

P/S AMPLITUDE AND MOMENT TENSOR DISCRIMINATION OF EXPLOSIONS AND EARTHQUAKES AT DISTANCES LESS THAN 100 km

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1. SUMMARY

Explosions and earthquakes are effectively discriminated by P/S amplitude ratios for moderate magnitude events ($M \geq 4$) observed at regional to teleseismic distances (≥ 200 km). It is less clear if P/S ratios are effective explosion discriminants for lower magnitude events observed at shorter distances. We report new tests of P/S and other local seismic source discriminants. An extensive local distance dataset with single-fired borehole explosions and earthquakes near Mt. St. Helens was used to evaluate parameter choices for calculating P/S ratios and explore dependencies on depth, distance, magnitude, site effects, and number of stations in the seismic array. A frequency band of 10–18 Hz performs better than lower or narrower bands because explosion-induced S amplitudes diminish relative to P for higher frequencies but there is large variability among sources and receivers. Source depth and magnitude exhibited weak influences at local distances. Site responses for earthquakes and explosions are correlated with each other and with shallow crustal Vp and Vs from travel-time tomography. Overall, we find high potential for local distance P/S explosion discrimination near Mt. St. Helens, with binary classification results of $\geq 98\%$ true positives and $\leq 6.3\%$ false positives when using the array median from ≥ 16 stations. Performance is reduced for smaller arrays, especially those with ≤ 4 stations, thereby emphasizing the value of array data for discriminating low-yield underground explosions.

For the Mt. St. Helens dataset, we also analyzed focal mechanisms with first motion polarities, S/P amplitudes, and waveform-based moment tensor inversion. While the fraction of positive first motion polarities is higher for explosions (94.63% versus 53.45%), limited coverage of the lower hemisphere results does not preclude fitting the explosion data with double-couple solutions. Focal mechanism estimates improved with the addition of S/P amplitudes mapped onto the lower hemisphere. On average explosions produce a wider variety of potential fault plane orientations for $M > 2$ events, but double couple solutions remain viable. Waveform-based moment tensor inversions were challenged by the simplicity of Green's functions for 1D structures compared to the complexity of observed signals at > 0.5 Hz.

Combining P/S ratios with $M_L - M_C$, which is a depth sensitive measure for local events, was tested with the Mt. St. Helens dataset and three other local distances datasets: the Salton Trough rift in southern California, the Bighorn Mountains and surrounding basins in Wyoming, and the Nevada National Security Site. Each dataset contained single-fired borehole explosions and earthquakes with most source-receiver distances < 200 km. We find that P/S ratio and $M_L - M_C$ exhibit complementary sensitivity for local explosion discrimination. Benefiting from the dense monitoring networks, the joint method improves the discrimination performance in each locality without site corrections. Binary classification resulted in true positive rates of 100% for all four datasets. False positives rates were 1.11% (Mt. St. Helens), 0% (Salton Trough), 0% Wyoming, and 1.14% (SPE). As the localities benefitted from unusually dense array

coverage (i.e., 50–100 stations), further tests are needed to evaluate performance with more limited numbers of stations and test transportability beyond the four localities used here. Joint P/S and M_L - M_C classification could benefit local-regional scale screening as well as future developments of machine-learning based seismic source classifiers.

2. INTRODUCTION

Seismic detection and discrimination of explosive sources are among the most useful tools for detection of underground nuclear weapons tests and a key component of verifying compliance with nuclear test-ban treaties (Bowers and Selby, 2009). Methods for seismic discrimination of nuclear explosions and earthquakes were initially developed for events observed at regional to teleseismic distances (≥ 200 km), which generally requires $M \geq 4$ (Richards and Zavales, 1990). P/S amplitude ratios are effective discriminants of explosions and earthquakes at teleseismic distances based on empirical evidence that large explosions ($M \geq 4$) produce greater P/S amplitude ratios compared to tectonic earthquakes (e.g., Taylor et al., 1989; Kim et al., 1993; Walter et al., 1995; Hartse et al., 1997; Xie and Patton, 1999; Jenkins and Sereno, 2001; He et al., 2018; Walter et al., 2018). However, efforts to use P/S ratios at local distances have shown mixed results, leading to questions about the effectiveness of this discriminant for local crustal propagation (O’Rourke et al., 2016; Pyle and Walter, 2019). The ubiquity and underlying cause(s) of the mixed results are not well constrained, which prevents reliable prediction of where P/S discrimination will be effective at local distances. This study seeks to increase the empirical basis for assessing the reliability of local distance P/S discrimination, including testing of implementation choices and performance in multiple localities.

Focal mechanism and moment tensor inversions are also useful explosion discriminants with a strong observational basis for success beyond local distances and for $M > 3$ sources (Jost and Hermann, 1989; Minson and Dreger, 2008; Ford et al., 2009). The applicability and discriminating power of moment tensor estimates is more uncertain for local distance events because relatively few studies have applied full moment tensor inversions to $\sim M 1$ sources (e.g., Alvizuri and Tape, 2016). Here we seek to test the ability of these methods to discriminate between earthquakes and controlled explosions, $\sim M 1$ - 2.3 , with a dense local broadband array. Inversions explore a mix of constraints including first-motion polarities, S/P amplitudes, and waveform fitting.

A third type of commonly applied seismic metric for preliminary event classification or ‘screening’ is differential magnitude analysis. At teleseismic distances the difference m_b - M_s has long been shown to help identify potential explosions that produce stronger body waves but weaker surface waves relative to earthquakes (Stevens and Day, 1985; Russell, 2006; Selby et al., 2012). At local distances recent work has shown that M_L - M_C is a discriminant of event depth and consequently helps identify explosions which are typically very shallow compared to earthquake sources that typically occur at depths of several km or more (Holt et al., 2019; Koper et al., 2021).

Given that coda energy is commonly abundant in local distance recordings and that part of the wavefield is not included in P/S ratios, there may be complementary sensitivity to source properties. Consequently, we test classification jointly using P/S ratios and M_L - M_C in the final portion of this report.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Data

This study uses seismic recordings of earthquakes and single-fired chemical explosions in shallow boreholes. Most analysis focused on data from the area near Mt. St. Helens in southwestern Washington (Figure 1a, Table 1), which was used to optimize P/S ratio discrimination for local distances and initially test joint P/S and M_L - M_C discrimination. Three additional local datasets (Figure 1b–d, Table 1) were incorporated in the final stages of the project to test the transportability of analysis methods beyond the Mt. St. Helens area.

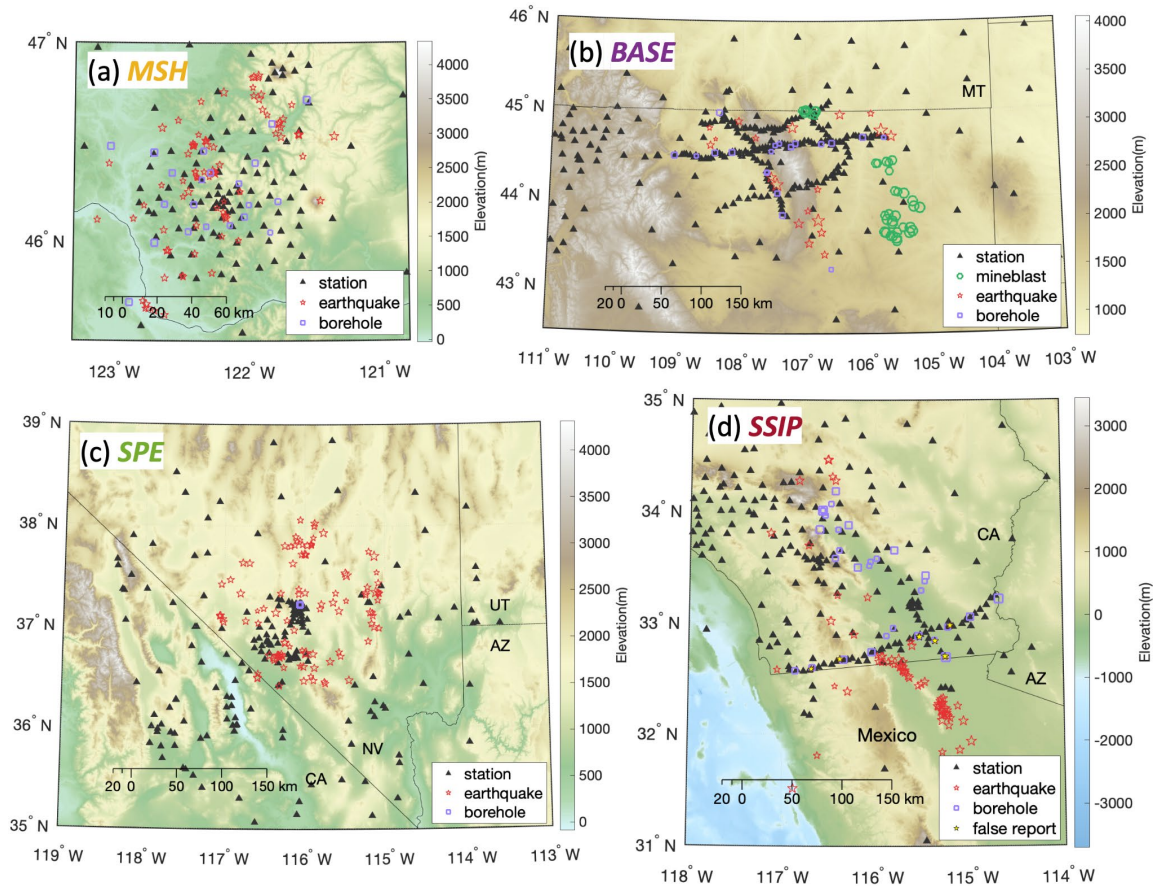


Figure 1. Seismic networks and events for the four local datasets (a–d). See Table 2 for details of the six “falsely reported” earthquakes in SSIP (d).

Table 1. Source information for the four study areas.

Dataset	Time period	Distance (km)	Number of earthquakes [M _L range]	Number of borehole shots [M _L range]	Number of mine blasts [M _L range]
iMush	2014-06-20 2018-06-30	0–150	91 (406) [1.5–3.3] ([1–3.3])	23 [0.9–2.3]	0 [-]
BASE	2010-06-21 2010-09-26	20–350	19 [0.3–2.7]	21 [0.7–1.7]	37 [1.8–3.3]
SPE1	2011-01-01 2018-12-31	0–300	110 [1.0–4.4]	5 [1.2–2.1]	0 [-]
SSIP	2011-02-28 2011-03-17	0–300	70 [1–3.8]	41 [0.6 – 2.1]	0 [-]

Near Mt. St. Helens, explosions were detonated for the controlled source component of the iMUSH (imaging Magma Under St. Helens) project to image the magmatic system underlying (Hansen et al., 2016; Kiser et al., 2016, 2018). Eight of the 23 boreholes were loaded with 907 kg of explosive, and the other 15 were loaded with 454 kg. Earthquake source information from 2014 to 2016 was provided by the Pacific Northwest Seismic Network, which contributes to the United States Geological Survey Comprehensive Catalog (ComCat; United States Geological Survey, 2020). Earthquakes within 75 km of Mt. St. Helens with $M_L \geq 1$ were used (a total of 406, where 90 events with $M_L \geq 1.5$ were used for joint analysis). These criteria provide a close match to the magnitude and distance range of the explosions (M_L 0.9–2.3; calculated based on waveform amplitudes instead of yield; Table 1).

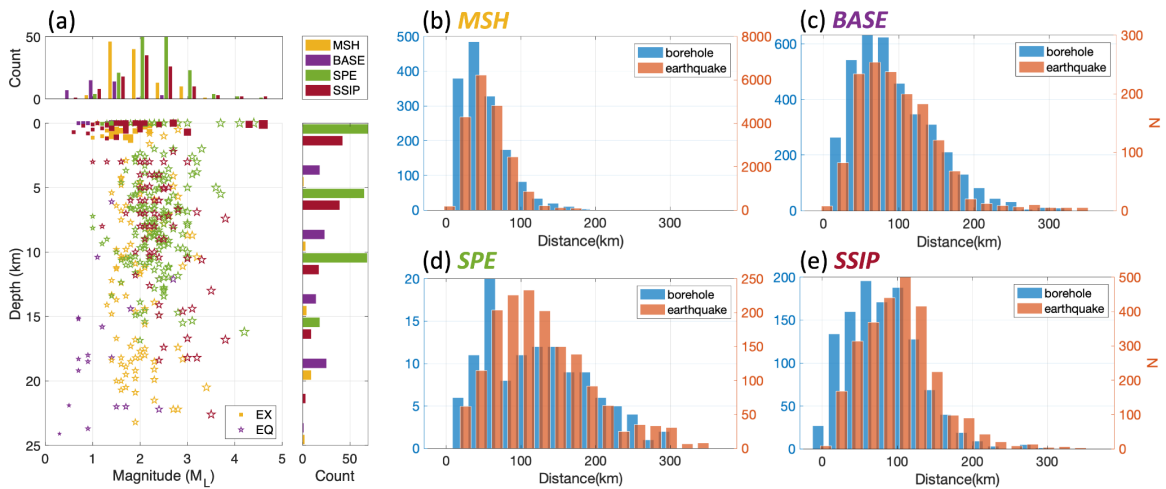


Figure 2. Event depths and source-receiver distances. *a)* Magnitude and event depth distributions for the four datasets (Figure 1). *b–e)* event-station distance distributions. EX-explosives (borehole events), EQ-earthquakes.

The primary seismic waveform data for Mt. St. Helens area are from the broadband part of the iMUSH project (Crosbie et al., 2019; Han et al., 2018; Mann et al., 2019; Ulberg et al., 2020). The iMUSH broadband network (XD 2014–2016) was combined with permanent broadband networks (CC and UW) to create a composite network of up to 95 stations within 75 km of Mt. St. Helens (Figure 1a). Most source-receiver distances are concentrated at <120 km (Figure 2). Based on the minimum sample rate of 40 Hz, we limited our analysis to frequencies ≤ 18 Hz. The Mt. St. Helens dataset used in this study is openly available (<https://doi.org/10.5281/zenodo.5115136>) Examples of explosion and earthquake record sections from the broadband array are shown in Figure 3. The example events have equal local magnitudes ($M_L=1.9$), and they are plotted after application of band-pass filtering from 2 to 6 Hz. The explosion source exhibits a stronger P wave than the earthquake, while the earthquake exhibits a more prominent S wave (Figure 4).

