

EFFECT OF THE EXPLOSIVE DETONATION PRODUCTS ON SEISMIC COUPLING: AN EXPERIMENTAL FIELD STUDY USING ALUMINIZED EXPLOSIVES

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14. ABSTRACT Understanding explosion source processes is of great importance for seismic event characterization. Weston Geophysical conducted a series of chemical explosions using various explosives with different properties in order to investigate their effect on seismic signatures. Previous experimental data (NEDE, e.g. Martin et al, 2012) suggest that low-frequency <i>P</i> -wave amplitudes are affected by the explosive velocity of detonation (VOD) and by the volume of gaseous products created during the detonation (Stroujkova, 2015). The new experiment conducted in New Hampshire in 2016 was designed to isolate the effects of the amount of the explosive gases by using aluminized and non-aluminized explosive pairs. Our new results confirm NEDE findings and indicate that seismic amplitudes and source signatures are affected not only by the explosive yield and VOD, but also by the thermodynamic characteristics of gaseous products and by the presence of fluids in the emplacement medium.					
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1. SUMMARY

The objective of the project is to investigate the effect of the volume of the detonation products released into the cavity on seismic radiation. Our analyses of previous experimental data (NEDE1 and NEDE2, e.g. Stroujkova et al, 2012) suggest that the low-frequency amplitudes are determined not only by the explosion yield, but also by the amount of released gas (Stroujkova, 2015). However, NEDE experiments used explosives that not only released different amounts of gas, but also had different detonation velocities affecting the shock wave propagation. For the new explosion field experiment (GAS2016) we used explosives with similar detonation velocities but different volumes of detonation products (e.g. gases) in order to isolate the effect of the steady state gas expansion on the seismic radiation. Differences in the cavity gas volume were achieved by: a) adding aluminum powder to reduce the amount of gas, and b) adding water to produce vapor. The hypothesis being tested is: “Does an increase in the volume of cavity gas cause an increase in the low frequency component of the spectra?” The experiment included explosions detonated using aluminized and non-aluminized explosive pairs to study the effect of aluminum on seismic radiation (e.g. TNT – Tritonal, ANFO – ANFO/Al).

The major activity during Year 1 was execution of the experiment (GAS2016). The explosions were recorded by a network of seismometers and accelerometers fielded from near-source to local distances. Additional post-shot borehole geophysical logging was conducted to address the alternative mechanisms for the low-frequency amplitude increase, namely the source function broadening due to late-time damage (cracking) versus the increase in the cavity size causing the increase in reduced displacement potential (RDP).

The analysis of the seismic signals from explosions conducted using explosives with different amounts of gas detonation was performed during Year 2. The main focus of the analysis included: (a) insight into the role of gas effects on seismic wave generation, which is essential if chemical explosions are to be used as surrogates for nuclear tests and (b) improved methods of discriminating chemical explosions from small nuclear explosions. The important part of the research involved a study of the radiation pattern of the radiated seismic waves. A relative moment tensor technique applicable to shallow events and incorporating both *P* and short period surface waves (*Rg*) was developed and tested on the experiment data. In addition, we explored use of the principal component analysis for explosion discrimination.

The major milestones of the work performed during this period include:

1. Preliminary computations in order to design the charges for the experiment. This work is covered in Chapter 2 of this Report.
2. Experiment preparation, including site selection, drilling and blasting. The experiment was conducted in August of 2016. This work is covered in Sections 3.2 – 3.4 of this Report.
3. Seismic data acquisition, involving seismic network installation and data recording. The seismic data collected during the experiment was archived and submitted to IRIS

Data Management Center. The details of the data collection are covered in Section 3.5 of this Report.

4. Drilling back into the shot boreholes and geophysical site characterization (well logging) is described in Chapter 4 of the Report.
5. Analysis of the seismic waveforms and spectra is provided in Chapter 5.
6. Chapter 6 describes using the principal component analysis for explosion discrimination.
7. Analysis of the focal mechanisms, including the development of the relative moment tensor inversion suitable for shallow events, is provided in Chapters 7 and 8.

The accomplishments during the period of performance include 1 article published in the *Seismological Research Letters*, 1 articles submitted for publication, 2 articles to be submitted (pending clearance from the AFRL) and a poster presentation at the American Geophysical Union Fall Meeting. The list of the articles is provided below:

Stroujkova, A., M. Leidig, J. Lewkowicz, T. Rath, T. Bradstreet, V. Napoli, P. Hubbard, J. Salerno, K. W. Robbins, C. Marrero, 2017. A New Experimental Field Study of the Effects of Explosive Detonation Products on Seismic Radiation, *Seism. Res. Lett.*, *First Published on June 21, 2017*, doi: 10.1785/0220170032.

Stroujkova, A, 2018. Relative Moment Tensor Inversion with Application to Shallow Explosions and Earthquakes, To be submitted to *Bull. Seism. Soc. Amer.*

Stroujkova, A, 2018. Rock Damage and Seismic Radiation: a Case Study of the Chemical Explosion Experiment in New Hampshire, To be submitted to *Bull. Seism. Soc. Amer.*

2. PRELIMINARY COMPUTATIONS

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2.1. Introduction

During the initial stage of the project we calculated the detonation parameters for various types of explosives, including the amount of the detonation products, pressure and the velocity of detonation (VOD).

In order to choose the optimal explosives and the charge sizes for the experiment a series of numerical calculations were performed, including: a) thermochemical calculations using the Becker-Kistiakowski-Wilson (BKW) Equation of State (EOS) in order to calculate the amount of gas, pressure and temperature for each explosive type, and b) hydrodynamic simulations using the Nobel computer code (e.g. Mader, 1998) in order to compare potential wave amplitudes generated by each charge.

2.2. Thermo-Chemical Calculations of the Detonation Products Using BKW

The analysis of data from New England Damage Experiment (NEDE, e.g. Stroujkova, 2015) suggests that the amplitudes of seismic waves produced by small chemical explosions are not simply a function of the explosion yield. Rather, the low frequency component of the spectra correlates with the amount of gas released in the cavity. A simplified thermochemical analysis can explain these observations. In this section we present: a) the analysis of the chemistry of the explosives and the amount of gas released during detonation, and b) the relationships between the amount of gas and the low-frequency seismic amplitudes.

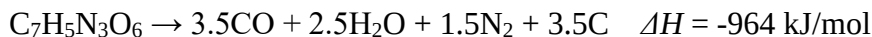
In order to design the explosive charges for the experiment we calculated various characteristics for different explosives. To calculate the explosion parameters we chose the BKW EOS, given by

$$\frac{pV}{RT} = 1 + xe^{bx}, \quad (1)$$

$$x = \frac{\kappa \sum x_i k_i}{VT^{0.5}}, \quad (2)$$

where x_i and k_i are the mole fractions and covolumes of each gas species of the detonation products, and κ and b are the empirical constants. There are three commonly used computer codes for calculations using this EOS: BKW (Mader, 1967), RUBY (Levine and Sharples, 1962) and TIGER (Cowperthwaite and Zwisler, 1974). Using these codes one can calculate Chapman-Jouguet (CJ) pressure p_{CJ} , volume V_{CJ} , temperature T_{CJ} , velocity of detonation D_{CJ} and the adiabatic constant γ_{CJ} , as well as release isentropes, the amount of gas products and the heat of detonation for each explosive. BKW code was chosen for this project because it is freely available (e.g. Mader, 1967).

