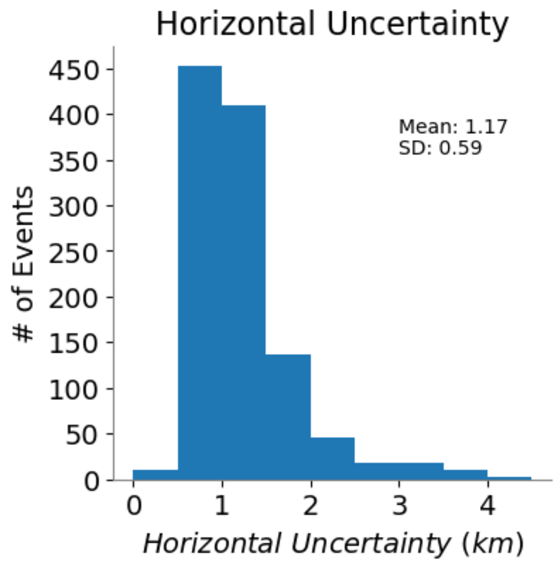

Figure 4: Distribution of formal horizontal uncertainty for events in the PASEIS catalog.

In general, as the number of stations used for event location increases, the horizontal uncertainty decreases, as illustrated in Figure 6. However, when the location uncertainty is examined as a function of magnitude, we find that for events with magnitude 2 or larger this trend does not hold (Figure 7). This is because waveforms from larger seismic events are generally easier to analyze than waveforms from small events, and therefore arrival times may be more accurately picked, leading to a more accurate location even when fewer stations are used.

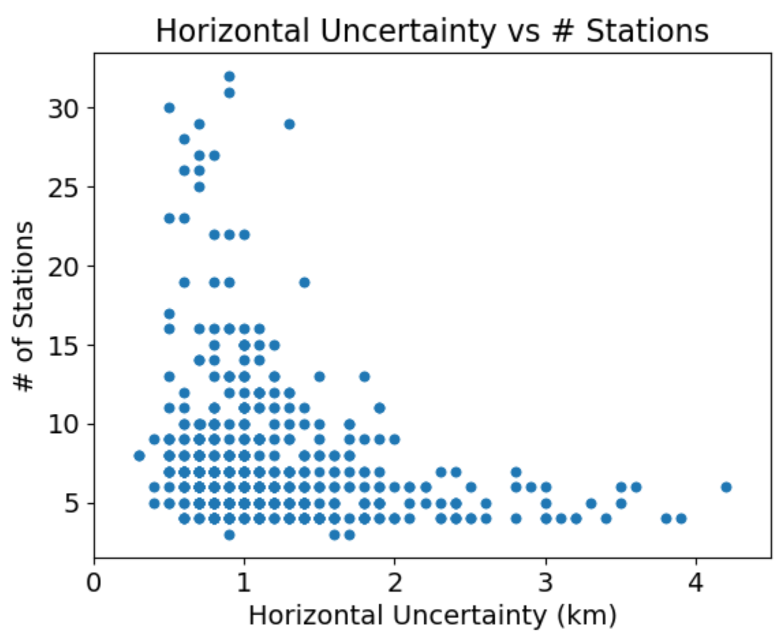

Figure 5: Horizontal uncertainty in event location vs. the number of stations used for the event location for all 1,102 events in the PASEIS catalog (many events have the same uncertainty and number of stations used for location). There is a clear trend that shows horizontal uncertainty decreases as more stations are used in the location.