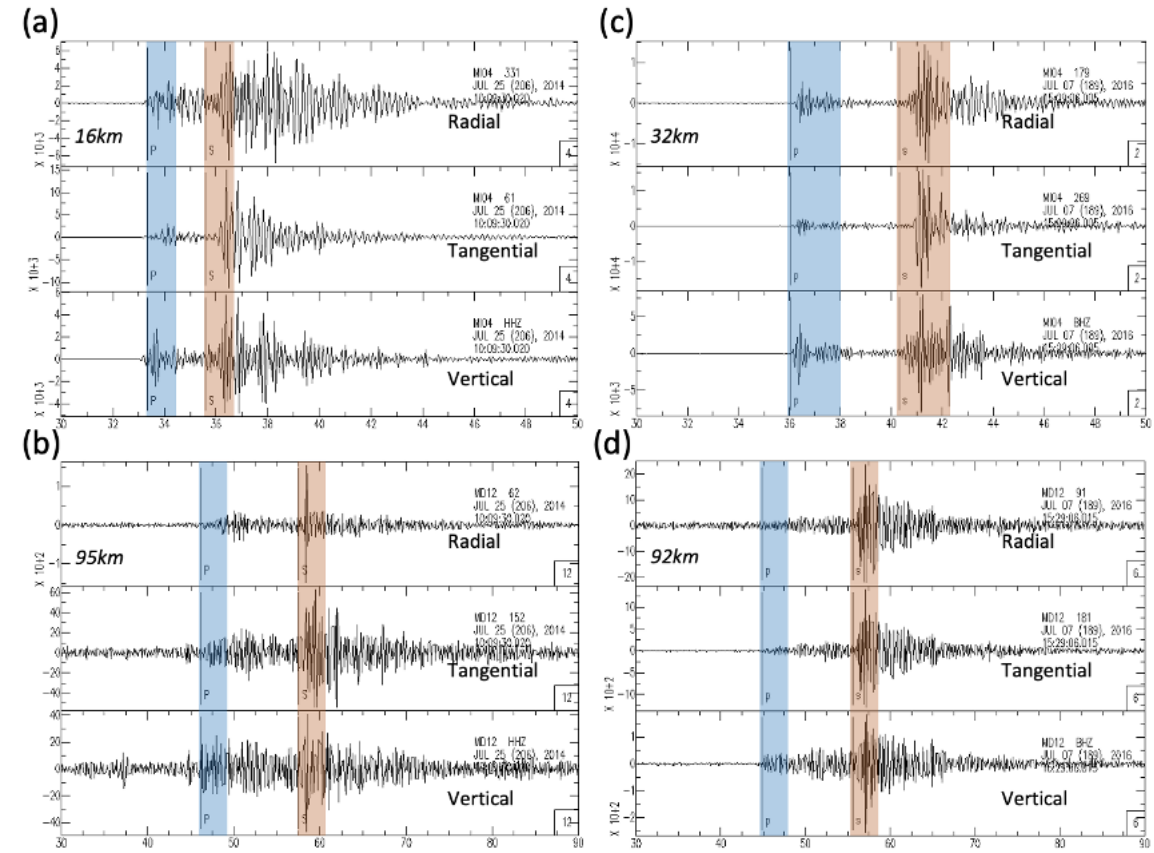


Figure 3. Example of phase windowing on unfiltered waveforms. *a) and b): explosive source* ($X4$, $M_L 1.3$; see Table S1) recorded at near and far source stations. *c) and d) earthquake* (2016/07/07 15:29:36 UTC, $M_L 2$, depth=18.2 km; also see Table S1) recorded at near and far source stations. Note in *b) and d)*, the time scales are 3 times of *a) and c)* and the phase windows are bounded by 3 sec.

A secondary source of seismic waveform data near Mt. St. Helens are vertical-component geophones deployed during the iMUSH controlled source imaging experiment (Hansen et al., 2016; Kiser et al., 2016, 2018). Our analysis of P/S energy focuses on three-component recordings, so we only present record sections from the vertical geophones to illustrate local phase propagation (Figure 4). In Figure 4, the geophone seismograms for 23 explosions (70,944 source-receiver pairs) were binned in 1-km distance intervals and the median envelope in each bin is plotted with trace-normalized amplitude. The high density of recordings illustrates S -wave existence starting at small distances and extending across the array. Comparison of the 2–6 Hz and 6–18 Hz envelopes in Figure 4 shows diminished S wave amplitudes relative to P for higher frequencies. Due to the short duration of the geophone deployment and movement of most geophones during the experiment, there are few opportunities for comparison with earthquakes. Consequently, we focus on the broadband data for further analysis.

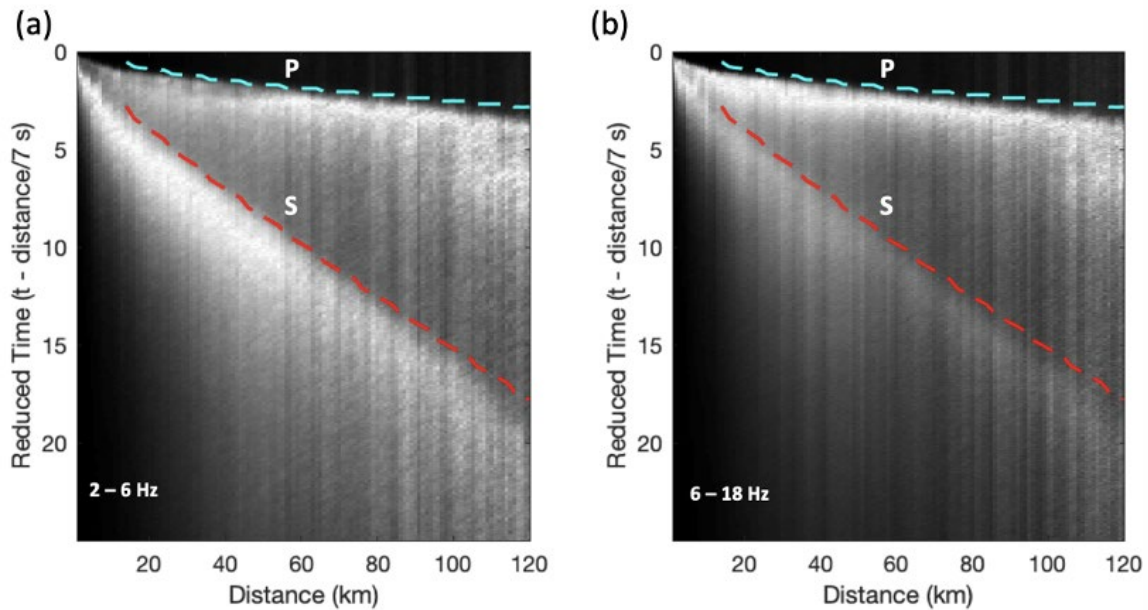


Figure 4. Stacked geophone recordings of explosions. *a)* Median envelopes of geophone seismograms from all 23 explosions in 1 km distance bins. Seismograms were bandpass filtered from 2–6 Hz before envelope calculation, median-stacking, and trace-normalization. *b)* Same as *A*, except that seismograms were bandpass filtered from 6–18 Hz.

Three additional local distance datasets were used for subsequent tests of the P/S discrimination approach initially optimized for the Mt. St. Helens area: the Bighorn Arch Seismic Experiment (BASE), Source Physics Experiment phase 1 (SPE), and Salton Seismic Imaging Project (SSIP). The BASE project was conducted in 2010 to image the Bighorn Arch (Figure 1b; Worthington et al., 2016). The dataset contains 21 explosive sources (M_L 0.7–1.7; loads 113–907 kg), 19 earthquakes (M_L 0.3–2.7), and 37 mine blasts (M_L 1.8–3.3) recorded by ~90 broadband stations and ~180 short-period stations.

Most mine blasts are located to the southeast of the array (Figure 1b). The SPE phase 1 data set includes five borehole shots (M_L 1.2–2.1, loads 90–5,035 kg) in 2011, which occurred in the area of prior underground nuclear explosion tests in the U.S. (Figure 1c; Snelson et al., 2013). They are fired at the same location at the center of the array with variable depths (Figure 1c). The station coverage of these events ranges from ~3–35 km, which makes it the smallest among the four datasets. We used 110 earthquakes (M_L 1.0–4.4) that occurred in the area during or after 2011. SSIP conducted an active source seismic survey in 2011 to image crustal faults and constrain rifting processes (Figure 1d; Han et al., 2016; Fuis et al., 2017). Up to ~80 broadband stations were available during SSIP in 2011 and 126 explosions were single-fired with loads ranging from 3 to 1,440 kg. To ensure a comparable magnitude to earthquakes and the other 3 datasets, we only used 41 shots with loads >200 kg (M_L 0.6–2.1). The USGS catalog returns 76 events (M_L 1–3.6) during the month, including 6 borehole shots mis-cataloged as earthquakes (Table 2). The remaining earthquakes are mostly located within Mexico along the Imperial Fault Zone.

Table 2. Explosions reported as earthquakes by USGS.

Catalog Time (UTC)	Catalog Latitude	Catalog Longitude	Catalog Depth	Catalog M_L	Shot ID	True time (UTC)	True Latitude	True Longitude	Load (kg)
2011-03-06 12:09:02.400	32.703	-115.260	10	2	10460	12:09	32.69438	-115.25193	1367
2011-03-06 10:33:00.400	32.677	-116.386	3	1.8	20550	10:33	32.67207	-116.34656	911
2011-03-06 10:12:01.620	32.841	-115.367	13	1.7	10670	12:12	32.84924	-115.3718	458
2011-03-06 10:09:01.370	32.981	-115.205	4.8	1.7	21640	10:09	32.9638338	-115.2313188	592
2011-03-06 09:02:59.800	32.59	-116.693	0.6	1.5	20220	09:03	32.6008	-116.68154	684
2011-03-06 07:15:01.490	32.879	-115.535	17.2	2.1	21330	07:15	32.8851499	-115.5409971	911

The reported origin times of the six events are within 0.2–2.4 sec of and co-located with the six shots on March 6, 2011.

3.2 Calculation of local P/S ratios

Windowing of P and S energy on the three-component time series is a key processing step for calculation of P/S amplitude ratios. Requiring visually prominent picks is undesirable because it would bias the measurements toward events with clear P and S phases, whereas it is equally important to measure weak phases. Additionally, choosing only the component(s) with the strongest signal (e.g., vertical and/or radial) could bias the results by ignoring some energy scattered onto other components. We take the simple approach of using travel time estimates from locally specific 1-D velocity models to window the P and S phases and measure energy on all three components for both phases

(Figure 5). Using all three components may be done with the raw channel orientations (usually east, north, and vertical) or any orthogonal three-component transformation (e.g., radial, tangential, and vertical). Transformations such as L-Q-T or P-Sv-Sh are avoided because they would introduce greater dependence on knowledge of site-specific velocity structure (Vinnik, 1977; Kennett, 1991). Here, we used radial (R), tangential (T), and vertical (Z) components because these are often more intuitive than the raw channel orientations when plotting waveforms for visual inspection. Example waveforms show that significant energy is observed on all three components, including the tangential component for the P wave (Figure 3).

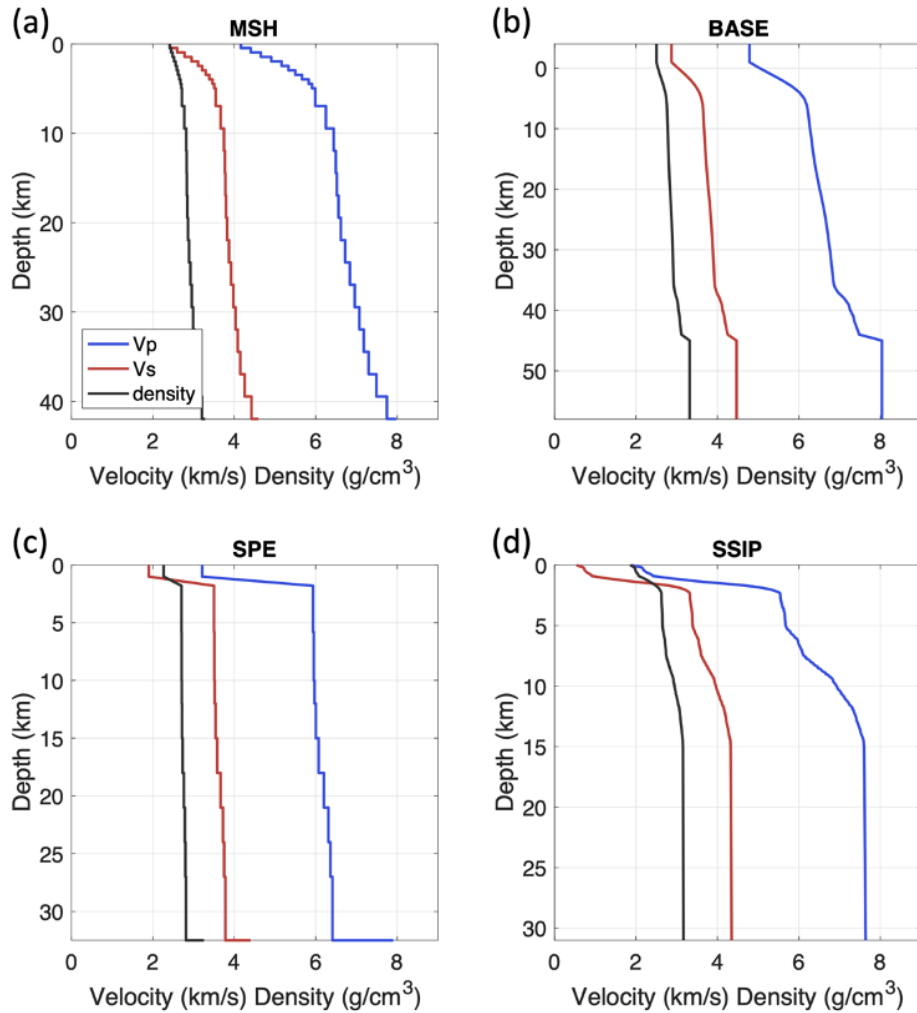


Figure 5. Velocity models used for the four study regions.

Timing of the windows is a challenge for local distance studies because the separation between the phases decreases with decreasing source-receiver distance. The time window duration used is 80% of the *S-P* time for smaller source-receiver distances. The window length transitions to a fixed value of 3 sec for distances beyond ~40 km. Observations at distances less than ~5 km are not used because isolation of *P* and *S*

phases is not reliable (i.e., window length <1 sec). Equal length pre-signal noise time windows were selected starting 10 seconds before the origin time of each explosion or earthquake source. We achieved similar P/S ratio results when increasing the maximum window length from 3 sec to 4, 5, and 6 sec for MSH. As our window is scaled with P - and S -wave arrival differences, such an increase only changes the window widths at larger distances (i.e., $\sim >50$ km). For the SSIP dataset, we expanded the maximum time window to 4 sec because it increased the number of acceptable seismograms by $\sim 17\%$. Travel time deviations from 1D predictions are expected to be large in the SSIP area because crust thickness varies from ~ 20 – 40 km and thick Quaternary sediments contrast strongly with exhumed batholiths (Han et al., 2018).