A basic description of chemical reactions to illustrate the effect of aluminum on explosive detonation is provided below. The decomposition products were calculated based on Kistiakowski-Wilson rules (e.g. Akhavan, 2004). The approximate reaction for the decomposition of the TNT:



Adding aluminum results in exothermic reactions releasing additional heat:



The volume of gas is reduced, while the heat increases in the first two reactions. In the third reaction the volume of gas does not change. Thus, adding aluminum powder to the explosive mixture increases the amount of heat (energy) released during the detonation, accompanied by the reduction in the amount of the detonation products. It also results in somewhat lower VOD (Table 1).

Table 1. Detonation parameters for some explosives calculated using BKW

Explosive	ρ_0 (g/cc)	D (km/s)	p_{CJ} (GPa)	T_{CJ} °K	V_{gas} (mol/kg)	Q (MJ/kg)	TNTe
TNT	1.64	6.95	20.6	2935	25.76	5.588	1
RDX	1.8	8.76	34.8	2600	33.83	6.545	1.17
COMP B	1.713	8.08	28.4	2780	30.87	6.202	1.11
ANFO	0.88	5.41	7.46	2303	43.76	4.183	0.75
Tritonal (TNT/Al)	1.74	6.7	19.7	5196	19.14	8.564	1.53
Torpex (COMP B/Al)	1.81	7.60	26.79	5218	21.35	8.241	1.47
ANFO/Al 80/20	1.02	5.58	8.71	4067	34.21	6.713	1.20

The differences between the explosives include different amounts of released energy and explosive products per unit mass, different detonation velocities and detonation pressures. As a result, the released energy is partitioned differently between the thermal and mechanical energy. Table 1 shows the results of the calculations using the BKW code for several explosives. In addition Table 1 provides the values of the TNT energy equivalent calculated as the ratio of the detonation heats Q_{expl}/Q_{TNT} . Notice significant differences between the CJ temperatures, pressures, as well as the amount of gas for different explosives. Aluminized explosives generate higher temperatures than non-aluminized explosives. They also release less gas than non-aluminized explosives.

The calculation results shown in Table 1 were used to determine the optimal charge weights and the explosive combination for the experiment. We added ANFO and an ANFO/Al pair because 1 kg of ANFO releases twice the amount of gas released by either Tritonal or Torpex. Also, aluminized ANFO (ANFO/Al) releases a similar amount of gas and has a similar TNT equivalent (based on heat of explosion) as pure COMP B, while having significantly lower VOD and higher temperature of detonation. By comparing the explosives with different characteristics, we are trying to determine the effect of each explosion parameter on the seismic radiation.

One of the challenging problems is choosing the explosive equivalence criterion. For instance, if we use the energy (heat) equivalency, then the weight of a TNT charge would be larger by a factor of 1.53 than the weight of a Tritonal charge. However, much of the Tritonal energy is released as thermal rather than mechanical energy. In an attempt to address this uncertainty we performed numerical simulations of the explosions to determine the relative amplitudes for different explosives.

2.3. Preliminary Hydrodynamic Calculations Using Nobel

Preliminary hydrodynamic calculations were performed in order to compare the amplitudes from different explosive charges. The modeling was performed by Charles Mader using the Nobel computer code for modeling compressible fluid dynamics with the detonation physics models (Mader, 1998). The code can describe one-dimensional slab or spherical geometry, two-dimensional slab or cylindrical geometry and three-dimensional Cartesian geometry. The strength is treated using an elastic-plastic model.

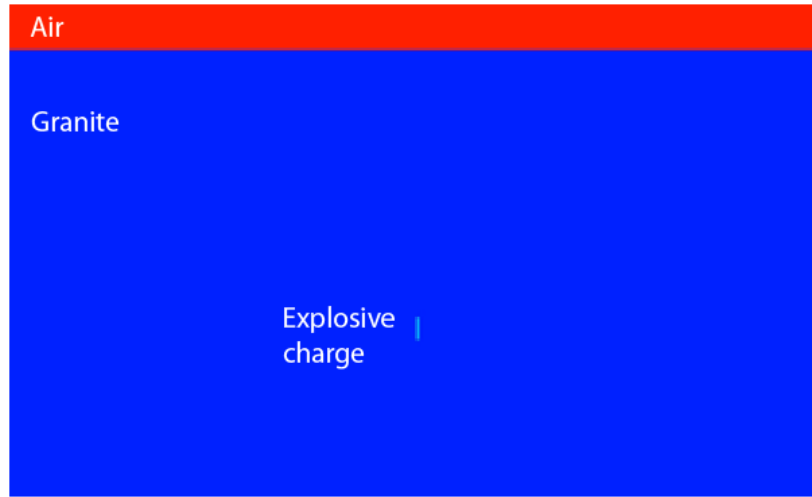


Figure 1. Geometry of the computational grid and the explosive charge

The geometry modeled was a 40 meter diameter, 20 meter long cylinder of granite with 200 cm of air on the top of the cylinder (Figure 1). An explosive cylinder 20 cm in diameter and 100 cm long was centered at 1250 cm with a 10 cm long detonator located between 1300 and 1310 cm, below the explosive column.

The Granite model used for the calculations had a density of 2.627 g/cc. The Hugoniot was described using the Sesame Equation of State Tables as a function of shock (U_s) and particle velocity (U_p) as:

$$U_s = 4.93 + 0.372 U_p \text{ to } 34 \text{ GPa and} \\ U_s = 2.103 + 1.629 U_p \text{ above } 34 \text{ GPa (e.g. McQueen et al, 1967).}$$

The shear modulus for this granite model was chosen as 27.9 GPa and $(2/3)Y_0 = 290 \text{ MPa}$ (where Y_0 is the yield strength). This would describe granite with imperfections such as voids and fractures.

Since constant volume charges were used (1m length, 20 cm diameter), the yield varied between the charges. The calculations were performed for the following explosive charges:

1. 53.8 kg of Comp B 60/40 RDX/TNT (59.7 kg TNTe).
2. 56.9 kg of Torpex 42/40/18 RDX/TNT/Al (83.6 kg TNTe).
3. 27.6 kg of ANFO (20.7 kg TNTe).
4. 32.0 kg of ANFO/Al 80/20 (38.5 kg TNTe).