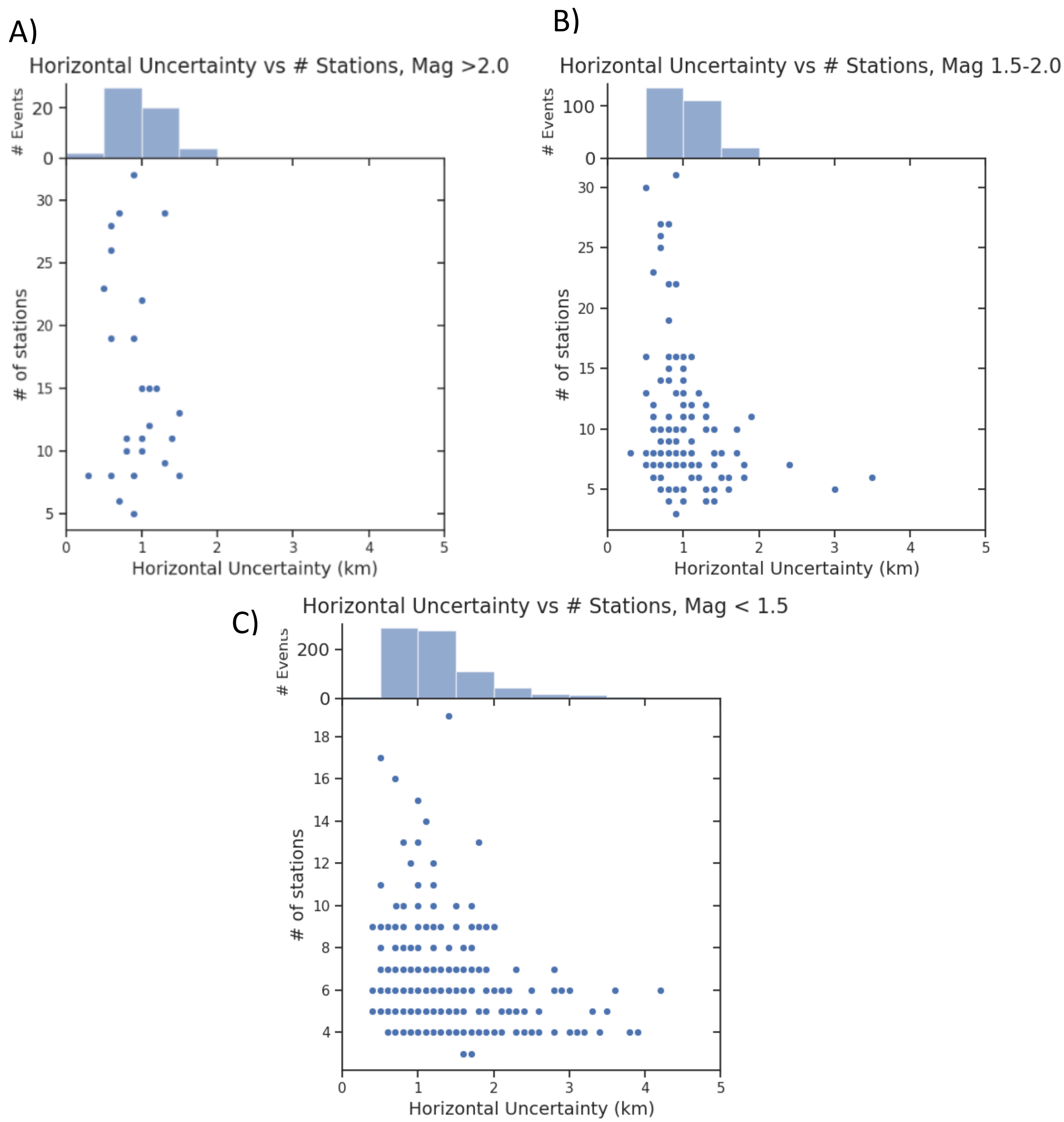

Figure 6: The same plot as in Figure 6 but for events with magnitude greater than 2.0 (A), magnitude between 1.5 and 2.0 (B), and magnitudes less than 1.5 (C). The histogram at the top of each plot shows the number of events in a given horizontal uncertainty bin.

To investigate if there are geographic differences in horizontal uncertainty estimates that might arise because of the use of a single 1D velocity model for event location, horizontal uncertainty estimates for seven regions across the state are shown next (Figure 8).

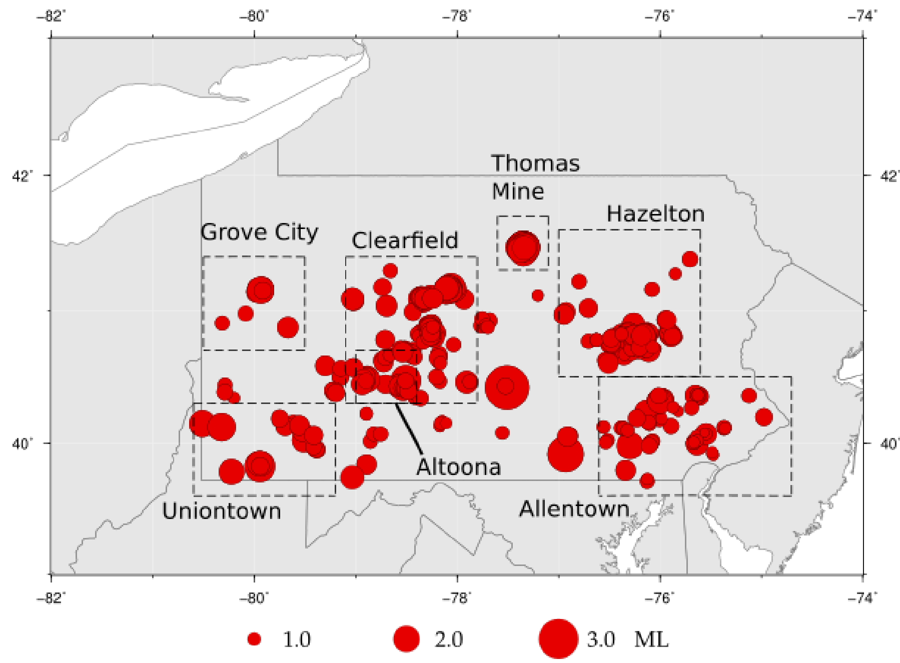

Figure 7: Seismic events in the PASEIS catalog grouped regionally. Regions are named for towns located within each region.