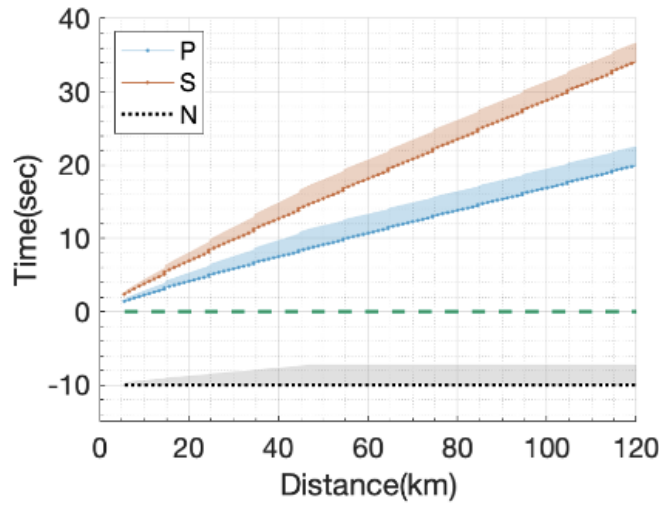


Figure 6. Phase windowing based on travel times from a local 1D velocity model for the Mt. St. Helens area.

Equation 1 shows how the windowed P , S , and noise (N) time series are used to calculate the P/S ratio. Subscripts are used to denote a term for each of the three orthogonal components. The windowed time series is squared and summed for each term.

$$R_n = \frac{\sqrt{(P_R^2 + P_T^2 + P_Z^2) - (N_R^2 + N_T^2 + N_Z^2)}}{\sqrt{(S_R^2 + S_T^2 + S_Z^2) - (N_R^2 + N_T^2 + N_Z^2)}}, \quad (1)$$

The same pre- P noise (Figure 6) energy is subtracted from both P and S -waves. Thus, our signal-to-noise ratio (SNR) criterion is only applied based on pre-event noise so that events with strong P coda but weak S waves are not discarded. Modified after O'Rourke et al., 2016, our equation also accounts for the P energy from tangential components. Such modification led to better separation between the P/S ratios for explosions and earthquakes across all distances (Figure 7).

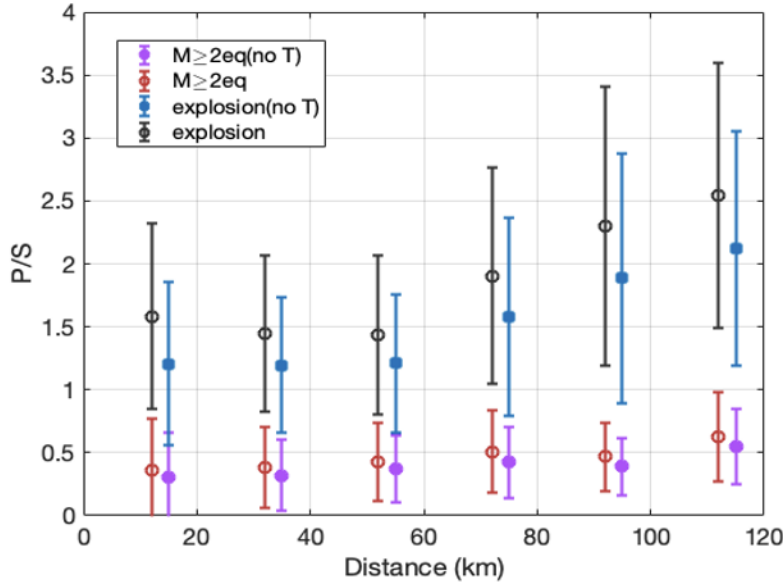


Figure 7. Effect of transverse component P-wave energy on P/S ratios. The error bars show medians and SMAD values of 10–18 Hz P/S ratios in 20 km bins.

To optimize the frequency bands of local P/S ratio calculations, we tested seven narrow and two wide ranges (Figure 8), where a Butterworth filter was applied to the response-corrected waveforms after demeaning and detrending. In general, higher bands provide larger separation in the median P/S ratios between earthquakes and explosions, while broader bands help to decrease the variance and stabilize discrimination of individual events (Figure 8). With respect to source discrimination, 10–18 Hz is the preferred frequency band for this local-distance dataset and it is used for all further analysis and other regions. Furthermore, we observe a frequency dependence of P/S ratios, with the ratio increasing with frequency for both earthquakes and explosions, although the increase is more pronounced for explosions. Such preference of higher frequencies revealed by the three-component broadband array data is consistent with the observation from the vertical-component geophones, showing that S -wave amplitude diminishes relative to P for higher frequencies (Figure 4).

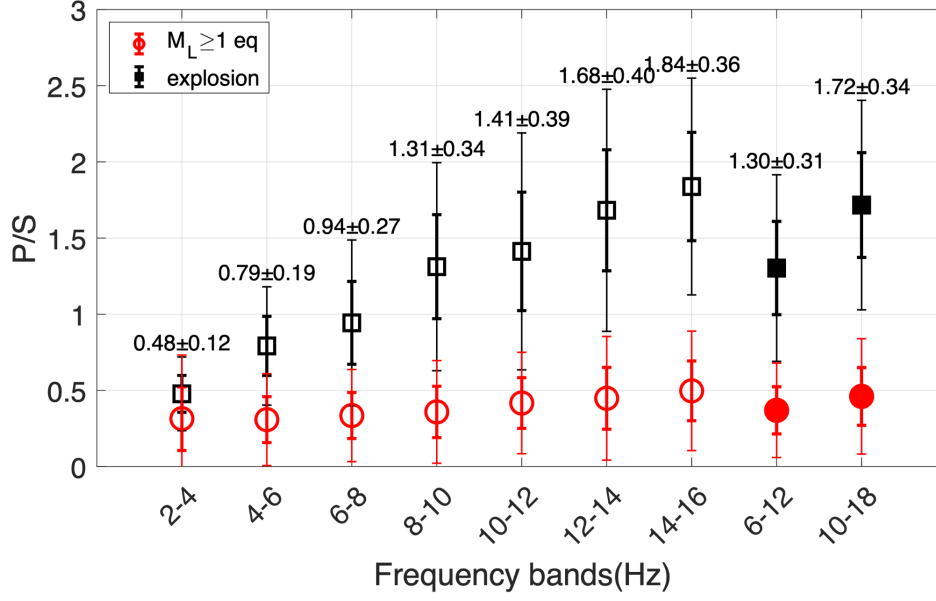


Figure 8. Frequency dependence of P/S ratio. Median P/S ratio for explosions and earthquakes for nine different frequency bands. Bold error bars are SMAD and thin bars are 2-scaled median absolute deviation (i.e., $2 \times \text{SMAD}$). The median $\pm$ SMAD for explosions are labeled.

Site corrections are often applied to P/S ratio-based discrimination measurements to minimize the effects of structural heterogeneity near individual stations (e.g., Walter et al., 1995) because the fine-scale structure that influences high-frequency amplitudes is usually not well constrained by tomography models. Benefiting from the large number of broadly distributed stations in the study area, we estimated station-based site corrections using P/S ratios of earthquakes (Figure 15a–c). This was chosen to mimic the circumstance in which P/S corrections could be estimated using only earthquake data and then applied to subsequent events of unknown physical origin. The correction is calculated as a normalization of event-averaged P/S ratio at each of the N stations:

$$C_{1, 2, 3 \dots N} = R_{eq@station(1, 2, 3, \dots n)} / \text{mean}(R_{eq@station(1, 2, 3, \dots n)}), \quad (2)$$

where $R_{eq@station(1, 2, 3, \dots n)}$ is a vector that contains N values, each corresponding to an event-averaged P/S ratio (i.e., calculated from up to 406 earthquakes) at a given station after the SNR control. For each event (explosion or earthquake) recorded at a subset of m stations, its P/S ratio is then corrected by dividing $C_{1, 2, 3 \dots m}$. The outcome of site correction is discussed in Section 4.1.

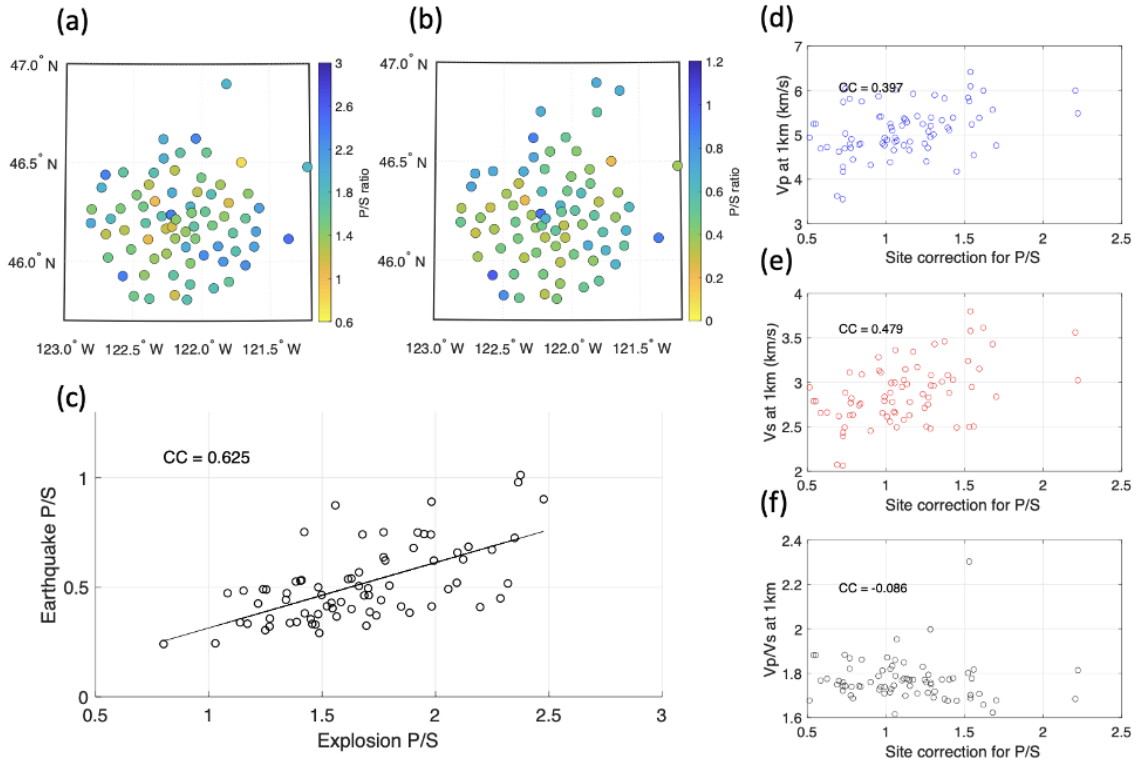


Figure 9. Site corrections and crustal seismic structure (calculated at 10-18 Hz). *a)* Map of station-averaged P/S ratios for explosions. *b)* Map of station-averaged P/S ratios for earthquakes. Note that the color scale is different from A so that the similarity in spatial pattern is easier to identify. *c)* Scatter of station-averaged P/S ratios for earthquakes versus explosions. *d-f)* Scatter plots of site correction versus V_p , V_s , and V_p/V_s at 1 km depth from Ulberg et al., 2020. CC: cross-correlation coefficient.

The composite array used near Mt. St. Helens provides better seismic sampling than is available in many areas where explosion monitoring is a salient (Figure 1a). Up to 95 stations are available during the 2-year period, but not all stations/components are available the entire time and meet the $\text{SNR} > 2$ threshold. To evaluate the potential of our preferred method and parameter set, we used bootstrap resampling tests to simulate results for different subset array sizes (Figure 10). For each subset, the cumulative array was randomly resampled 1,000 times (without replacement) from the 74 common stations that recorded all earthquakes and explosions without any prerequisite (i.e., SNR). Within each sampled set, the array-median P/S ratios for earthquakes and explosions were calculated after applying the SNR control. Thus, the bootstrapping approach attempts to simulate the realistic scenario that not all stations in an array produce useful results for every event.

3.3 Quantifying P/S discrimination performance

To evaluate the effectiveness of P/S discrimination of explosions and earthquakes we consider measurement distributions for a simple summary view and optimized binary classification using the receiver operating characteristic (ROC) curve (James et al., 2013). For measurement distributions, the array median and scaled median absolute deviation (SMAD) of all the individual P/S ratios are used (Figures 7&8). The one SMAD intervals of P/S ratios overlap for lower frequency bands and most narrow frequency bands. Distributions of P/S ratios are typically not Gaussian (i.e., long-tailed), so the SMAD and median values are preferred instead of the standard deviations.

To evaluate the performance of different frequency bands and array sizes, we use the ROC curve framework (James et al., 2013), which shows the diagnostic performance of binary classifiers calculated from: true positive, false positive, true negative, and false negative results (Figure 10). In this case for explosions and earthquakes, we treat explosions identified correctly as “true positives” and earthquakes identified as explosions as “false positives” (vice-versa for earthquakes). For each P/S ratio value used as a discrimination threshold, the point along the ROC curve is determined by the rate of true positives and false positives (Figure 10). The optimal discrimination threshold is chosen by maximizing the area under the curve (AUC) of the ROC. Thus, an ideal classifier would plot in the upper left corner corresponding to 100% true positives and 0% false positives. ROC curves are calculated for a variety of parameters including different numbers of seismographs, event magnitudes, and frequency bands (Figure 10). The results are discussed in Section 4.1.