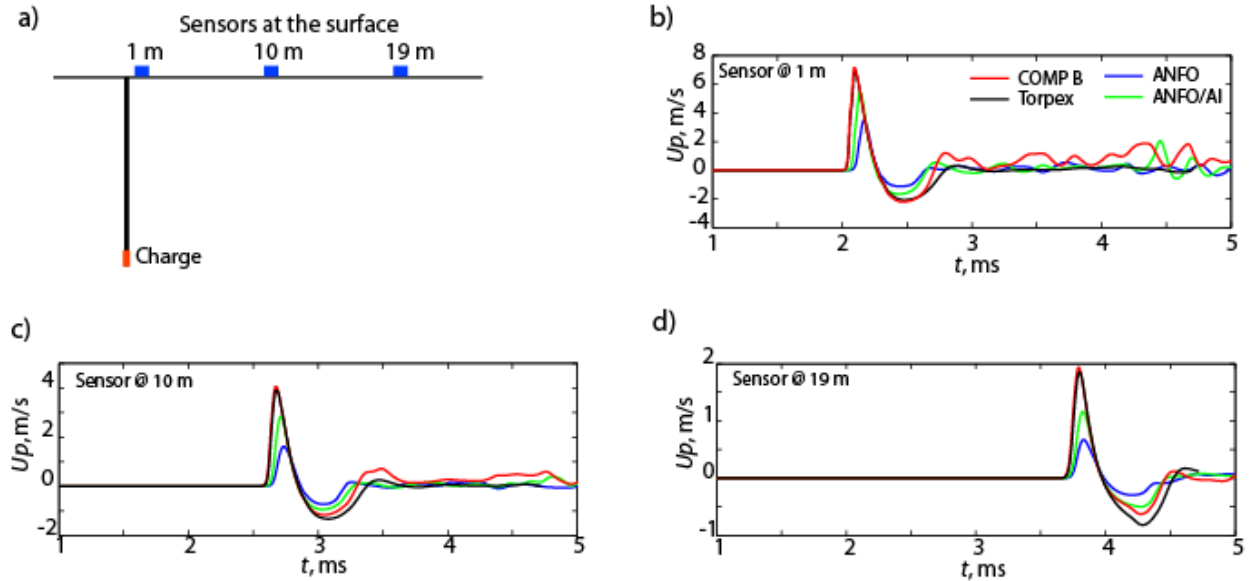


Figure 2. a) Schematic cross-section showing the charge and the points where the particle velocities were recorded ("sensors"). *Calculated waveforms are shown at the free surface at the following distances: b) 1 m, c) 10 m, and d) 19 m.*

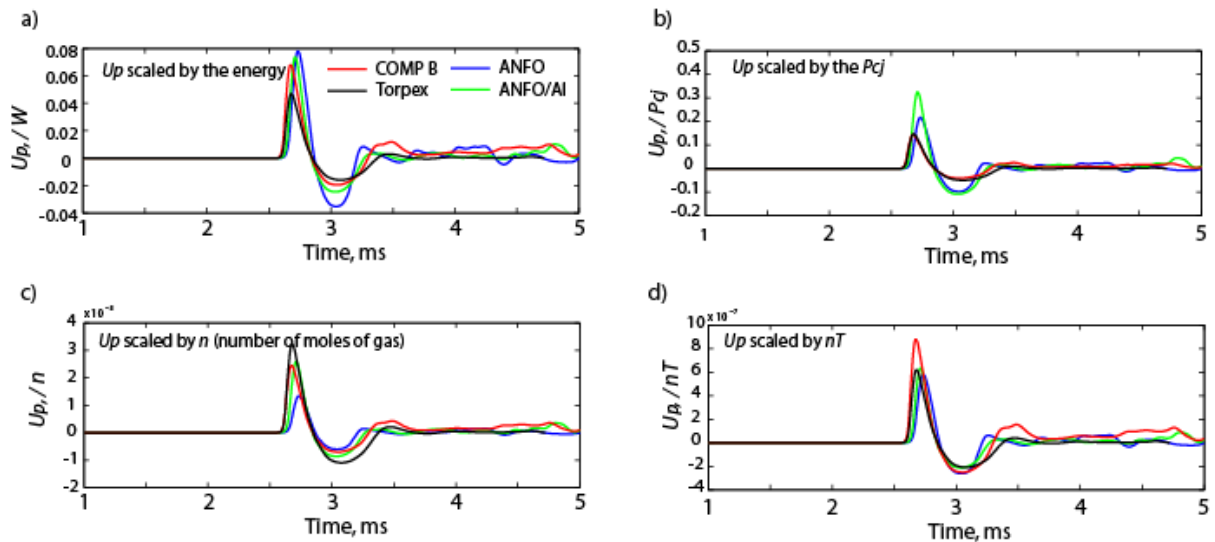


Figure 3. Calculated waveforms at 10 m (same as in Figure 2c) scaled by the following quantities: a) yield in TNT equivalent (heat), b) CJ pressure (p_{cj}), c) amount of gas released by the charge in moles (n), and d) the number of moles multiplied by the temperature of detonation (T_{cj}).

Figure 2 shows the waveforms recorded at the granite-air boundary at distances of 1 m, 10 m and 19 m from the borehole. To find correlations between the amplitudes and various parameters we scaled waveforms by the yield, detonation pressure, the amount of gas and the amount of gas multiplied by the temperature (Figure 3). No clear correlation with any of these quantities is observed. Slightly better correlation is observed with nT , which determines the equilibrium gas pressure at the constant volume.

Theoretically the shock wave amplitude is determined by the CJ pressure, which in turn is determined by the VOD and the explosive density. The explosive pairs of straight and aluminized explosives (e.g. TNT and Tritonal) have similar detonation pressures while releasing different amounts of heat and gas. Therefore, it was decided to use equal weight charges within each pair (e.g. 62 kg of each TNT and Tritonal). The amount of ANFO is calculated based on its TNT equivalent of 0.8 (instead of the 0.75 used in Table 1). Therefore, the weight of the ANFO and ANFO/Al charges were chosen to be approximately 78 kg.

2.4. Conclusions Regarding Preliminary Computations

Preliminary thermochemical and hydrodynamic calculations were performed in order to design the charges to be used in the experiment. Initially we were planning on using COMP B (RDX/TNT 60/40) and Torpex (RDX/TNT/Al 42/40/18) pairs. The COMP B charge that we initially planned to use was purchased earlier (for NEDE), but was not used because it did not fit into the NEDE borehole (as the manufacturer did not follow specifications). However, during GAS2016 experiment, the boreholes were drilled with sufficiently large diameters to accommodate the COMP B charge. However, we became aware that Torpex was not available for purchase from any of the manufacturers at the time of the experiment. Therefore, instead of earlier planned COMP B/ Torpex pair, the TNT/Tritonal pair was used.

Based on the thermochemical calculations, the following charges were selected for the experiment:

1. 62 kg of TNT
2. 62 kg of Tritonal
3. 62 kg TNT in water-filled borehole
4. 78 kg of ANFO
5. 78 kg of aluminized ANFO (ANFO/Al 80/20)
6. 78 kg of water-resistant ANFO in water-filled borehole.

Thus, six explosions were detonated during the experiment. Two of them were detonated in water-filled boreholes in order to study the effect of water (coupling) on seismic amplitudes and spectra. The remaining four shots were detonated in dry boreholes.

3. GAS2016 EXPERIMENT

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3.1. Introduction

Weston Geophysical Corp. conducted a series of chemical explosions using four different explosive types in order to investigate their effect on seismic signatures. Previous experimental data (NEDE, e.g. Martin et al, 2012) suggest that low-frequency *P*-wave amplitudes are affected by the explosive velocity of detonation (VOD) and by the thermodynamic characteristics of gaseous explosive products (Stroujkova, 2015). The new experiment conducted in New Hampshire in 2016 was designed to isolate the effects of the amount of the explosive gases by using aluminized and non-aluminized explosive pairs.

In August, 2016 Weston Geophysical conducted the field experiment (GAS2016). This work included site preparation, drilling, blasting and seismic data acquisition. The experiment took place in Twin Mountain, NH, between August 8 and 13. Subsequent cleaning (de-stemming) of the shot boreholes was performed on August 15-16. The explosions were monitored using a dense seismic network, consisting of 45 3-component seismic instruments deployed from near field to local distances (between 1.5 m and 10 km), including short-period seismometers and high-g accelerometers. The data recovery was 95%.