Figure 9 shows histograms of the horizontal uncertainty for each region. For these regions (Allentown, Altoona, Clearfield, Grove City, Hazelton, Thomas Mine, and Uniontown), while there are subtle differences in horizontal uncertainty estimates, with the Thomas Mine region showing the lowest average horizontal uncertainty of 1.04 km and the Allentown region showing the highest average horizontal uncertainty of 1.26 km, overall the horizontal uncertainties for each region are similar. We therefore conclude that the 1D velocity model used for locating seismic events across the Commonwealth is fairly representative of average crustal structure in Pennsylvania and does not lead to significant geographic variations in location uncertainty.

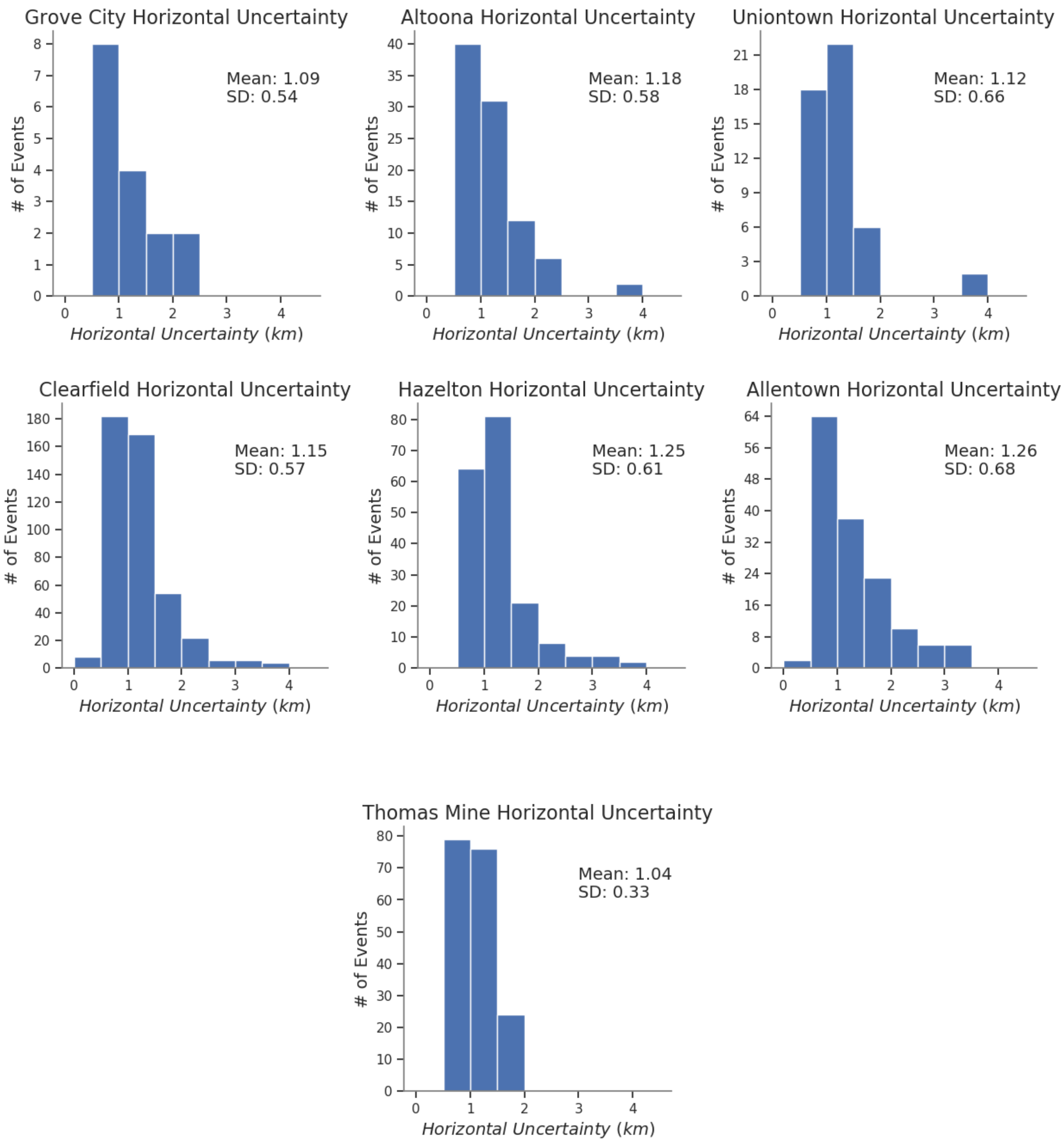

Figure 9: Formal horizontal uncertainty distributions for the regions shown in Figure 8.