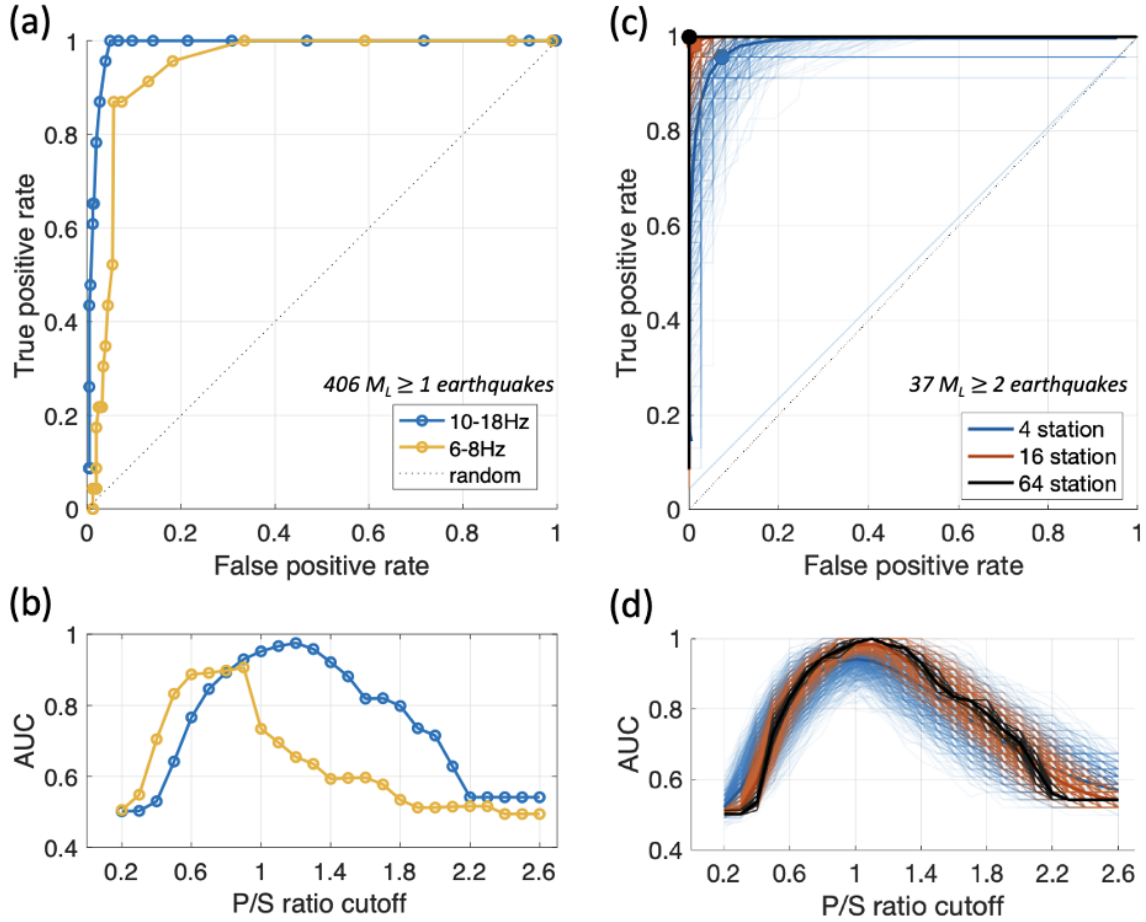


Figure 10. Binary classification performance using P/S near Mt. St. Helens. *a)* ROC curves for P/S ratio threshold optimization at 10–18 Hz and 6–8 Hz. *b)* Area under curve (AUC) for searched P/S ratio thresholds (0.1 step size from 0.2 to 2.6). The preferred P/S ratio cutoff is 1.2 at 10–18 Hz (AUC=0.98), which leads to a true positive rate of 100% and false positive rate of 4.93%. *c&d)* Similar to *a&b)* but showing bootstrapping results using only $M_L \geq 2$ earthquakes. The bold lines are averaged curves from 1,000 subsets and the three dots mark the highest AUC. Note that a few outliers exhibit near-random performance for the 4-station case (light blue near the diagonal in *c*) and a few others may reach AUC=1 while the averages (bold curves) are below 1 for 4-station and 16-station cases (in *d*).

3.4 Combining P/S and M_L-M_C

Based on recent results showing the effectiveness of M_L-M_C as a depth discriminant and consequently a useful identifier of potentially man-made events (Holt et al., 2019; Koper et al., 2021), we were motivated to test joint use of P/S and M_L-M_C . An additional motivation comes from the fact that the measurements use different parts of the local wavefield. M_L-M_C relies on lower frequencies (<10 Hz) and incorporates coda duration, while P/S as implemented here focuses on higher frequencies (i.e., 10–18 Hz) and only the amplitudes of the two major body wave arrivals. M_L-M_C values used in this report were provided by Dr. Koper and colleagues at the University of Utah and most were

previously published in Koper et al., 2021. We only briefly review their method for calculating M_L - M_C and proceed to investigation of their potential for joint discrimination of earthquakes and borehole explosions.

M_L and M_C values for all events are calculated from the waveforms; none of the M_L values are adopted from monitoring catalogs. Thus, all magnitude calculations are conducted without prior information of source type. To enable comparison of different localities and minimize region-specific parameters, a consistent calibration of both M_L and M_C (optimized for Utah) is used for all datasets (Pechmann et al., 2006; Voyles et al., 2020). When calculating the M_L , the regional broadband seismic records (i.e., “HH” and “BH” components) were converted to Wood-Anderson seismometer equivalent response. The station amplitude was then measured from the two horizontal-components without station or distance corrections (e.g., Richter, 1958).

For M_C calculation, the formula inherits the current duration magnitude definitions of University of Utah Seismograph Stations (Pechmann et al., 2006) with a modified cutoff threshold (SNR=2). All vertical components of high gain seismometers are corrected for instrument response and filtered between 1–10 Hz. The envelopes of seismographs are generated for coda windowing, which starts with the maximum S-wave magnitude and ends with the designated SNR cutoff. The M_C at a station is then calculated from the measured coda duration using the equations described in Koper et al., (2021). Note that the SNRs here are from single (vertical) components, different from the three-component SNR used for P/S ratio. For both M_L and M_C measurements, the final event magnitudes are determined as the median from ≥ 3 valid station-based measurements.

For joint P/S and M_L - M_C analysis, only source-receiver pairs that passed quality control for both methods were used. All P/S measurements for the joint analysis were conducted with the 10–18 Hz frequency band. The same processing steps were applied to the four local distance datasets described in Section 3.1. Each dataset includes natural earthquakes and similarly designed shallow borehole explosions; however, the geologic settings vary dramatically, allowing for an initial test of transportability.

3.5 Binary classification performance for the joint method

One popular metric to evaluate the performance of binary classification is the Mahalanobis distance (Δ^2 ; Tibi et al., 2018). The Mahalanobis distance mathematically quantifies the distance between a single data point and 2-D Gaussian distribution by considering the variances along the two different dimensions. The Mahalanobis distance between two populations can also be calculated by subtracting their discrimination scores (D):

$$\Delta^2 = D(\mu_{ex}) - D(\mu_{eq}) \quad (3)$$

Such discrimination scores were applied to forensic seismology by Kim et al., 2018, where a linear discrimination analysis (LDA) was performed. However, LDA assumes the two metrics share the same variances, which is often not the case. The assumption is also invalid for our joint analysis between P/S and M_L-M_C , where the two measurements have substantially different distributions. A potential solution is to use P/S ratios in the log scale and adopt a quadratic discrimination function (QDF). Following Tibi (2021), the bivariate QDF takes different means and covariances into consideration (see equations 1–4 in Tibi, 2021; also see Tibi et al., 2018). Unfortunately, the inclusion of covariance penalties, also increases the sensitivity of discrimination score to outliers, especially for larger datasets with non-Gaussian distributions like P/S ratios. In contrast, the ROC evaluation is event-oriented (see Section 3.3). The TPR and FPR are used instead of variances (e.g., standard deviation from L2 norm; or median absolute deviation from L1 norm). The TPR and FPR (and AUC; or recall and precision) parameters are more resistant to outliers, analogous to event-based L1-norm evaluations. For comparison, the covariance ellipses of the two populations overlap at two standard deviations in the P/S vs. M_L-M_C domain. For record-based P/S ratios, the distributions for earthquakes and explosions overlap across most distances like previous studies, even when median absolute deviation is used (e.g., Figure 7&8). In general, AUC evaluates a discrimination that has been performed on known datasets, whereas Mahalanobis distances could reflect the robustness of the discriminations that may transfer to future applications.

3.6 Focal mechanism analysis

To evaluate the focal mechanisms of the studied events, we first picked first-motion P polarities for all explosive sources and 37 $M_L > 2$ earthquakes. In total, >5000 vertical component waveforms filtered between 1–15 Hz were picked for first-motion polarity. Following the manual of FOCMEC (Snoke, 2003), we label each first motion pick with one of four categories: U (up), D (down), + (potentially up), and - (potentially down). The waveforms without clear first motion polarity are abandoned. We retain 1,404 and 2,304 effective picks for explosive sources and earthquakes, respectively (Figure 11).

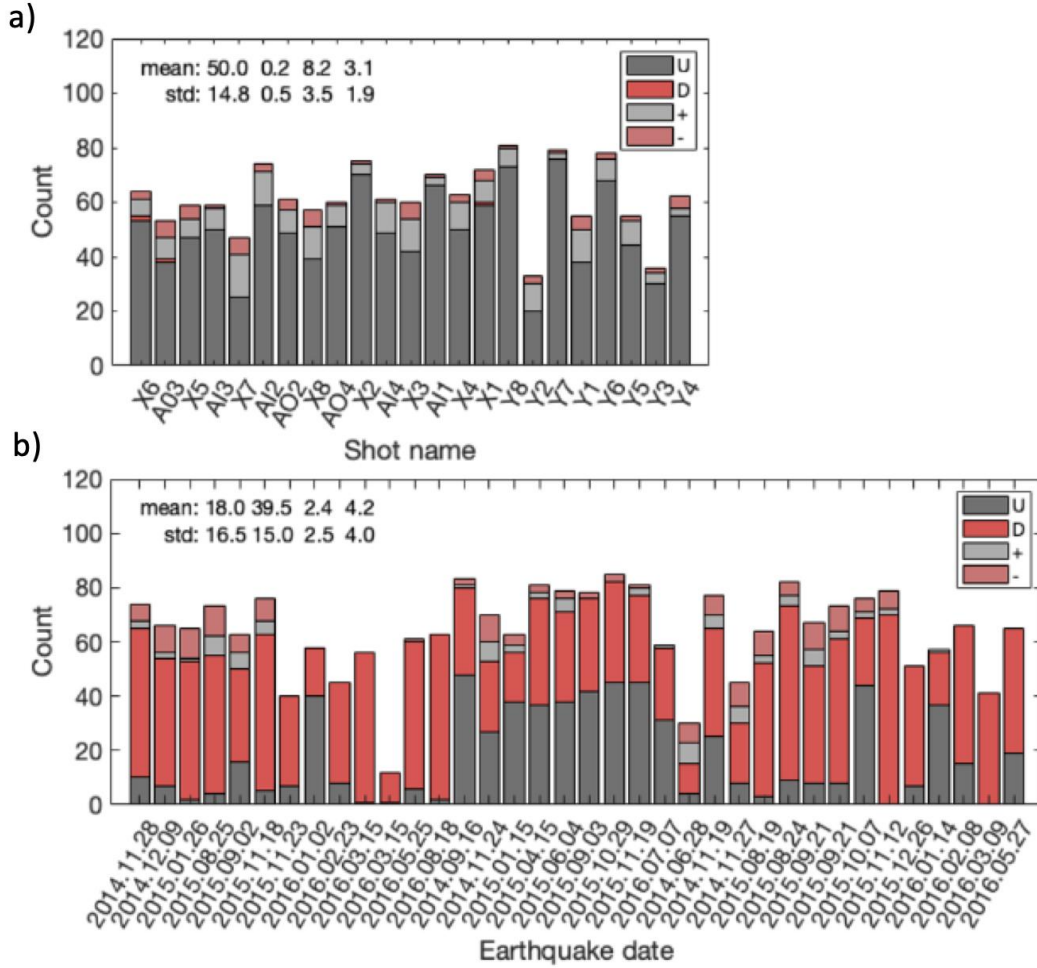


Figure 11. Statistics of valid first motion picks. a) Histograms for four types of P-wave first motions picked for explosions and b) $M_L > 2$ earthquakes. The average (mean) and standard deviation (std) for numbers of four types of picks are labeled in the figures, following the order of the legends.

The valid picks were initially passed to FOCMEC for focal mechanism fitting. As the package was set up to fit double-couple solutions, ideally the explosive sources would not lead to acceptable fault plane solutions and the earthquakes would. However, many earthquakes and explosions could not be fit by FOCMEC (see Section 4.3).

To augment the constraints on the focal mechanisms, we incorporated results from P/S ratios and adopted the HASH method (Hardebeck and Shearer, 2002, 2003). HASH uses S/P ratios mapped onto the lower hemisphere to reduce non-uniqueness of first motion inversions with limited coverage. Table 3 records the detailed parameter sets for HASH. The results from HASH may include one or more acceptable focal mechanisms along with quality grades. In this study that focuses on discrimination between earthquakes and explosions, we investigate differences between the number and quality of focal mechanism solutions between the two source populations. Examples from individual events and summary results are presented in Section 4.3.

Table 3. HASH parameters.

source error	0.1 km (epicenter) 1 km (depth)
minimum number of polarity pick	10
azimuth gap	90 (deg)
take off angle gap	90 (deg)
number of trials	30
maximum output solutions	300
possibility of false picks	0.05
source-station distance limit	100 km
angle for computing mechanisms probability	45
number of velocity models	1

3.7 Waveform-based moment tensors

Another way to resolve the focal mechanisms of such low-moderate earthquakes is moment tensor inversion. A Green's function library is generated for Mt. St. Helens region using frequency-wavenumber method (Saikia, 1994) based on a simplified 27-layer 1D velocity model (Kiser et al., 2019; Figure 5a). The distance and depth ranges are 5–200 km and 0–24 km with 1 km steps, respectively, corresponding to the study scales (Figure 2). The sample rate for the synthetic waveforms was set to 0.2 sec, corresponding to a Nyquist frequency of 2.5 Hz. The library allows us to simulate waveforms for both the explosives and earthquakes by convolving an isotropic source or a strike-slip source (or a mix of these two) with the calculated Green's functions. Waveforms examples are shown and discussed in Section 4.3.

The full moment tensor inversion is then conducted in the time domain (i.e., TDMT_INV; Dreger, 2003), where three component waveforms and the synthetics are filtered with a preferred frequency band (e.g., ~0.2–2 Hz for local scales). Different from most geophysical inversion problems, such inversion for full moment tensor is, theoretically, an overdetermined issue: only six independent tensor values are recovered (e.g., Jost and Herrmann, 1989). However, successful inversions highly depend on the SNR of the observed waveforms, as well as the accuracy and resolution of the Green's

function library from the 1-D velocity model. To accommodate such, especially for the site side, shifts and weighting are commonly applied to individual stations. The TDMT_INV package was developed for regional-global-scale fitting for surface waves and has been successfully applied to joint fitting of body and surface waves at regional scales (e.g., Wang et al., 2018). In such cases, higher frequencies and weights are used for body waves and the shifts are different from these applied to surface waves (i.e., similar to “Cut and Paste”; Zhu and Helmberger, 1996).

4. RESULTS AND DISCUSSION

4.1 *P/S* ratio results focusing on the Mt. St. Helens study area

Earthquakes and explosions of comparable magnitudes near Mt. St. Helens exhibit distinctive event-median *P/S* ratio distributions using the preferred 10–18 Hz frequency band (Figure 12). The median event-based *P/S* for earthquakes is 0.59 with an SMAD of 0.21, and the median *P/S* for explosions is 1.88 with an SMAD of 0.38 (Figure 12a). While the medians are separated by nearly 2 SMAD, there are a small number of outlier earthquakes that exhibit *P/S* overlapping with the explosion distribution (Figure 12a). The values reported above were obtained without any corrections applied.