3.2. Drilling and Site Preparation

The experiment was conducted in a granite quarry in the town of Carroll, NH (Figure 4). The dominant rock type observed in the boreholes is granite with bands of mafic minerals including possible amphibolites at some locations/depths.

Initially seven large-diameter (9.8”) boreholes for the large charges and three smaller diameter (4.5”) boreholes for the calibration charges were drilled. The test site configuration is shown in Figure 4. Four of the large-diameter boreholes were dry at the time they were drilled in early July of 2016, while three were producing water (Table 2). At the time of the experiments the dry boreholes were filled with surface run-off and needed to be evacuated. All four holes were pumped dry at the time the charges were loaded.

The shot holes were originally drilled to almost the same depth (approximately 42’), but drill cuttings and mud settled back into some of the holes and reduced the planned hole depths. SH4 blasthole was only 35 ft deep on the day of the shooting. All other holes were not affected as much. The blasthole depths on the day of the shooting are shown in Table

2. Note that the borehole wall of SH4 was shifted due to the blasting of the previous shots, and the blasters were unable to load the charge (8" in diameter). As a result, SH4 was not used and was filled with stemming after the experiment.

Table 2. Characteristics of the drilled blastholes

Shot #	Intended Explosive type	Water	Latitude	Longitude	Depth, m	Notes
SH1	TNT	Dry	44.2942°	-71.5544°	12.6	Dry hole. Light colored softer gneiss.
SH2	Tritonal	Dry	44.2944°	-71.5542°	12.6	Dry hole. Light colored softer gneiss.
SH3	TNT	Wet	44.2943°	-71.5546°	12.6	Water in the hole. Greenish hard rock.
SH4	ANFO	Wet	44.2941°	-71.5547°	12.6	Water in the hole. Light softer gneiss.
SH5	ANFO/Al	Dry	44.2940°	-71.5545°	12.6	Dry hole. Light colored softer gneiss.
SH6	COMP B	Dry	44.2941°	-71.5541°	12.6	Dry hole. Darker colored hard gneiss.
SH7	COMP B	Wet	44.2939°	-71.5542°	12.6	Water gushing at 9' @ ~30 gal/min. Fractured dark gneiss.
CA1	Booster	Wet	44.2940°	-71.5546°	12.6	-
CA2	Booster	Wet	44.2943°	-71.5544°	12.6	-
CA3	Booster	Dry	44.2941°	-71.5543°	12.6	-

3.3. Blasting

Six explosions and three calibration shots were conducted during the experiment (Table 2). The following explosives were used to conduct the shots: TNT, Tritonal (TNT/Al 80/20), ANFO, and aluminized ANFO (ANFO/Al 80/20). In addition COMP B boosters were used to initiate the charges and for the calibration shots.

The explosion time was determined using the Weston Inexpensive Timing System (WITS) designed as a loop wire forming a closed circuit with a low voltage recorded with a high sample rate digitizer (RefTek RT130). One end of the wire is connected to the digitizer and the other is typically taped to the detonation booster. When the booster detonates, the circuit is broken and the digitized signal drops to 0 V, indicating detonation. Timing accuracy for the WITS system is 2 ms.

Three complete explosive charges were ordered from Accurate Energetics Systems Inc. for this series of explosions. They included two charges of pure TNT each weighing 137 lbs. and one charge of Tritonal (80% TNT & 20% Aluminum) also weighing 137 lbs. Each

complete charge was cast in increments or segments with nine segments completing a 137 lb. charge (Figure 5).

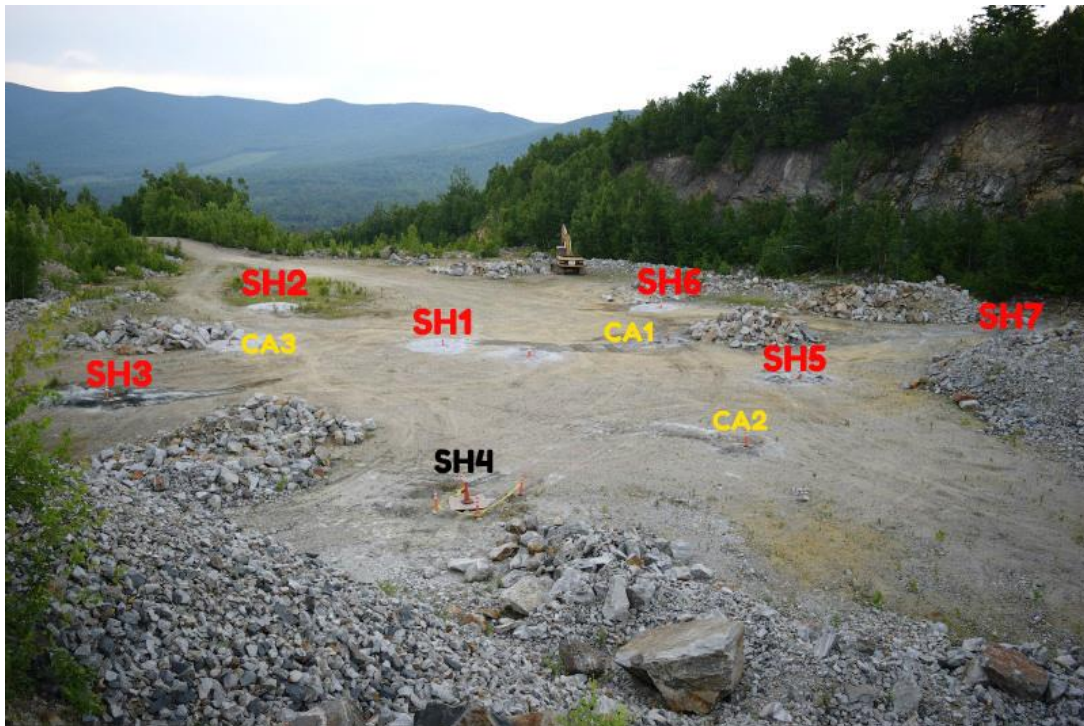


Figure 4. A photograph of the test site with drill sites for each blasthole marked in red (for the large shots) and yellow (for the calibration shots). Prospective hole SH4 could not be loaded and was abandoned.



Figure 5. Cylindrical segment 2 of the TNT charge 1 with weight of 15.4 lbs.



Figure 6. A bottom segment of the Tritonal charge with a booster well.