3.2 Ground Truth Derived Horizontal Uncertainty

To estimate the horizontal uncertainty in event locations using the ground truth method, we use events from four mining locations where we can associate individual events with blasting from a specific mine (Figure 10).

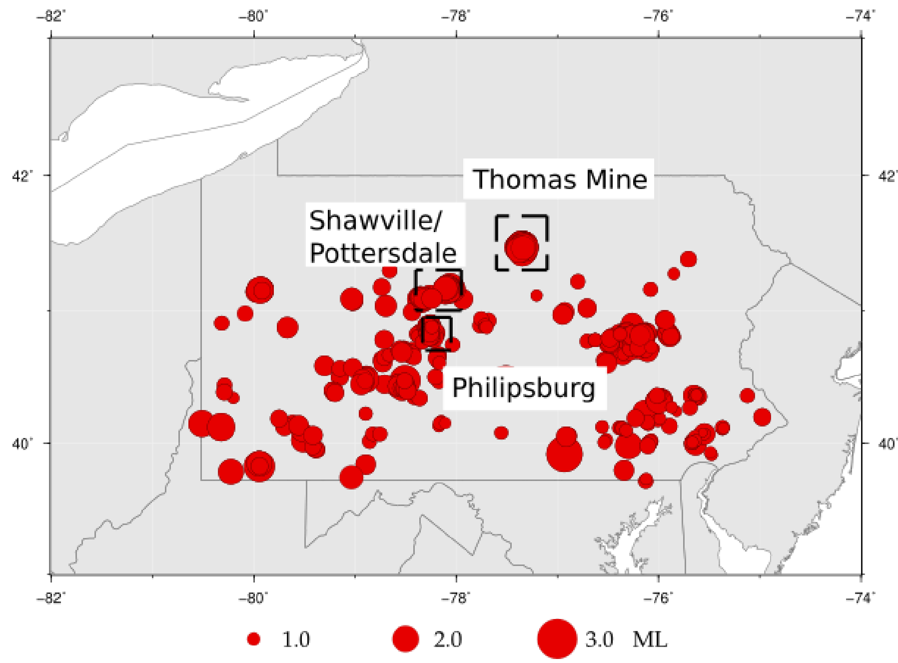

Figure 10: PASEIS event map showing mine locations used for the empirical ground truth analysis of location uncertainty.

The ground truth uncertainty results are similar for all four mines, ranging from 1.6 to 1.9 km. The ground truth uncertainty is approximately 0.6 km greater than the formal uncertainty estimate for each mine, indicating that the formal uncertainty may systematically underestimate the actual location uncertainty by about 0.6 km. Additionally, the standard deviation (sd) is slightly higher for the ground truth uncertainty estimates than for the formal uncertainty estimates for each mine. Nevertheless, the range of location uncertainties (0 to 4.2 km) for the two methods (formal uncertainty vs. ground truth) is the same. The results for each mine are summarized in Table 1, and event location maps and histograms showing the distribution of uncertainty estimates using formal uncertainties and ground truth uncertainties are shown Figures 11-17.

Region	Mean Ground Truth Uncertainty (km)	Ground Truth (sd)	Mean Formal Uncertainty (km)	Formal (sd)
Philipsburg	1.90	1.07	1.18	0.52
Thomas Mine	1.74	0.77	1.04	0.33
Shawville	1.63	0.76	1.04	0.59
Pottersdale	1.64	0.85	1.06	0.65

Table 1: Results from the ground truth uncertainty analysis for the four mining regions.