A potential empirical site correction was considered because variations in station-averaged *P/S* ratios from earthquakes and borehole explosions exhibit similar spatial patterns, despite the generally higher *P/S* ratios for explosions (Figure 9). A scatterplot of the earthquake versus explosion station-averages shows an approximately linear trend, with a correlation coefficient of 0.625 (Figure 9). The correlation indicates that small ($\sim M$ 1–3) earthquakes may provide a useful basis for determining empirical *P/S* site corrections for explosions. However, the resulting improvement appears to be subtle (Figure 12b). Application of site corrections increased the difference between the median explosion and earthquake *P/S* ratios from 1.29 to 1.41, but the SMAD values also increased slightly for explosions (0.38 to 0.43) and earthquakes (0.21 to 0.23). While considering potential physical parameters underlying the site response, we found that the site correction terms are positively correlated with shallow crustal velocities. A recent velocity model from local travel time tomography study around Mt. St. Helens (Ulberg et al., 2020) was used to estimate the depths that exert the greatest influence on *P/S* station-averages. The V_p , V_s , and V_p/V_s values from the tomography at 1-km depth were interpolated to the location of each station. Cross-correlation coefficients for the site correction terms are 0.397 for V_p and 0.479 for V_s . Site corrections exhibit a weaker correlation (–0.086) with V_p/V_s (Figures 9d–f). The correlation coefficients are similar for all layers near sea level (± 2 km), but the correlation diminishes at greater depths suggesting that the site correction is primarily influenced by uppermost crustal structure.

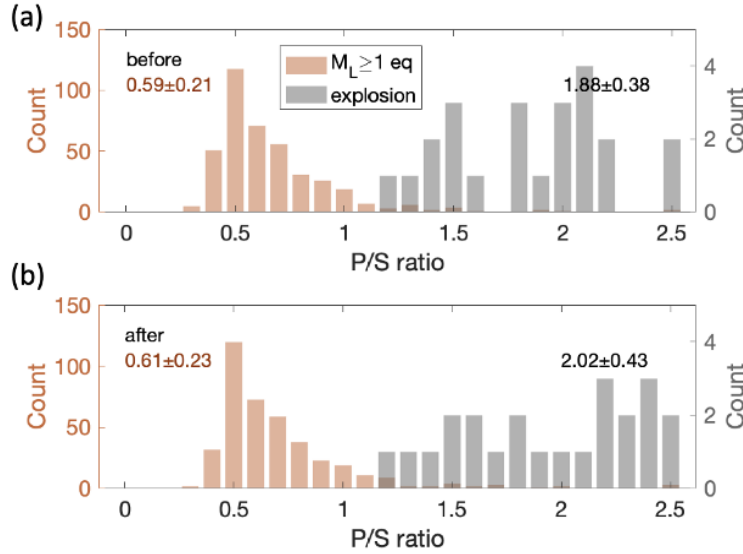


Figure 12. Site corrections and P/S ratios (calculated at 10-18 Hz). *a) Histograms of array-averaged P/S ratios for all explosions and earthquakes. b) Same as a, except the P/S site correction term is applied. The median $\pm$ SMAD of the P/S ratio distributions are labeled in corresponding colors.*

Below we consider potential dependence of P/S on distance, magnitude, and source depth, initially focusing on the Mt. St. Helens area which received the greatest scrutiny (Figures 13&14). For M_L up to 1.7 there is no clear trend in P/S versus magnitude (Figure 13b). For the highest three magnitude bins, 1.9–2.3 there is a positive trend in explosion P/S ratios but the earthquake P/S ratio remains nearly constant (Figure 13b). We note that the largest increase, found for the $M_L=2.3$ bin, is based on only two events. We consider this a weak basis for developing a magnitude correction. Our results suggest that magnitude dependence should be considered in greater detail including multiple types of magnitude estimates before a correction scheme is applied at local distances.

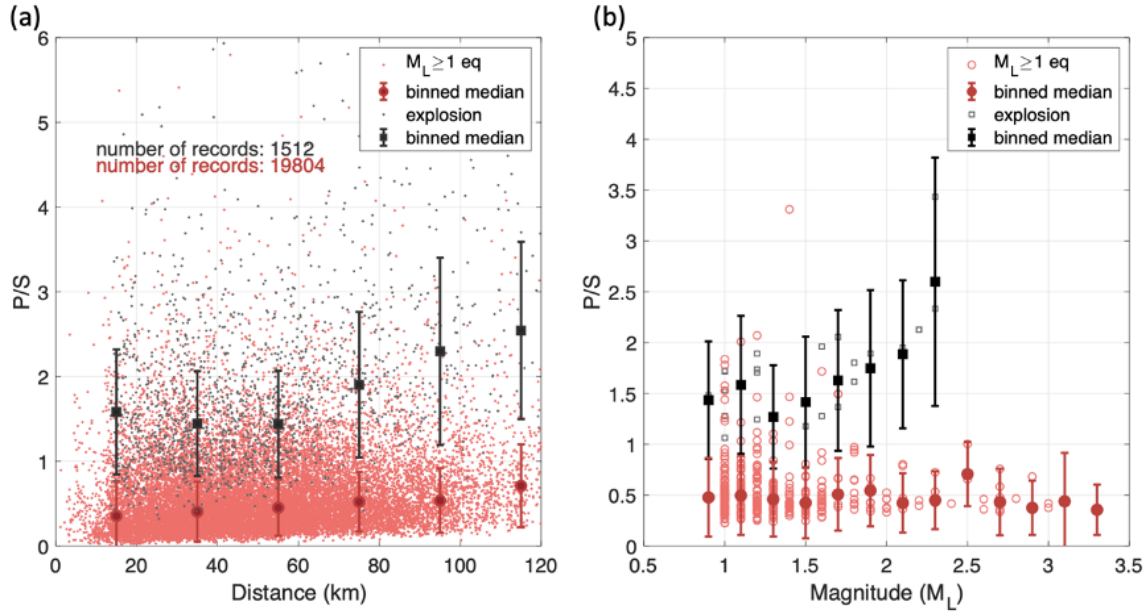


Figure 13. Distance and magnitude effects (calculated at 10-18 Hz). *a)* P/S versus distance averaged over 20 km with step size of 20 km for all source-station pairs of earthquakes and explosions. *b)* P/S ratio versus magnitude with bin size of 0.2. Error bars indicate the SMAD calculated from station-based ratios of all events within each magnitude bin.

Distance dependence is routinely corrected in P/S discrimination studies at regional to teleseismic distances (Anderson et al., 2009; Walter and Taylor, 2001). In the local-distance dataset from the Mt. St. Helens, there is not a strong distance dependence given that the SMAD intervals overlap for measurements in a range of 20-km distance bins (Figure 13a). The density of observations decreases at distances >90 km where the binned median values begin to define a positive slope. A broader perspective is gained by considering P/S ratio versus distance for all four localities with uniformly processed P/S ratios (Figure 14). Here, the distance range is increased up to 200 km, but still most of the propagation path would be in the continental crust rather than in the mantle as for farther regional or teleseismic events. The four localities do not show a consistent distance trend within the 200 km range (Figure 14). Binned median values increase slightly at distances <100 km, but at greater distances the values variably plateau or decrease among the four localities (Figure 14).

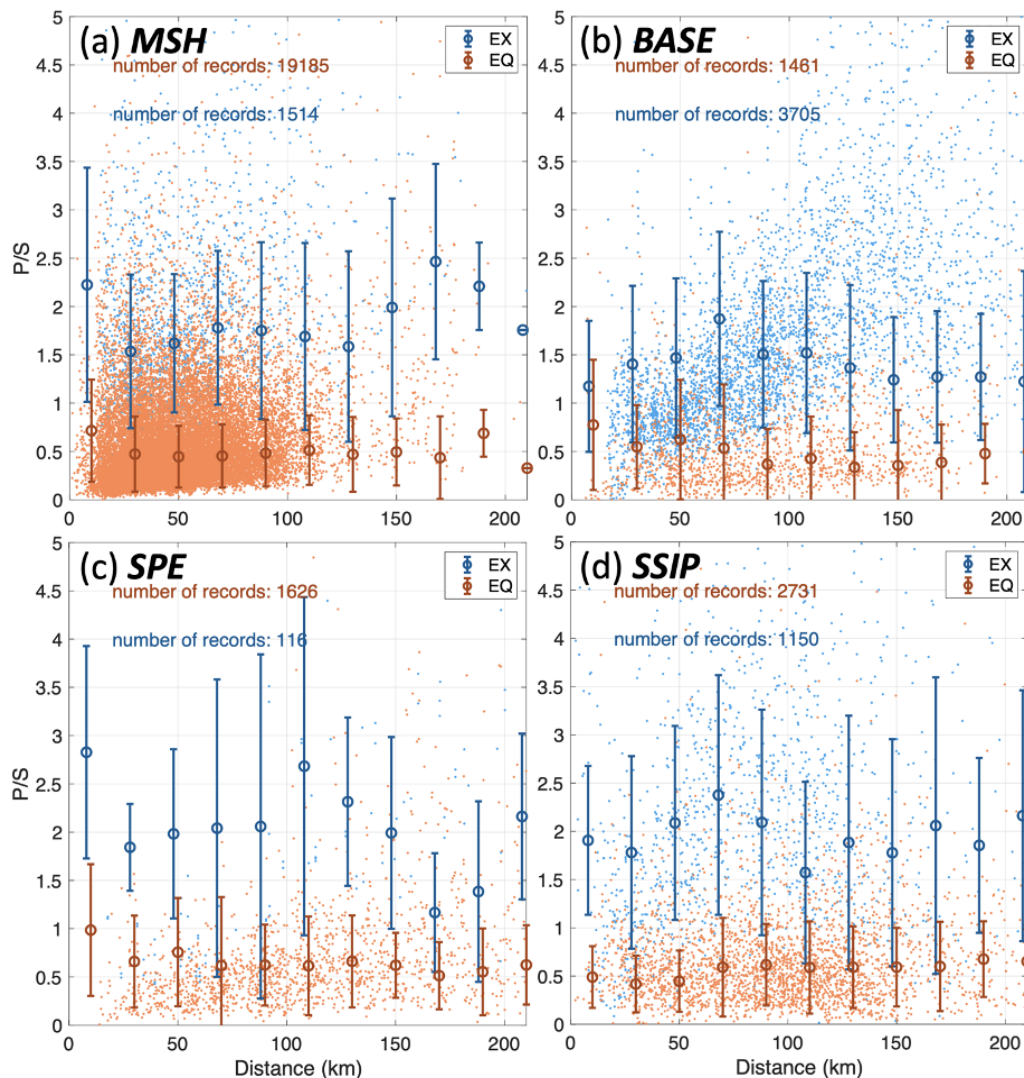


Figure 14. P/S ratio dependence on distances. Distances beyond 200 km are used for calculations but not shown for consistency. The bold bars are average and median absolute deviation for each 20-km bin. EX-explosives (borehole events), EQ-earthquakes.

The Mt. St. Helens area presents an interesting case for examining potential dependence of P/S on the source depth. Earthquakes in the dataset sampled depths from about 1 km beneath the surface (usually within the volcanic edifice) to ~20 km (Figure 15). The greatest variability in P/S and highest median values are observed for depths of 0–5 km based on the SMAD (Figure 15). However, the distance bins from 5–10, 10–15, and 15–20 km depths show similar P/S values. The values for the three deeper intervals have SMAD corridors that overlap the SMAD corridor for the shallowest 0–5 km depth. Based on these results we refrained from applying or attempting to develop a correction for source depth.

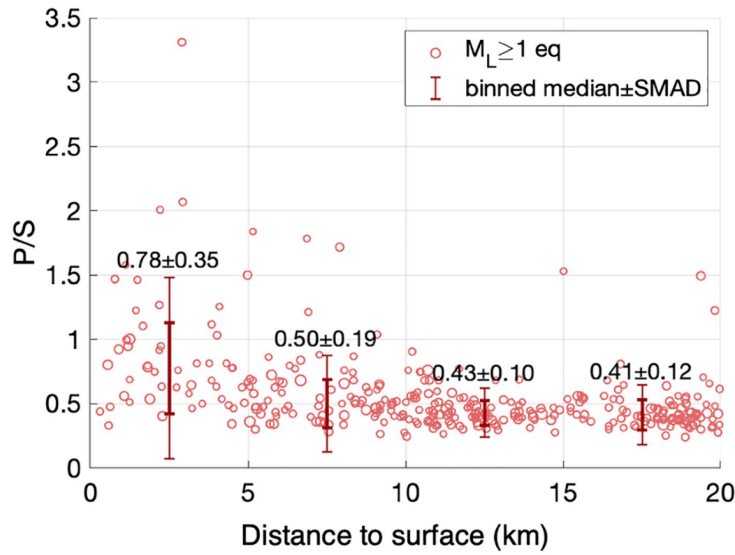


Figure 15. Earthquake P/S ratios versus source depth below surface. Red circles show array-averaged P/S ratios for individual earthquakes, with circle size scaled by $M_L(1-3.3)$. The four bold (thin) bars show median SMAD ($2 \times \text{SMAD}$) within depth bins: 0–5 km, 5–10 km, 10–15 km, and 15–20 km.

The results discussed so far in this section use event-median P/S values from the entire array. It is also instructive to consider variability for subsets of the total array and individual earthquake and explosion comparisons. One such comparison is presented using events with nearly co-located epicenters, within ~ 2.4 km (Figure 16). The explosion was detonated at only ~ 15 –20 m depth, while the earthquake has an estimated depth of 11.1 km. This pair was chosen because it is the closest pair of different source types available in our study. To evaluate the stability of the event-median P/S ratios for the explosion and earthquake in the presence of a smaller seismic array, we subset the array to only 20% of the total stations randomly sampled 1,000 times (Figure 16). The P/S ratios are well separated with an earthquake median value of 0.48 and an explosion median value of 1.89.

The summary of ROC-based binary classification results presented in Figure 10 shows examples of performance with different frequency bands, magnitude levels, and numbers of stations in the local monitoring array. Using the 10–18 Hz frequency band, all magnitudes, and the full seismic array results in 100% true positives and 4.93% (20 out of 406) false positives for a P/S ratio threshold of 1.2 (Figure 10). For comparison, a lower and narrower frequency band of 6–8 Hz results in 86.95% true positives and 5.67% false positives for a P/S ratio threshold of 0.9 (Figure 10). Discrimination performance generally improves with increasing event magnitude and array size (Figures 10c&d). Using all explosions and only $M_L \geq 2$ earthquakes, a threshold P/S ratio of 1.2 results in 100% true positives and 0% false positives. The M_L 0.9–2.3 explosions produced an

average of 66 stations with $\text{SNR} > 2$, while the M_L 1–2 earthquakes only averaged 47 stations with $\text{SNR} > 2$. So, the diminished discrimination performance for M_L 1–2 earthquakes is likely influenced by SNR at individual stations and the total number of stations available for analysis.