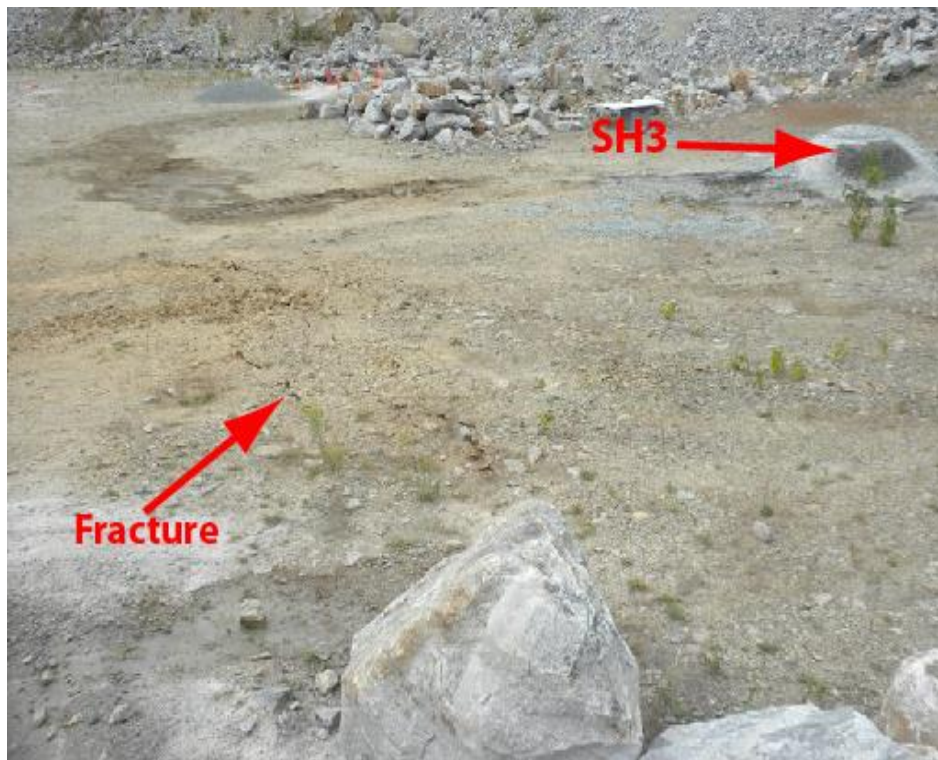


Figure 7. Surface fracture created by SH3.

Each complete charge was identified by Accurate Energetics Systems Inc. from 1 to 3, with charges 1 and 2 being TNT and 3 being Tritonal. Each of the segments was numbered one through nine, progressing from the bottom up and identified as being Tritonal or TNT. Figure 5 shows the number 2 segment of TNT charge number 1. The segments were also weighed by Accurate and the weight for each written on each segment below its number. The weight of the segments was as follows: For the TNT charges, segment 1 = 14.2 lbs.

and segments 2 through 8 = 15.4 lbs each. Segment 9 is 15 lbs. for a total of 137 lbs. For the Tritonal charge, segment 1 is 15.2 lbs, segments 2 through 8 are 16.5 lbs. each. Segment 9 weights 6.3 lbs, for a total of 137 lbs.

The bottom segment, in each of the 3 charges was cast with a booster well to accept a 1 lb. cast Comp B booster for priming (Figure 6). By having bottom center priming, it was possible to get a VOD trace from each charge as well as a precise timing of detonation. The assembled 50.5" (1.28 m) long charge with two Comp B boosters was placed in a cardboard tube to protect the wires before loading into the blasthole.

After loading the charges, the holes were stemmed with ¾" stemming (crushed rock pieces used to fill up the loaded borehole and help contain the explosion in the blasthole). Surface fractures were observed following SH1, SH3, SH5 and SH7 out to distances of 5-10 m from the blastholes (e.g. Figure 7). SH2 and SH6 produced very limited surface fracturing and some minor stemming ejection. SH1 (TNT) caused water ejection through nearby 4" boreholes (CA1, CA3 and BH01), which indicates that the explosion created fractures that connected to other boreholes. No ejection from the blasthole was observed for SH1.

Table 3. Explosion locations and origin times.

Shot	Date	Origin time (GMT)	Latitude	Longitude	Depth, m *	Explosive type	Yield (kg TNT)	Water
SH1	08.11.2016	23:30:31.045	44.29417°	-71.55435°	12.95	TNT	63.2	Dry
SH2	08.11.2016	19:08:46.404	44.29436°	-71.55422°	13.00	Tritonal	96.2	Dry
SH3	08.12.2016	14:41:35.217	44.29429°	-71.55456°	12.65	TNT	63.2	Wet
SH5	08.11.2016	22:13:25.735	44.29399°	-71.55448°	12.70	ANFO/Al	63.1	Dry
SH6	08.11.2016	21:17:56.761	44.29410°	-71.55409°	12.65	ANFO	94.1	Dry
SH7	08.12.2016	18:37:38.152	44.29387°	-71.55423°	12.50	ANFO	60.9	Wet
CA1	08.12.2016	20:00:35.512	44.29406°	-71.55430°	12.80	COMP B	0.5	Wet
CA2	08.12.2016	20:01:35.979	44.29402°	-71.55459°	12.50	COMP B	0.5	Wet
CA3	08.12.2016	20:02:36.402	44.2943°	-71.55438°	10.97	COMP B	0.5	Wet

* Depth of the boreholes on the day of the shooting.

3.4. Velocity of Detonation (VOD) Measurements

The velocity of detonation (VOD) was measured using a MREL HandiTrap II VODR. A resistance wire is taped to the booster and lowered down the hole. As the detonation wave propagates up the borehole, the resistance wire is melted and the recorder measures the decreasing resistance at 1 million samples per second. The resistance was then converted to distance and a velocity calculated.