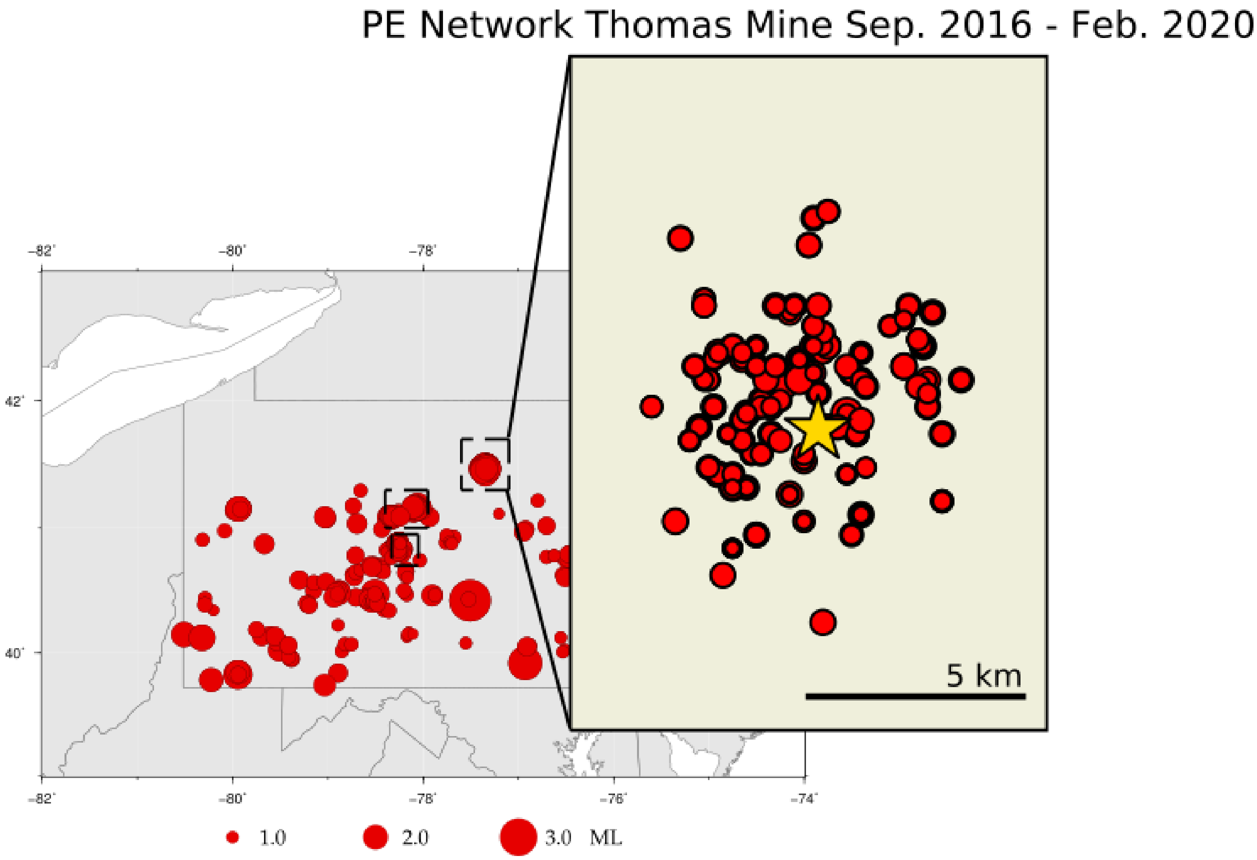

Figure 11: Seismic events located in the Thomas Brothers Coal mine. Seismic events are indicated by red circles and the mine location is shown as a gold star.

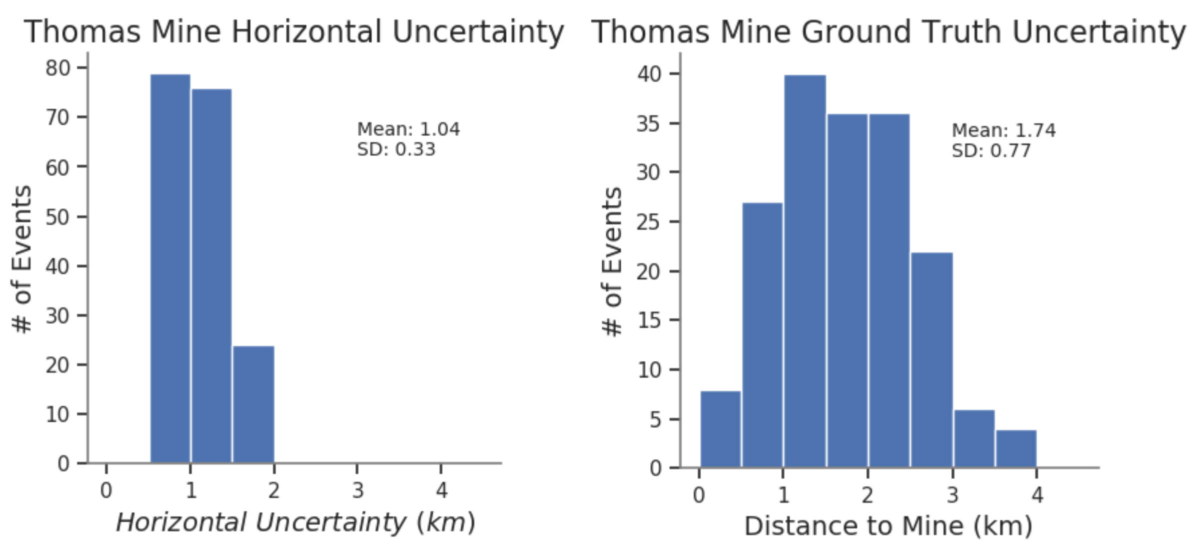

Figure 12: Formal horizontal uncertainty (left) and ground truth uncertainty (right) distributions for the Thomas Mine events.