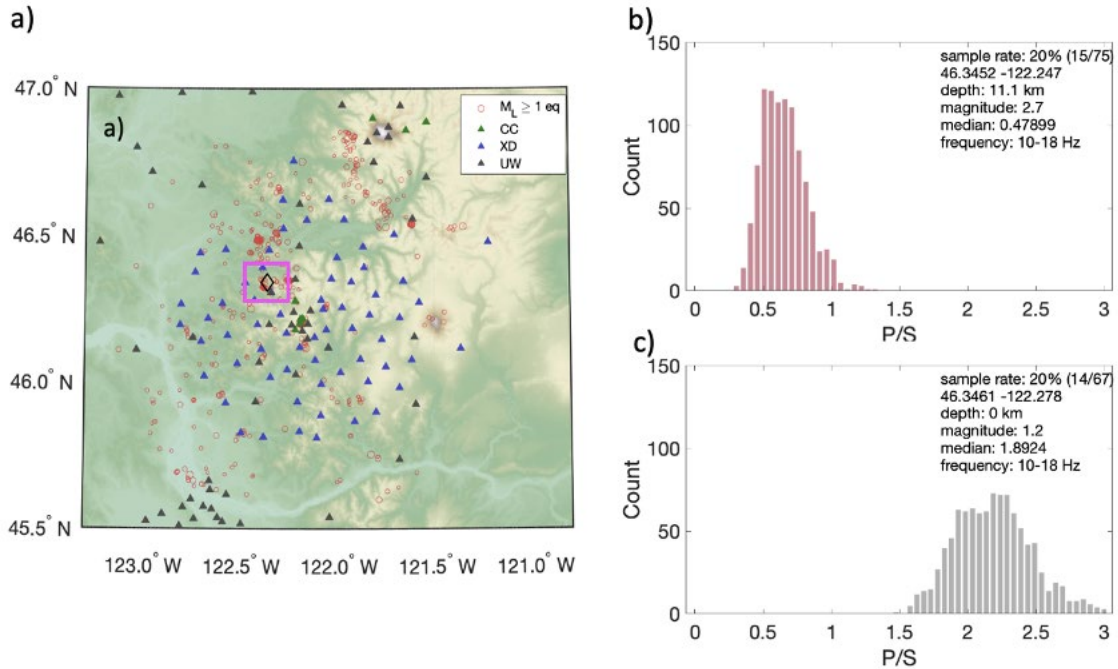


Figure 16. Bootstrap resampling test for a nearly co-located earthquake and explosion. *a)* location of the pair (magenta box). The horizontal distance between the sources is 2.4 km and the depth difference is 11.1 km. *b)* and *c)* Histograms for the P/S ratio determined from randomly selected (no repeat) subsets of ~20% of the available stations (14–15 stations).

ROC curves for seismic arrays composed of $N=4$, 16, and 64 seismographs illustrate the effects of array size (Figure 11c). For $N=64$, the bootstrap resampling results show that a maximum AUC of 1 is consistently achieved for discrimination of explosions and $M_L \geq 2$ earthquakes. For $N=16$, the average of the AUC maxima is 0.98. For $N=4$, the average of the AUC maxima reduces to 0.94 (Figure 10d). However, the ROC curves for $N=4$ are much more variable, including a few samples with near-random performance (Figure 10) and some extreme cases reaching the AUC maximum (Figure 10). Generally, larger array size is expected to better mitigate source and path variations, so the requirement could be much lower in the case where the explosion and earthquake sources are co-located. A separate bootstrap resampling test with an earthquake epicenter nearly co-located with an explosion shows that <16 stations are sufficient for robust discrimination (Figure 16), suggesting that the minimum number of stations could be much lower if the earthquake epicenter and suspected explosion are closely located.

Finally, we consider potential influences on outlier earthquakes with high P/S ratios that lead to false positive explosion classifications (Figure 17). Half (10/20) of the events that result in false positives come from events with <6 measurements that passed

quality control (the entire array was considered with an optimal filter of 10–18 Hz; Figure 17a). Therefore, the availability of multi-station measurements is a dominant factor. These events also tend to have lower magnitudes, but there is considerable variability as they span ~ 0.8 units of local magnitude (Figure 17b). The events span the full depth range from ~ 1 –20 km, further suggesting that source depth is not a strong control on P/S ratio at local distance in this study area.

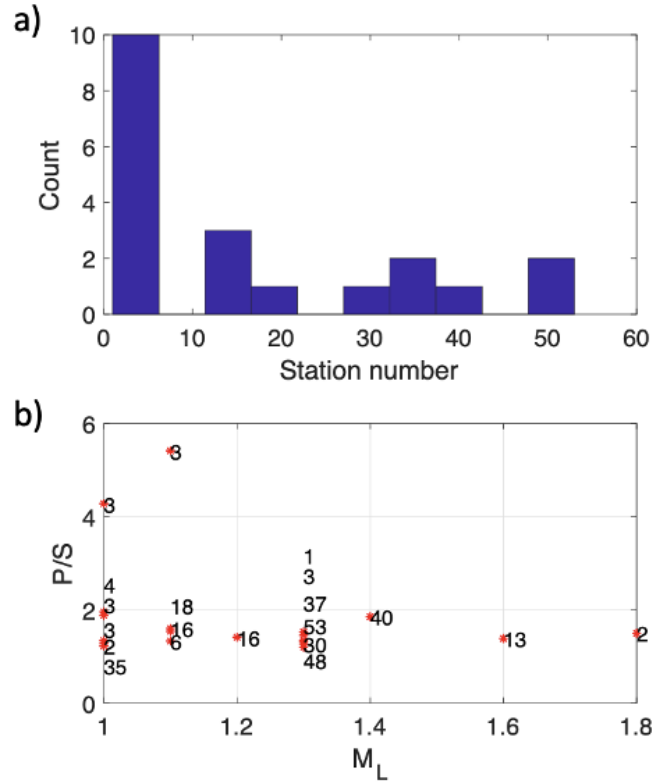


Figure 17. Station coverage of the high P/S ratio earthquakes. *These events lead to false positive explosion classifications. a) Histogram showing number of valid stations used to calculate the median value. b) Event P/S vs. magnitude with number of valid stations labeled. Note that these 20 earthquakes are sparsely located around Mt. St. Helens with depths ranging from 0 to 20 km.*

4.2 Joint method applied to four datasets

A total of 68 explosives and 262 earthquakes were analyzed with a minimum magnitude of 0.6 and 0.7, respectively. The two groups are well-separated in the joint P/S and M_L - M_C domain for each of the four study localities (Figure 18). The optimal joint cutoffs were determined from grid-searching over slopes and intercepts to define a linear binary classification threshold. An example grid search output is presented for the case where all four localities are merged (Figure 19). For individual datasets, the optimal slope and intercept vary (Figure 18). Optimal slopes range from ~ 0.7 –2.5 for individual datasets suggesting substantial contributions from both metrics. A very low slope (near 0) would indicate that the P/S ratio dominates, while a very steep slope (near vertical) would

indicate that $M_L - M_C$ dominates. Merging the four datasets results in optimal slopes from 0.7–2, which all provide similarly high AUC (Figure 19).

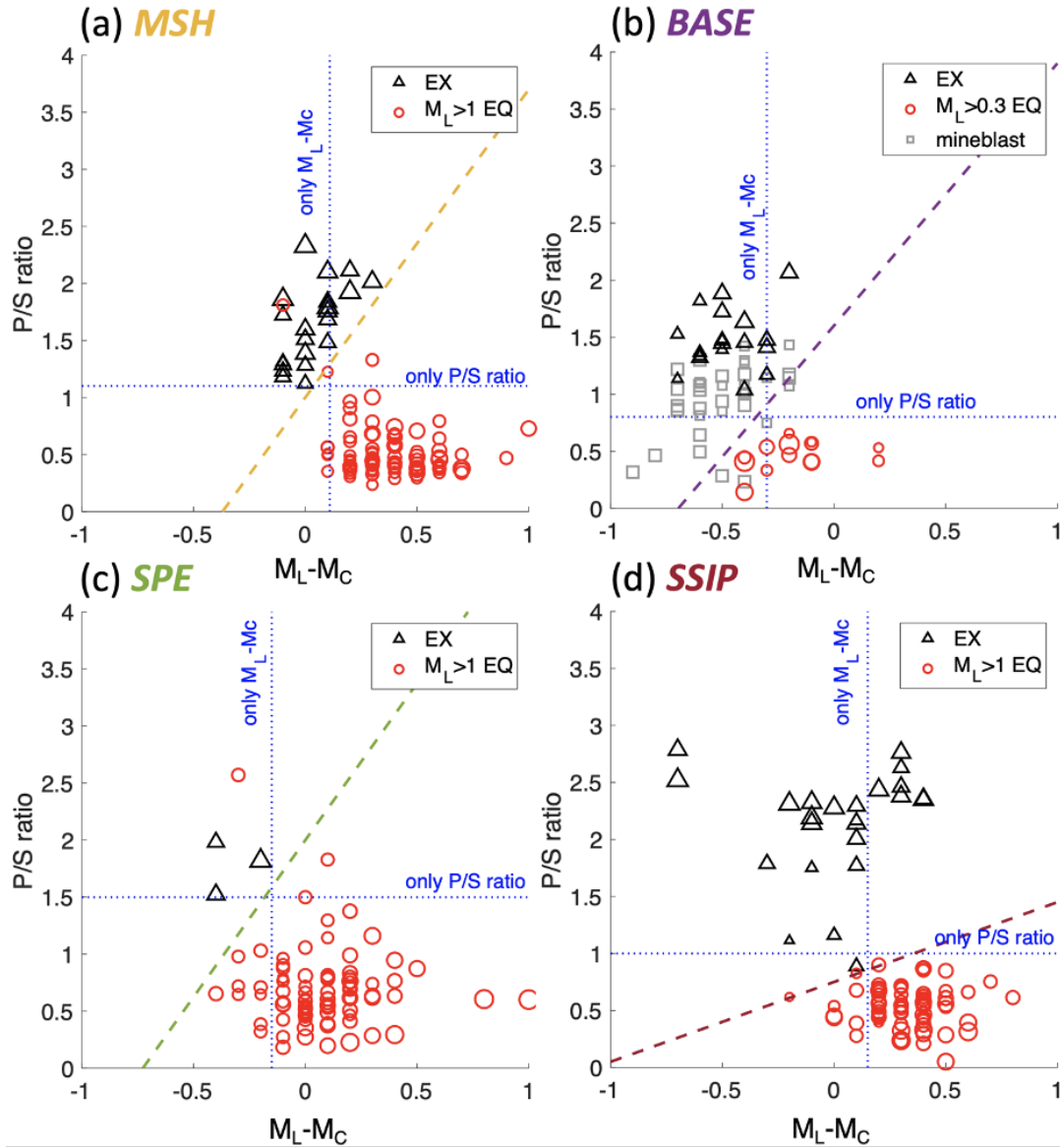


Figure 18. The four datasets analyzed in the joint domain. The horizontal and vertical dotted lines are best P/S ratio and $M_L - M_C$ cutoffs, respectively. The diagonal dashed lines are optimal joint cutoffs resolved via grid searching. For BASE, the results of 37 mine blasts are shown (grey squares) but excluded from further analysis.

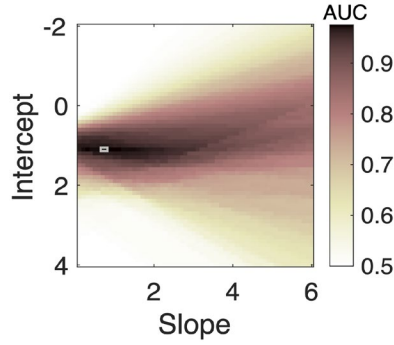


Figure 19. Grid search results for the best binary discrimination threshold. *The optimization uses all four merged local datasets. The grey rectangular highlights the optimal slope and intercept with $AUC=0.9755$.*

Overall, the joint method achieves better performance than either method for all four datasets (Table 4), leading to TPR=100% and FPR<1.2%. For regions that achieved TPR=100% with P/S ratio alone, the joint method would increase precision by ~15% (i.e., MSH and SPE) by rejecting more false positives. The approach is particularly effective for identifying the true explosives, with only 1 out of 68 borehole shots resulting in a false negative classification.

Table 4. Binary classification performance for three metrics.

Dataset	MSH	BASE	SPE	SSIP
Neq	90	14	88	70
Nex	22	19	3	22
P/S	1.1	0.9–1.1	1.5	1
TPR (recall)	1	1	1	0.96
FPR	0.03	0	0.02	0
precision	0.88	1	0.60	1
M _L -M _c	0.11	-0.3	-0.15	0.15
TPR (recall)	0.86	0.89	1	0.71
FPR	0.07	0.21	0.11	0.11
precision	0.76	0.85	0.23	0.68
Joint	[2.70 1.00]	[2.30 1.60]	[2.75 2.00]	[0.70 0.75]
TPR (recall)	1	1	1	1
FPR	0.01	0	0.01	0
precision	0.96	1	0.75	1

1. P/S ; 2. M_L-M_C ; and 3. Joint, where numbers in brackets are slope and intercept. For all cases, “explosive” is defined as “positive” (P). True Positive Rate-TPR (recall): $TP/(TP+FN)$; False Positive Rate-FPR: $FP/(FP+TN)$; Precision: $TP/(FP+TP)$. N_{eq} and N_{ex} are final numbers of earthquakes and explosives that have both valid P/S and M_L-M_C measurements.

The joint method demonstrates promising transportability for these four uniformly processed datasets. Although the discrimination thresholds vary between regions, the explosive sources and earthquakes always fall into two clusters in the P/S versus M_L-M_C domain (Figure 18). Such separation is preserved even after merging all four datasets as the covariance ellipses for the combined dataset remain separated at 1 standard deviation (Figure 20). Similarly high TPR ($>95\%$) and low FPR ($<5\%$) are achieved when a single threshold line is used for all four datasets (Figure 19), rather than individually optimized cutoffs for each array, leading to a maximum AUC=0.9755 (Figure 19).

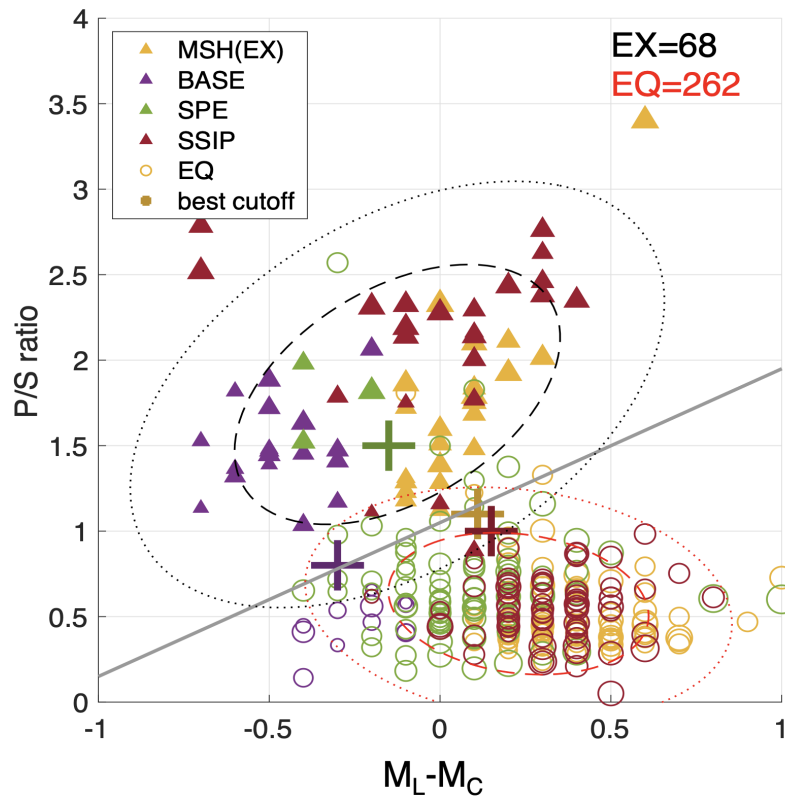


Figure 20. All event-based P/S or M_L-M_C of the four datasets as labeled. The cross symbols mark the best P/S and M_L-M_C cut offs for each dataset. The dashed and dotted ellipses are the covariance of one and two standard deviations, respectively. The grey line marks the best joint discrimination threshold determined from a grid search for maximum AUC (Figure 19).