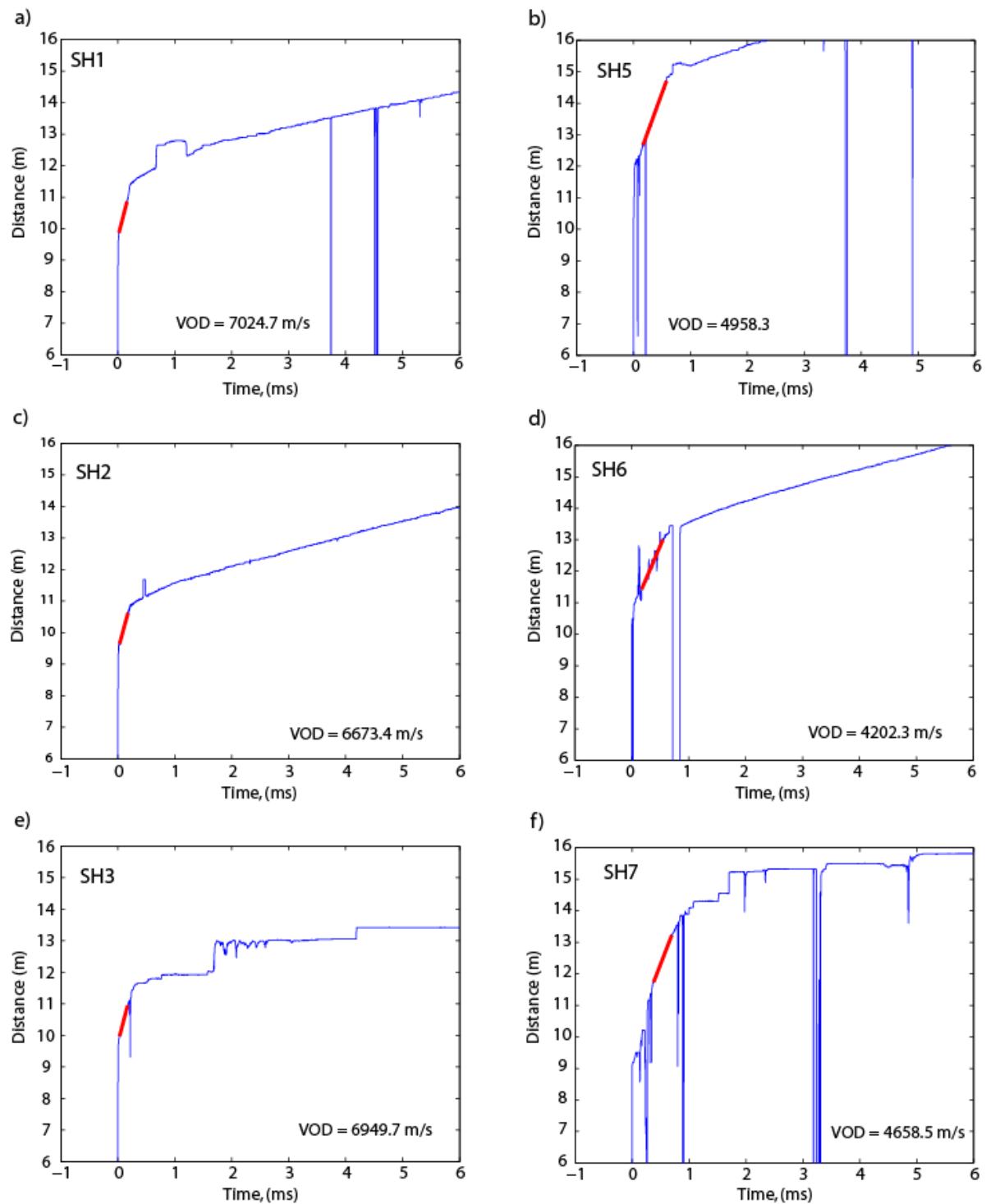


Figure 8. VOD measurements for a) SH1, b) SH5, c) SH2, d) SH6, e) SH3, and f) SH7. The slope of the red line segment indicates the velocity.

Figure 8 shows the plots of the wire length as a function of time for the six explosions. The VOD is calculated as a slope of the line during the stationary detonation. The TNT charge in a dry borehole detonated with a VOD of 7.02 km/s, the Tritonal charge with a VOD of

6.67 km/s, and the TNT charge in water-filled borehole had a VOD of 6.95 km/s. The first ANFO shot in a dry hole detonated with a VOD of 4.96 km/s, the ANFO/Aluminum mix detonated with a VOD of 4.20 km/s, and the last ANFO charge (6" in diameter) in the water-filled borehole detonated with a VOD of 4.66 km/s. Lower VOD for the aluminized explosives compared to non-aluminized is expected.

3.5. Seismic Data Acquisition

A seismic network was fielded from near-source to local distances (between 1.5 m and 9.5 km), including short-period seismometers and high-g accelerometers (Figure 9). In the near-field, five Endevco 25g accelerometers and six TerraTech 5g accelerometers were installed in close proximity to the explosions to record the near source ground motions. Figure 9 c-d shows the locations of the close-in sensors. The instruments located at the test bed were grouted. All of these instruments recorded three components (3C) of motion using Reftek 130 (RT130) data loggers placed in plastic tubs for protection.

The near-source accelerometers recorded at a sampling rate of 1000 samples per second. Unfortunately, one of the Endevco cables was damaged from previous experiments; therefore only four of these sensors were recording at each time. In addition, NS10 had a malfunctioning vertical component, while NS12 had malfunctioning horizontal components. The borehole accelerometer (BH01) recorded all shots, but we were unable to recover it out of the borehole.

The near-source stations were located at distances between 0.3–1.2 km with approximately 200 m intervals at various azimuths (Figure 9b) on the property belonging to the quarry owner. These stations utilized PASSCAL BIHO boxes (quick deploy boxes). Six of the on-property stations were equipped with 2 Hz Sercel L22 2Hz 3C sensors. The remaining 8 stations used 1 Hz L-4C 3D sensors.

In addition, 19 stations were installed off the quarry property at local distances between 1.2 km and 9.5 km (Figure 9a). All of these stations were equipped with PASSCAL BIHO boxes with 2 Hz Sercel L22 2Hz 3C sensors (Figure 9a). These stations were recording continuously with a sampling rate of 500 samples per second using RT130 digitizers, with the exception of several stations recording at 250 samples per second. The usable frequency band is between 2 and 205 Hz for most of the stations. All of the local data were recovered.

All explosions were recorded using a video camera situated at the upper level above the test site. The location of the camera is shown in Figure 9d.