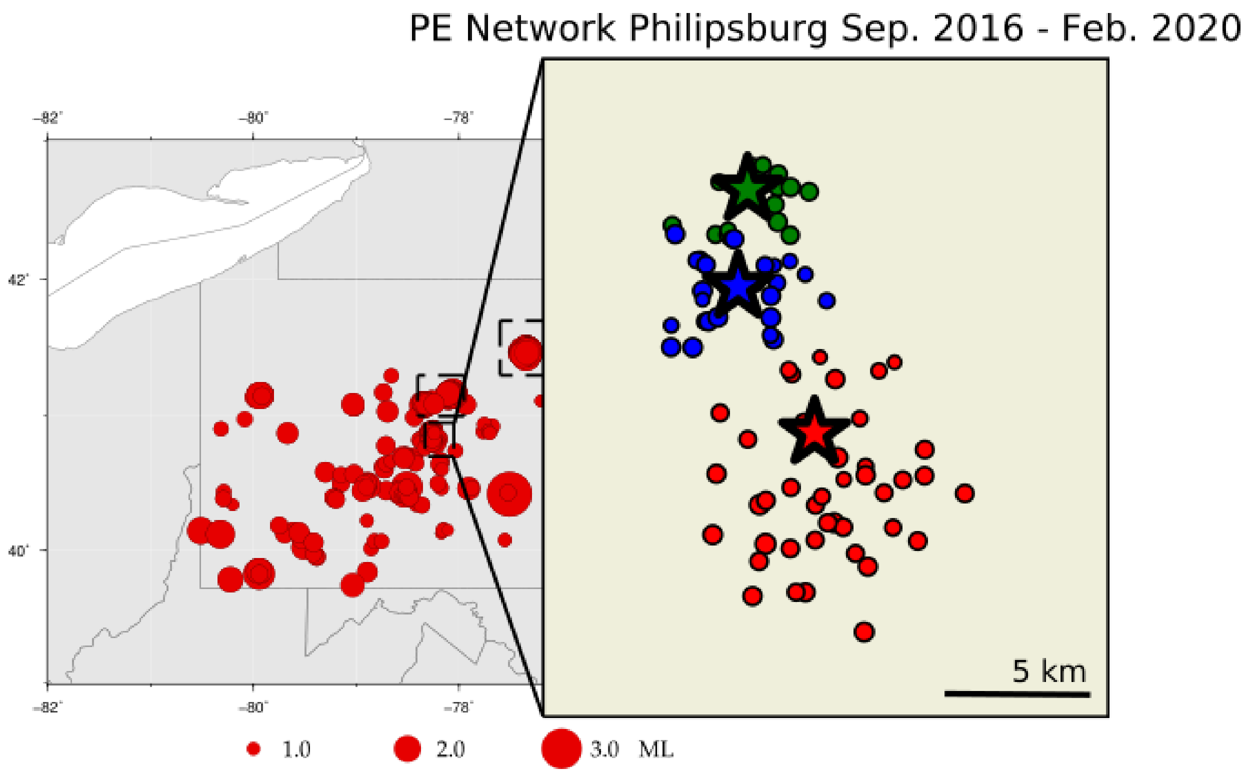

Figure 13: Seismic events and mines in the Philipsburg mining region. Events are marked by circles and mine locations are stars. Mines (stars) and their associated events (circles) are shown with the same color.