4.3 Focal mechanisms of the Mt. St. Helens

Variable coverage of the lower hemisphere strongly influences the results of focal mechanism inversions (Figure 21). The dense array near Mt. St. Helens can result in well constrained focal mechanisms if events occur in the middle of the array and at mid-crustal depths, but lower hemisphere coverage diminishes for events nearer to the

periphery of the array or near-surface events (Figure 21). Lower hemisphere sampling is generally more restricted for explosive sources because they are located near the surface, whereas the greater depth of earthquakes results in wider range of incidence angles within the local array (Figure 21). Limited coverage of the lower hemisphere can be mitigated by the addition of *S/P* constraints (Hardebeck and Shearer, 2003), which help constrain the location of the fault plane (Figure 21). The example in Figure 22 shows that without *S/P* constraints a dip slip fault plane solution would be acceptable, but with *S/P* included there is a clearly constrained strike-slip solution that is consistent with the NNW-strike common to many earthquakes near Mt. St. Helens (e.g., Stanley et al., 1996).

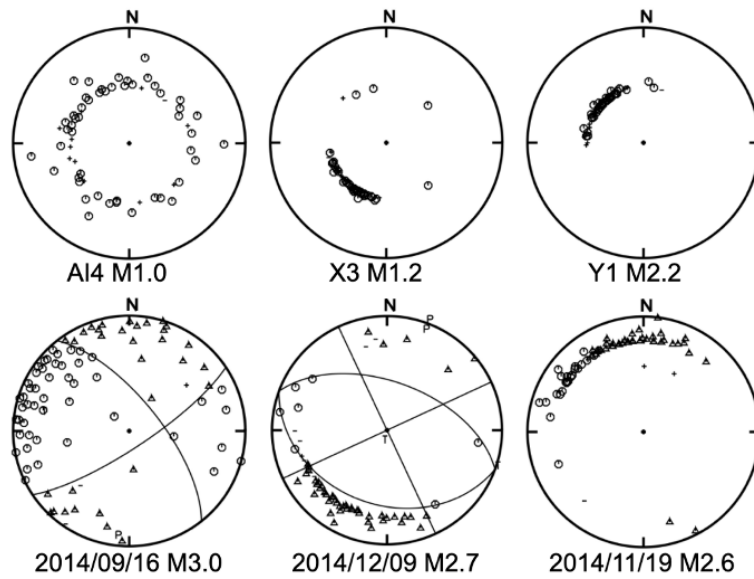


Figure 21. Examples of lower hemisphere coverage for *P* first-motion polarity picks. *Quality of coverage decreases from left to right. The top row is for explosive sources and the bottom row is for earthquake sources.*

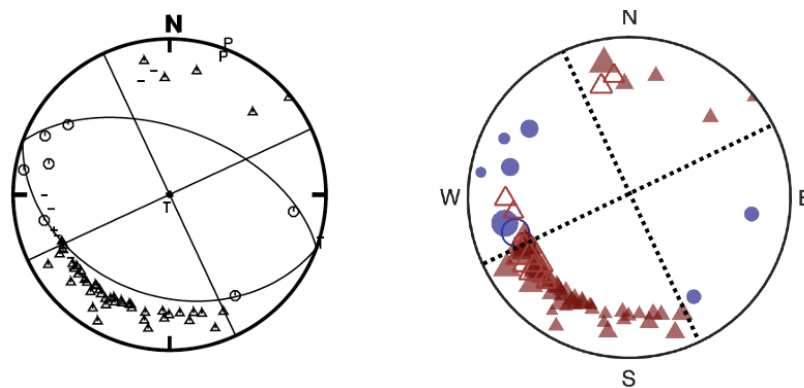


Figure 22. Example of adding *S/P* ratio for focal mechanisms. *The added constraint reduces the number of double-couple solutions and resolves the preferred the strike-slip mechanism.*

Summary results of the focal mechanism estimates with only first-motion polarities are shown in Figure 23 and analogous results including first-motion polarities

plus S/P ratios are shown in Figure 24. Without S/P constraints, only 44/63 earthquakes have acceptable solutions and 22/23 explosions. Adding S/P constraints on the lower hemisphere enables acceptable solutions for all earthquakes and explosions (Figure 23).

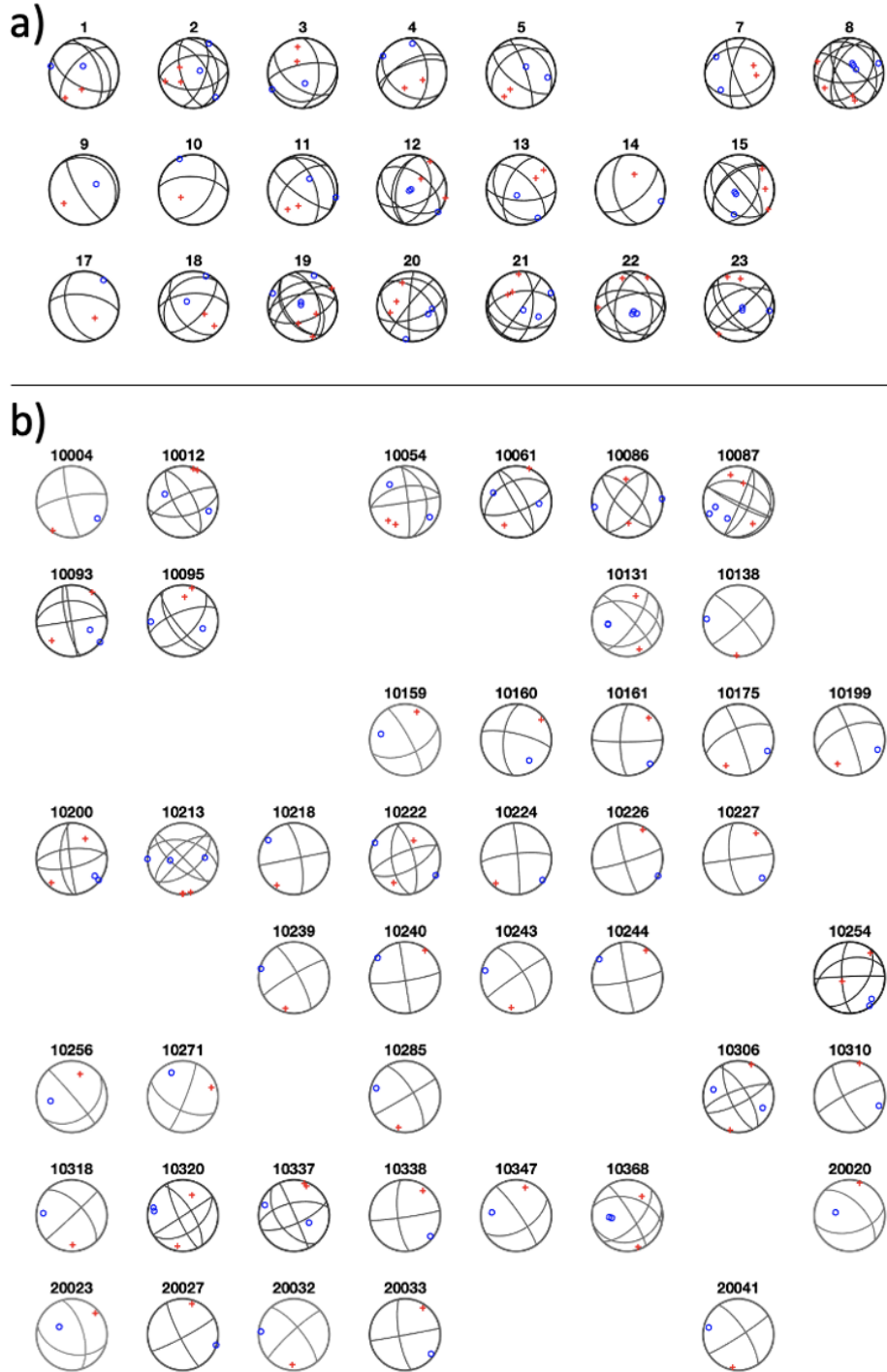


Figure 23. HASH fitting results. a) 21 out of 23 shots and b) 44 out of 63 $M > 1.3$ earthquakes within the St. Helens Fault Zone. Red cross and blue circle mark the P- and T- axis, respectively. The shades of the lines imply the hypocenter depths, where gray ones are deeper (down to ~25

km) and black ones are shallower (up to ~ 3 km). Empty spot means a qualified solution cannot be resolved.

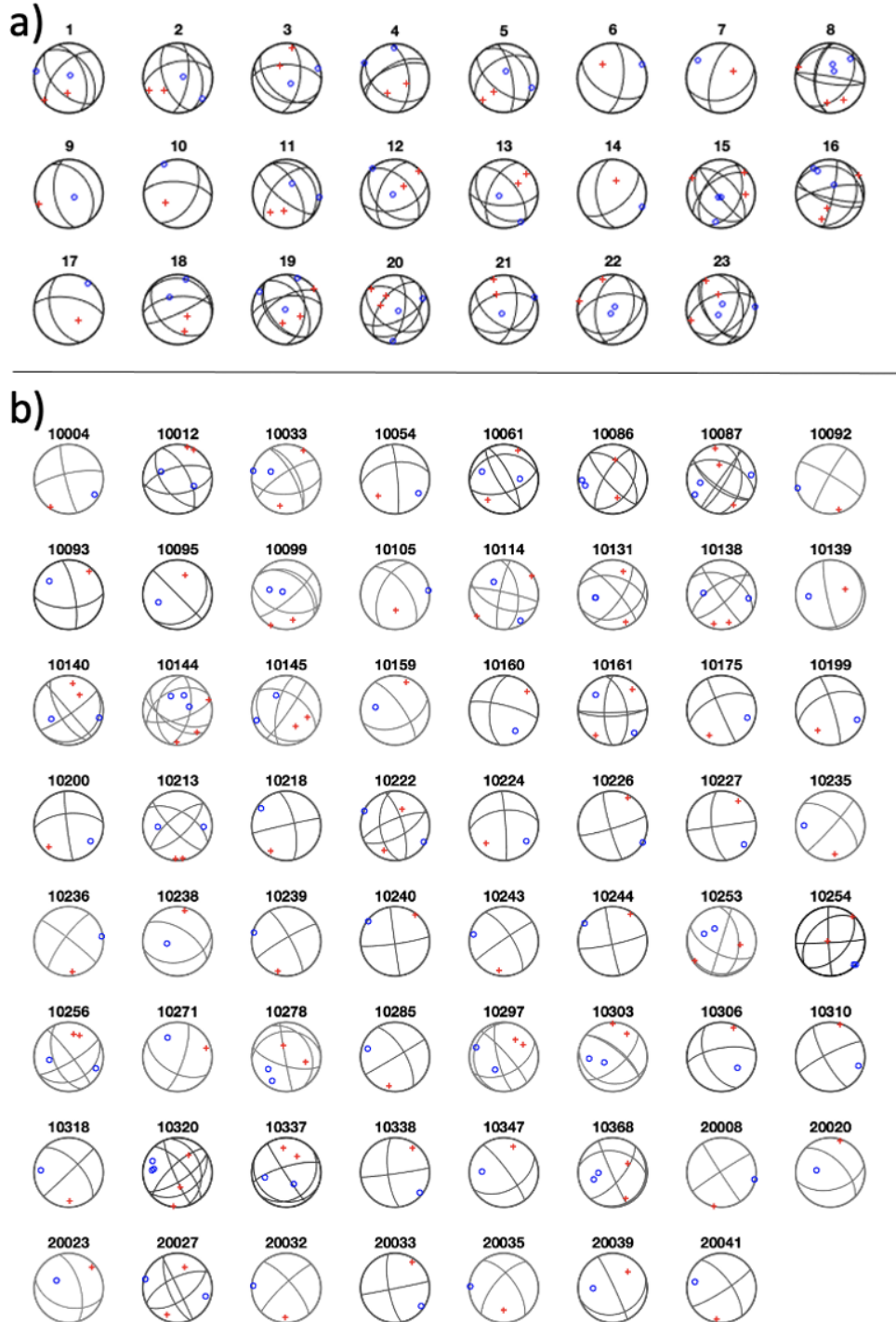


Figure 24. Same as Figure 23 but with S/P ratios added to the fitting.

We consider whether the quantity and quality of the potential fault plane solutions from HASH can be used as indicators of explosive sources. On average, explosions produce two fault plane solutions (median=2) and the earthquakes produce only 1.4 (median=1). Comparison of earthquakes and explosions based on HASH solutions can be further evaluated through two other parameters: P-axis orientations and fitting grades. The variability of P-axes can be used when analyzing clusters of events. Due to the randomness of fault plane solutions for the explosions, the P-axes are also more randomly distributed (Figure 25a&c). In contrast, stable and consistent P-axis are obtained from earthquakes within the St. Helens Fault Zone, consistent with the maximum horizontal stress orientation in this region (NNE; Figure 24). The explosive sources are more often poorly fit with “D” grades and adding the *S/P* ratios leads to limited improvements (Figure 25a&c). In contrast, earthquakes are typically fit with higher grades, about half of the events (31 out of 63) achieve a grade A (Figure 25b&d). Note that the grades are also related to azimuth and take-off coverage, where shallow events (e.g., explosive sources) are challenged by a narrower ranges of take-off angles

The above metrics are helpful for cluster analysis but would not provide effective discrimination for individual events. For example, several shots also produce ‘A’ or ‘B’ grade fault plane solution despite the high number of positive first-motion polarities (Figure 25a&c). We did not identify any clear spatial/magnitude pattern from the shots that produced apparently well-resolved focal mechanisms (e.g., Figure 21).