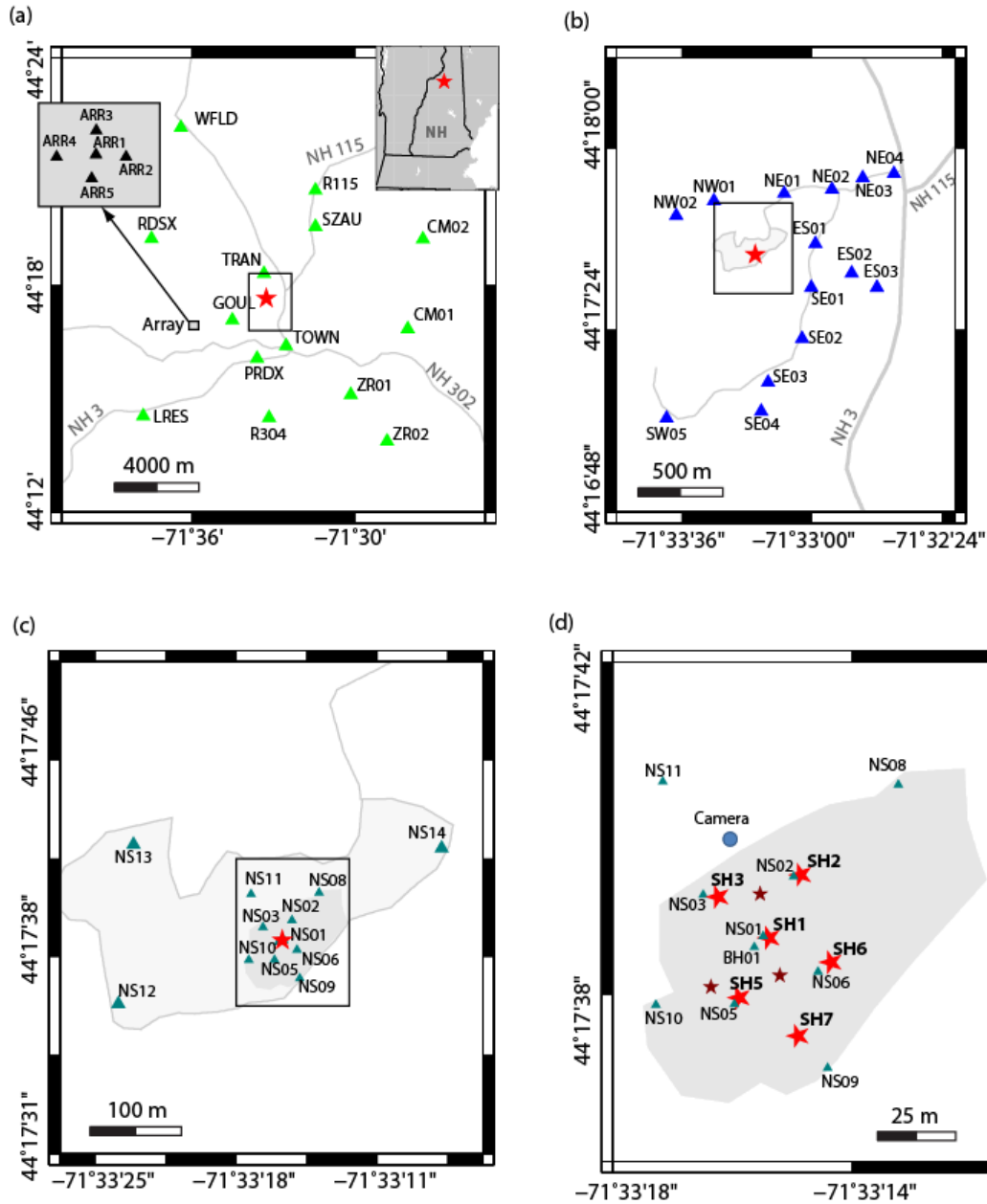


Figure 9. (a) Seismic stations deployed at local distances from the explosions near Twin Mountain, NH (USA). The green triangles show the local stations, the stars show the shot points. The insert in the upper right shows the regional map with the experiment location marked as a red star. The insert in the upper left shows the configuration of a short-period array, deployed in the area marked as a rectangle. The area surrounding the experiment site marked with a rectangle is enlarged in 9b. (b) The near-source network of the short-period seismometers. The blue triangles show the 3C stations (L22). The area within the rectangle is enlarged in (c). (c) Enlarged view showing the near-field accelerometers (teal triangles). (d) Enlarged view of the test site, showing the shot locations (red stars) and the near-source accelerometers. Location of the video camera is shown with a blue circle.

We recovered 94% of the seismic data. Some of the near-source data were lost due to damage to the instruments from strong ground motions and flying debris during previous explosions. One of the Endevco cables was damaged from previous explosions; therefore only four of these sensors were recording at each time. Station NS10 had a malfunctioning vertical component, while Station NS12 had malfunctioning horizontal components. All of the data recorded at distances over 200 m was recovered.

3.6. Seismic Data

In this section, we present examples of the waveforms collected during the experiment.

3.6.1. Near-Source Network. The near-source accelerometers were placed at distances between 1.5 and 200 m from the sources. Figure 10 shows the spall records from four of the explosions. Other shots did not have spall gauges. The near-source records show the impulsive shock wave arrivals, then a period of downward acceleration (dwell), and then a series of spikes resulting from slapdown(s). Notice that the time between the slapdowns is different between the shots. SH1 and SH6 produced the highest amplitudes for the first impulses. Interesting that overall SH1 and SH2 generated similar seismic wave amplitudes, while their near-source amplitudes differ by an order of magnitude. Figure 11 shows the records from Station NS01 for all six explosions.

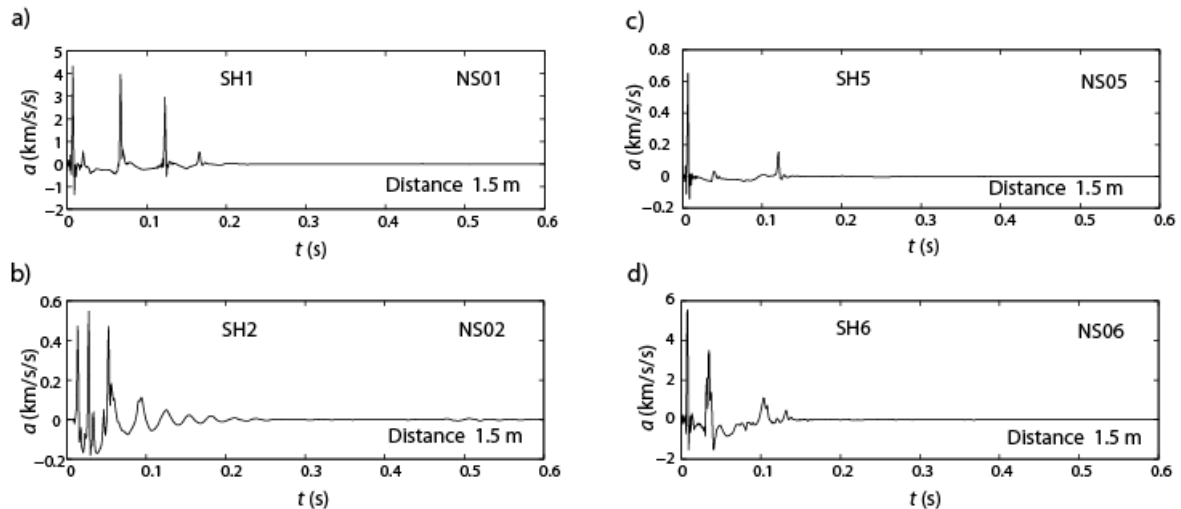


Figure 10. Accelerograms (vertical components) from the near-source accelerometers located at 1.5 m from the blastholes for: (a) SH1, (b) SH2, (c) SH5, and (d) SH6.

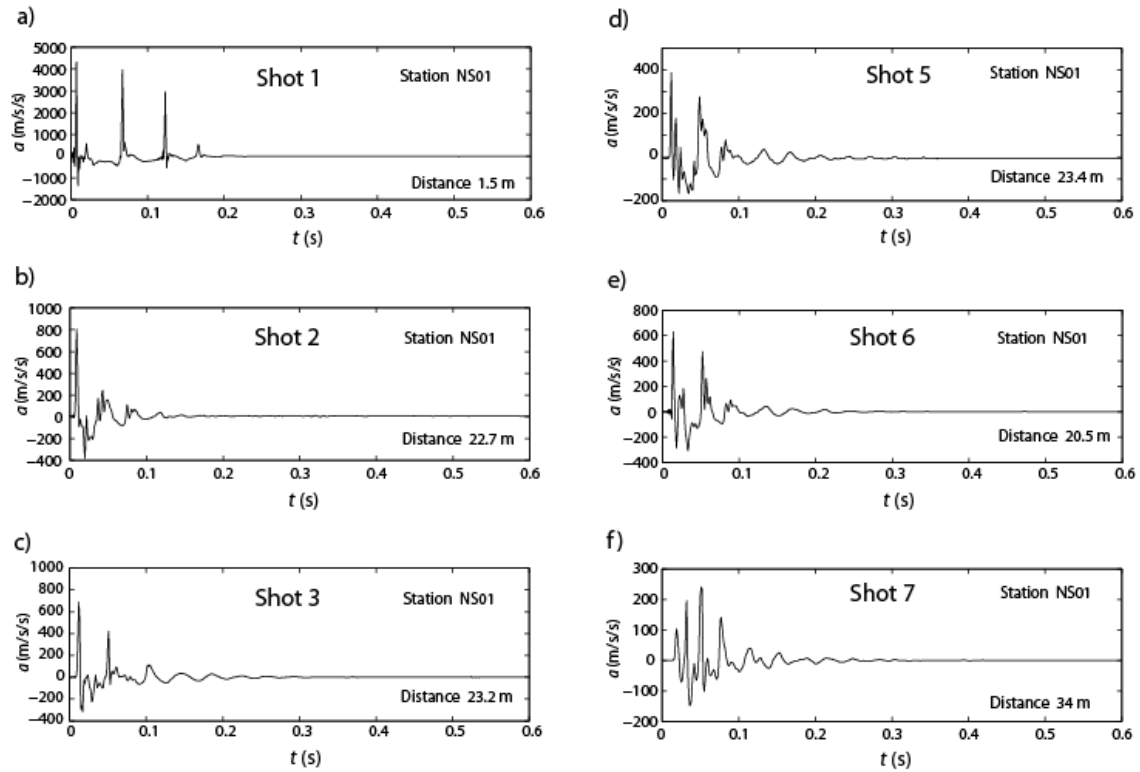


Figure 11. Accelerograms (vertical components) from the near-source accelerometer NS01 for: (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6 and (f) SH7.