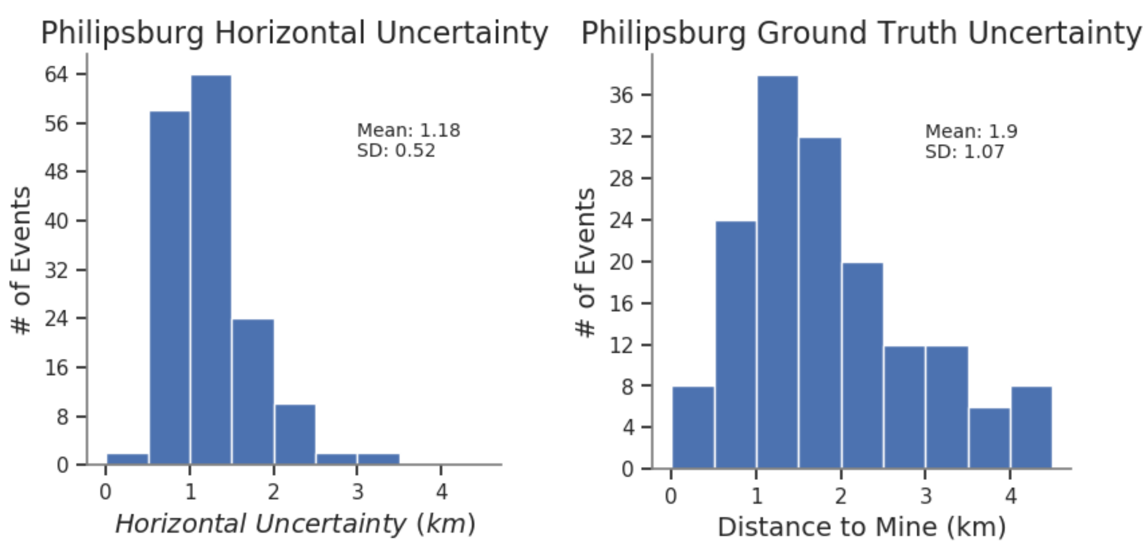

Figure 14: Formal horizontal uncertainty (left) and ground truth uncertainty (right) distributions for the mine events in the Philipsburg area.

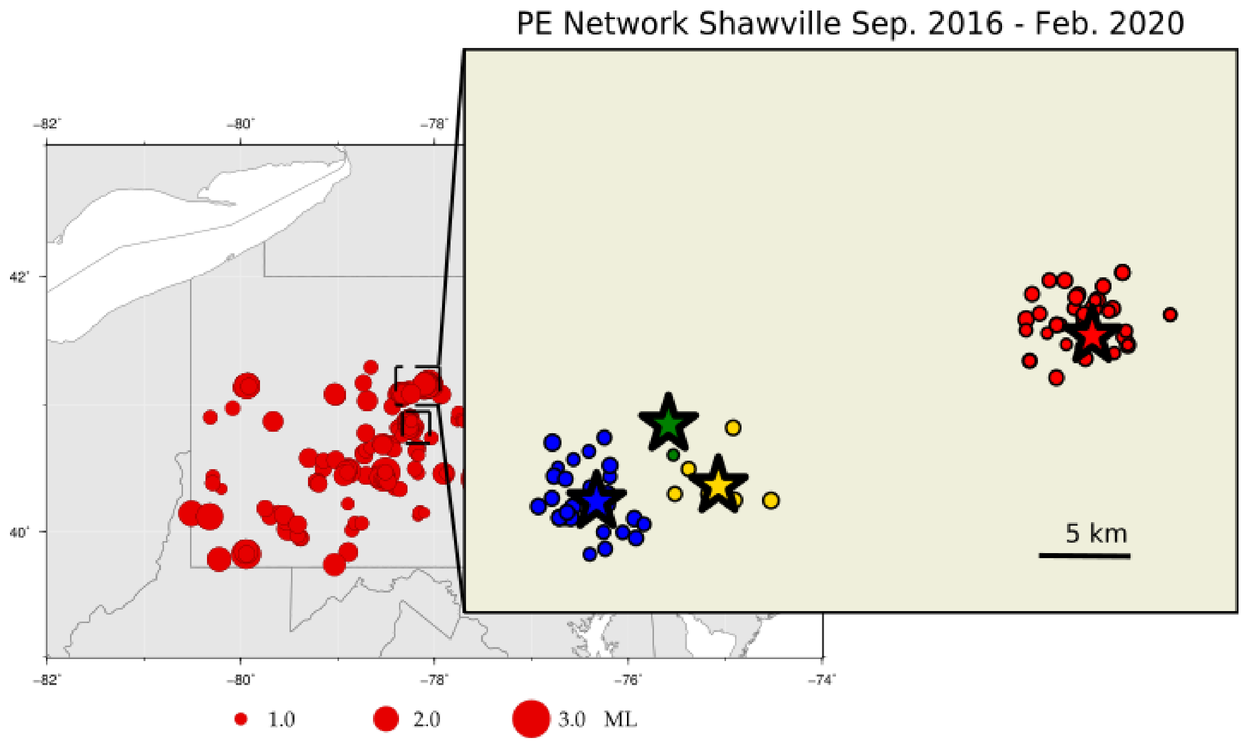

Figure 15: Seismic events and mines in the Shawville and Pottersdale mining regions. Mines (stars) and their associated events (circles) are shown with the same color. The Shawville region is comprised of the 3 mines (blue, green, and yellow) to the west and the Pottersdale region is the single mine (red) to the east.