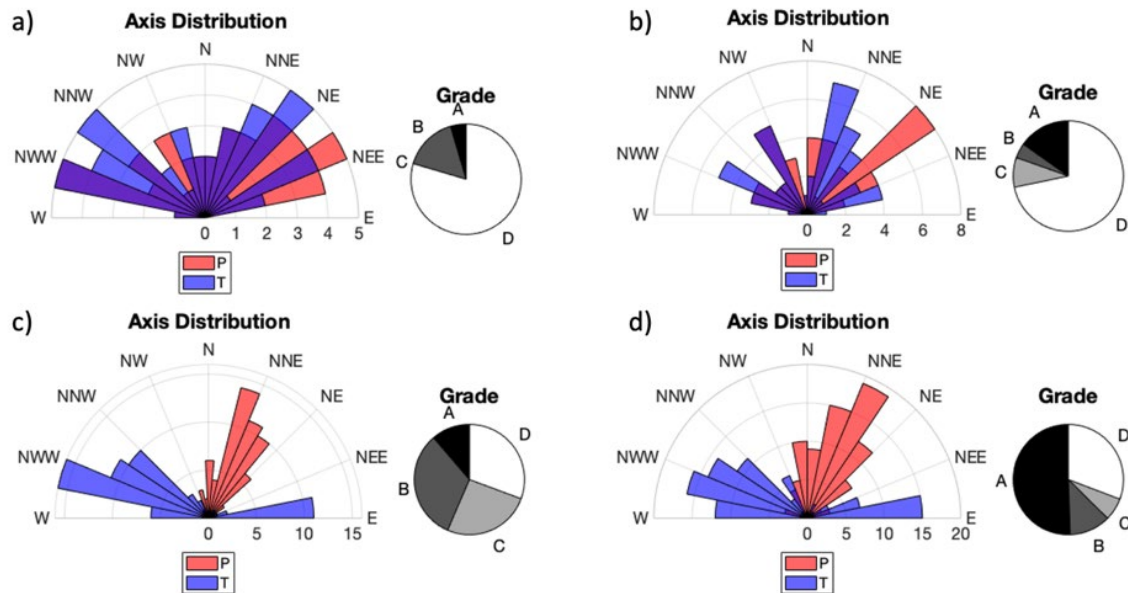


Figure 25. Statistical summary of focal mechanisms. *a)* explosive sources without *S/P* ratios. *b)* explosive sources with *S/P* ratios included. *c&d)* same as *a&b)* but for earthquakes. In each subplot, the left figure shows the azimuthal distribution of P- and T- axes of all possible solutions of all events and the pie-chart on the right shows the quality of fits (i.e., grades from HASH). Note the different count scales of the subplots.

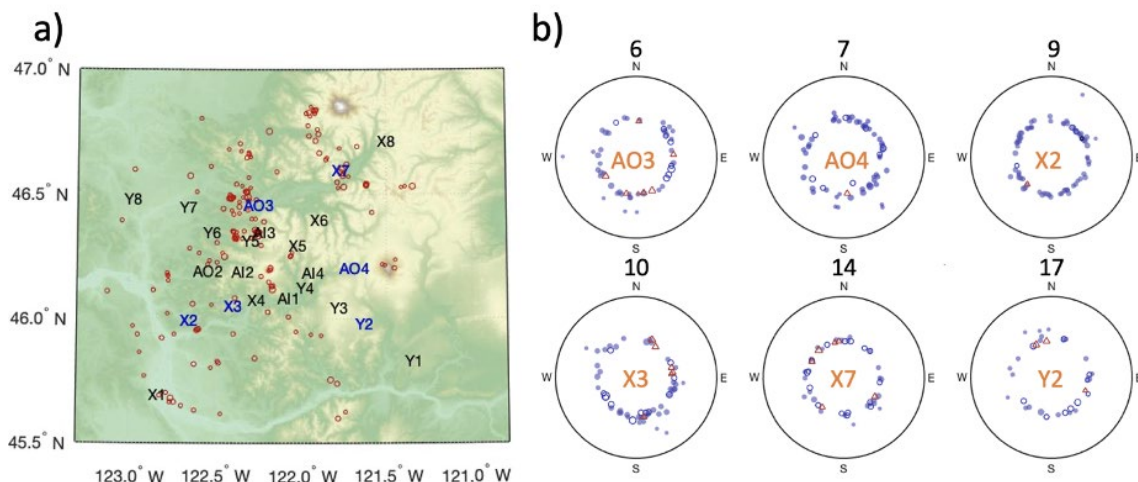


Figure 26. Shots with single fault plane solution from HASH. *a) Map view of shots (blue, shot ID 6, 7, 9, 10, 14, 17 in Figure 24). b) Polarity and S/P ratios for the six shots in a).*

Waveform-based moment tensor inversions were attempted because they could, in principle, identify non-double-couple components of the seismic source mechanisms. Due to the low SNR of surface waves for the low-yield explosive shots, we noticed that a higher frequency band (e.g., 0.5–2 Hz, Figure 27) is required compared to more conventional waveform-based moment tensor inversions that focus on <0.1 Hz surface waves. The waveform-based moment tensor inversion for the shots near Mt. St. Helens was not successful given that all variance reductions were below 10%. Waveform fits were too poor to provide compelling results even though we have a local 1-D velocity model optimized from the active source seismic experiment. The predicted Green's functions are far too simple compared with the observational data at frequencies near ~1 Hz (Figure 28).

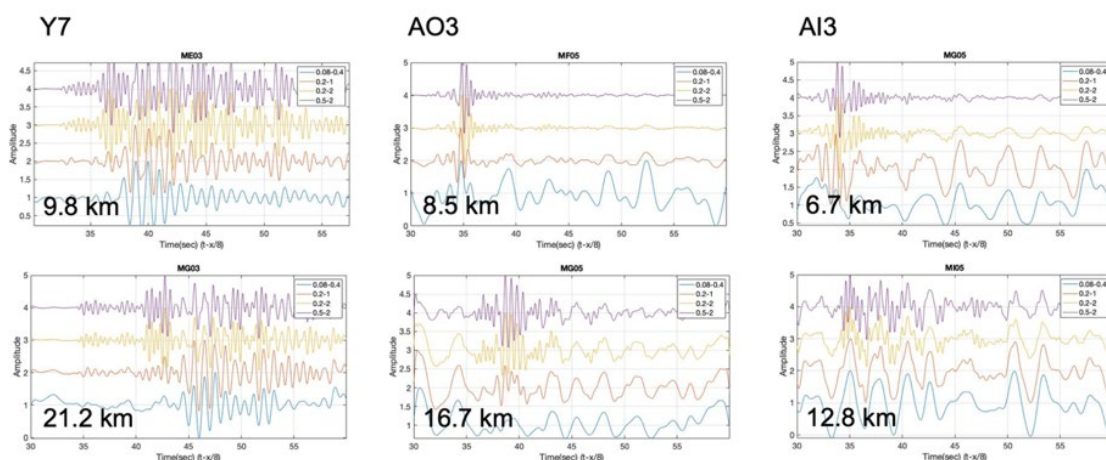


Figure 27. Example of observed waveform with variable distances and filters. *The top row shows three shots and bottom row shows three earthquakes. Within each panel, four frequency bands are shown: from bottom to top, 0.08–0.4 Hz, 0.2–1 Hz, 0.2–2 Hz, 0.5–2 Hz. Note that for stations >10 km, the signal to noise is only useful at frequencies higher than ~1 Hz. Both body and surface wave trains contain several periods at higher frequencies, increasing the difficulty of waveform fitting during moment tensor inversion.*

We summarize three challenges for the moment tensor inversion for explosive sources around the Mt. St. Helens: 1) complex coda wave (e.g., Y7 in Figure 27) possibly caused by topography and strong near-surface velocity variations; 2) strong trade-off between SNR and frequency, where lower frequency would benefit moment tensor inversions, but the SNR becomes insufficient; 3) T-component waveforms that cannot be modeled with 1D synthetics for explosive sources. Without a much more accurate Green's function library up to $\sim 1\text{--}2$ Hz, it does not appear practical to conduct waveform-based moment tensor inversions for the low-yield explosions in this study.

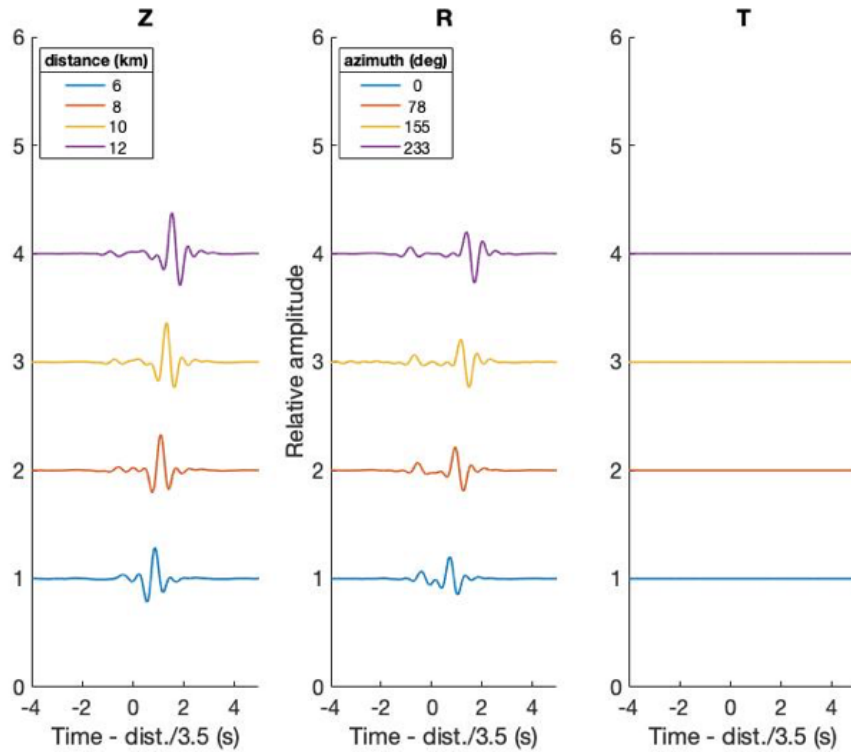


Figure 28. Example of synthetic waveforms for an explosive source. *Seismograms are filtered between 0.5–2 Hz. The waveforms are generated using models and methods described in Section 3.7.*

4.4 Future directions

The results here suggest that P/S discrimination is worth pursuing for local distance and low-yield explosive source discrimination. However, the parameters found to be optimal in this study are different from those commonly used in farther distance regional cases. Thus, it is important to consider how to handle the transition from the local to farther regional distance seismic recordings. For instance, variable frequency content with distance should be tested so that maximal information is extracted at near distances where higher frequencies are present without degrading the signal quality used for analysis of

recordings from farther distances. Additionally, small but potentially valuable improvements could be made with development of local distance corrections for site effects, and possibly corrections for distance and magnitude effects. The latter effects may take different functional forms or parameters for local crustal propagation compared to regional propagation that is largely in the upper mantle.

For local distances and low-yield events, moment tensor inversions may be more successful if they focus on high frequency waveform metrics without fitting the entire waveform. For example, HybridMT uses P amplitude and polarity to estimate moment tensors for small mining events and other types of low magnitude seismicity (Kwiatek et al., 2016). Our results suggest that adding *S/P* amplitudes mapped on the lower hemisphere carries useful information and could be a natural extension to explore. The combination of P polarity, absolute P amplitude, and the *S/P* ratio may be effective for constraining small event magnitudes and potential non-double-couple components. and able to resolve non-double-couple components (e.g., HybridMT, Kwiatek et al., 2016)

Joint use of *P/S* and M_L - M_C for efficient event screening appears promising based on the binary classification performance for the four localities tested here. Its effectiveness could be enhanced by considering development of locally specific corrections (e.g., site, path, and/or source location) where sufficient calibration data exist. Additionally, *P/S* and M_L - M_C could serve as valuable attributes in the testing and development of M_L methods for increasingly automated local distance classification of earthquakes and explosions. A potential benefit would be the physically intuitive information from *P/S* and M_L - M_C to complement the potentially ‘black-box’ results from approaches like deep neural networks applied to large libraries of raw seismic waveforms.

5. CONCLUSIONS

Influences on local *P/S* ratios are analyzed with 23 shallowly buried explosions and 406 $M_L \geq 1$ earthquakes near Mt. St. Helens. Optimized array-median *P/S* ratios achieve $\geq 98\%$ true positives and $\leq 6.3\%$ false positives when using ≥ 16 stations to classify explosions. Suggested adaptations for *P/S* discrimination at local distances include higher and wider frequency bands than are typical for regional discrimination (e.g., 10–18 Hz), incorporation of all three components for measurement of P and S, and application of SNR culling that is only based on pre-event noise so that weak S waves are not eliminated from measurement. The high performance mentioned above was achieved without site corrections; however, the correlation between station-averaged *P/S* ratios and upper crustal velocity structure from prior travel time tomography suggests that small improvements may be possible where seismic velocity constraints exist.

For source mechanism estimates, first-motion polarity and *S/P* amplitude metrics on the lower hemisphere are more promising than full-waveform inversions for $\sim M$ 1–2 events near the Mt. St. Helens. Limited coverage of the lower hemisphere may be a severe challenge for local distance studies with realistic array coverage, as even in the

dense array considered here it was possible to fit many explosions with double-couple mechanisms. Consequently double-couple solutions may be difficult to statistically reject at a level of confidence suitable for security interests.

For local distance explosion discrimination, P/S ratio and M_L-M_C exhibit complementary sensitivity and strong performance in the four study localities tested here. Their joint use warrants further investigation as a potentially valuable screening tool. Refinement of the method to include calibration of local site and/or path effects may be to achieve important gains in performance in areas where data are scarcer than in the localities considered here.

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List of Symbols, Abbreviations, and Acronyms

AFRL	Air Force Research Laboratory
AUC	Area Under Curve
CC	seismic network name (also cross-correlation coefficient in Figure 9)
BASE	Bighorn Arch Seismic Experiment
FK	frequency-wavenumber integration method (Saikia, 1994)
FOCMEC	First-motion-polarity based focal mechanism inversion package (Snoke et al., 2003)
HASH	Focal mechanism inversion package (Hardbeck & Shearer, 2002)
HybriMT	First-motion-polarity and amplitude based focal mechanism inversion package (Kwiatek et al., 2016)
iMush	imaging Magma Under St. Helens
LDA	linear discrimination analysis
m_b	Body-wave Magnitude
MDAC	Magnitude Distance Amplitude Correction
M_c	Coda Magnitude
M_L	Local Magnitude
M_s	Surface-wave Magnitude
MSH	Mount St. Helens
MTI	Moment Tensor Inversion
P/S	P-wave to S-wave ratio
QDF	quadratic discriminant function
ROC	Receiver Operating Characteristic
SMAD	scaled median absolute deviation
S/P	S-wave to P-wave ratio
SPE	Source Physics Experiment Phase 1
SSIP	Salton Sea Imaging Project
TDMT_INV	Time-domain Moment Tensor Inversion (Dreger, 2008)
TPR	True Positive Rate
USGS	United State Geological Survey
UW	seismic network name
V_p	P-wave velocity
V_s	S-wave velocity
XD	seismic network name

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