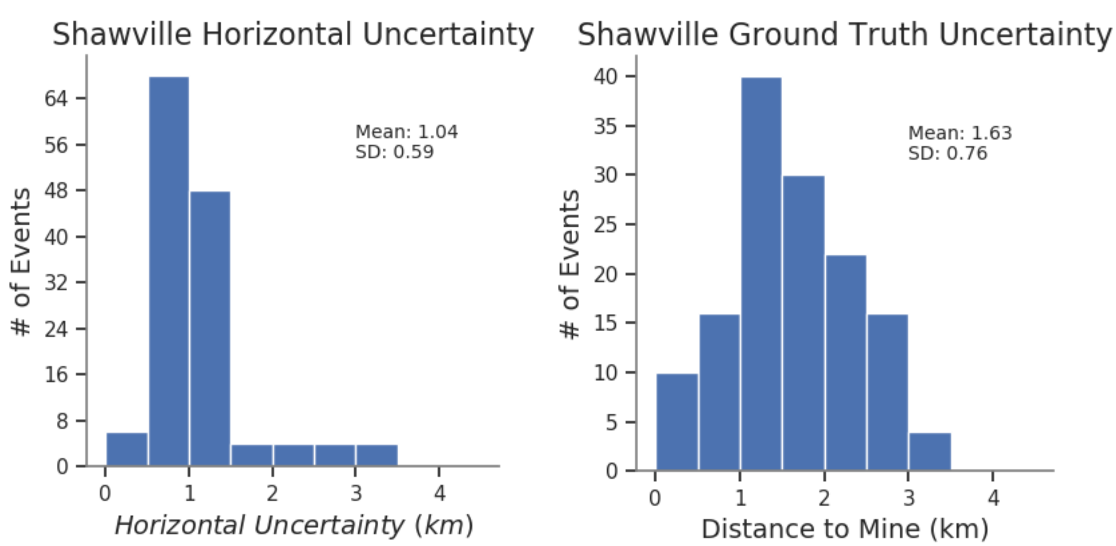

Figure 16: Formal horizontal uncertainty (left) and ground truth uncertainty (right) distributions for the mine events in the Shawville mining region.

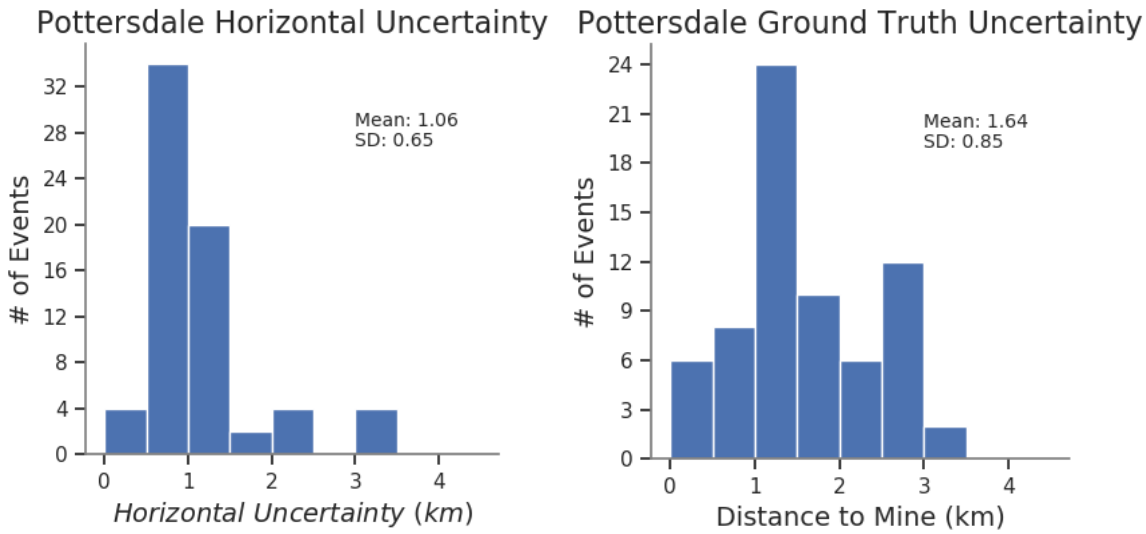

Figure 17: Formal horizontal uncertainty (left) and ground truth uncertainty (right) distributions for the mine events in the Pottersdale mining region.

4.0 Conclusions

The maximum uncertainty in horizontal locations reported in the PASEIS catalog is 4.2 km. The average formal uncertainty is 1.2 km, and is fairly consistent across the Commonwealth. The average uncertainty in horizontal locations estimated using mine blasts as "ground truth" is 1.7 km. There is a strong correlation between the number of stations used for locating an event and the horizontal uncertainty in the event location. In general, seismic event locations have lower uncertainty when more seismic stations are used in the location process. The 1D velocity model used for locating seismic events across the Commonwealth is fairly representative of average crustal structure in Pennsylvania and does not lead to significant geographic variations in location uncertainty.

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