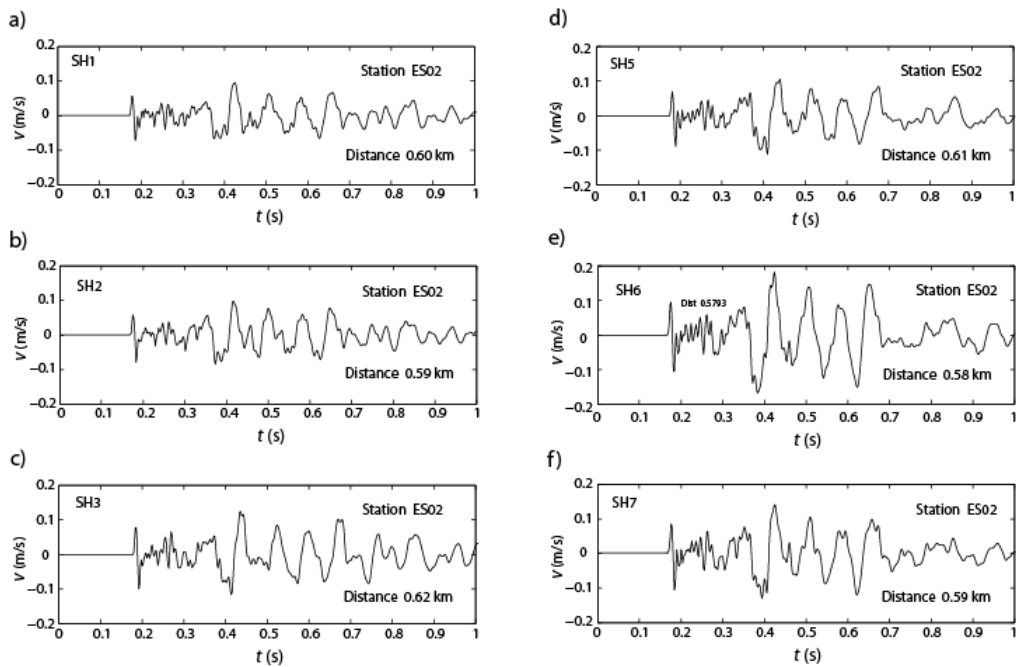


Figure 12. Vertical components of the velocity seismograms recorded by short period station ES02 for: (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

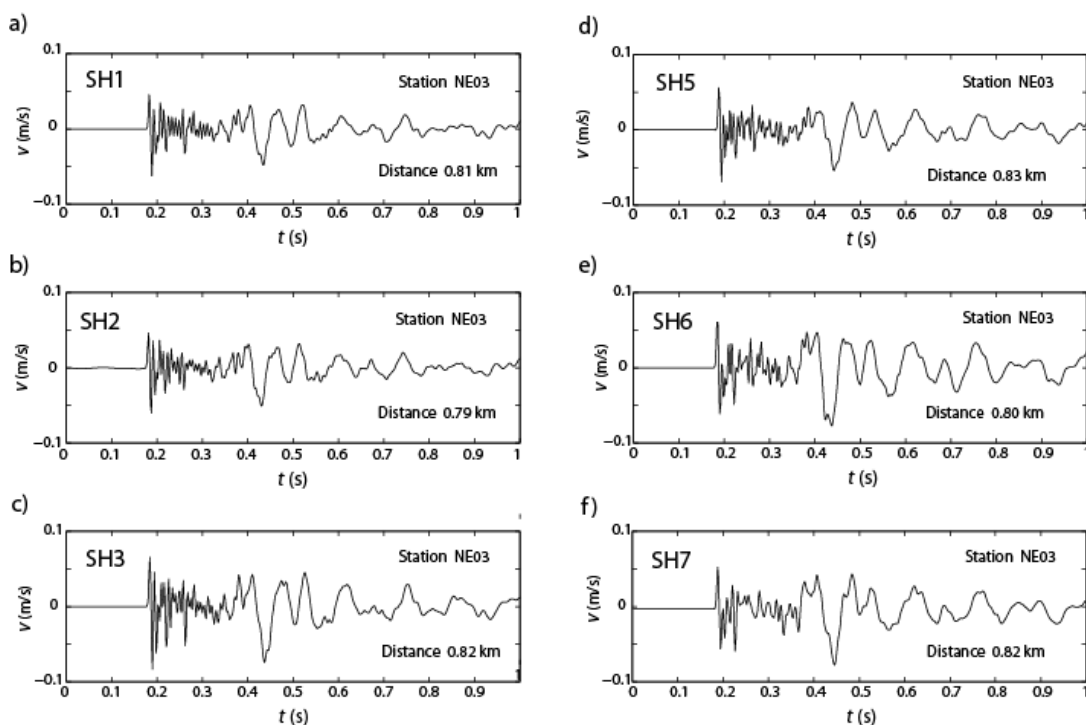


Figure 13. Vertical components of the velocity seismograms recorded by short period station NE03 for: (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

3.6.2. Short-Period Network. A dense geophone network was installed around the quarry. The near-source network consisted of 14 short-period 3C stations. All these stations were equipped with L-22 geophones at a sampling rate of 500 samples per second.

Figures 12 and 13 show seismic traces for all shots recorded by station ES02 and NE03 located at distances of approximately 620 m and 810 m from the sources, respectively. These traces for the same stations show the amplitude variations between the shots. SH1 (TNT) and SH2 (TNT/Al) amplitudes are nearly identical for both stations, as well as for the other stations of the network. The amplitudes produced by aluminized ANFO (SH6) are, however, higher than the amplitudes from the ANFO shot (SH5).

SH6 shows the highest amplitudes at ES02 for both *P* and *R_g*. Shot SH3 produced the highest *P*-wave amplitude of all shots at Station NS03. The amplitude variations between the explosions at different stations suggest non-isotropic source radiation patterns.

3.6.3. Local Network. Stations of the local network were fielded at distances between 1.2 and 9.5 km. The area surrounding the test site has rough topography. The test site is surrounded by the White Mountain National Forest with its rugged terrain in the East and South. Stations ZR01, ZR02, LRES, R304, CM01 and CM02 (Figure 9a) are located in the National Forest. The area to the west and north of the test site is somewhat less rugged.

The stations in that area were located in the residential properties, while two of the sites, TOWN and TRAN, were located on municipal property belonging to the Town of Twin Mountain near the town hall and the transfer station, respectively.

All of the local stations were equipped with L-22 sensors using R-130 digitizers. The stations were equipped with BIHO boxes (Figure 14).

A five-element seismic array was installed on private property approximately 3.7 km from the sources. The array configuration is shown in Figure 15. Four of the array stations were recording with a sampling rate of 1000 samples per second, while one of the stations (ARR3) was erroneously set to 250 samples per second (possibly due to malfunctioning equipment). Figure 16 shows the waveforms for all six explosions recorded at one of the array stations (ARR2).



Figure 14. Station CM02 located in the White Mountain National Forest.

Seismic waveforms recorded at the near-source distances have high signal-to-noise ratios (SNR), for both larger explosions and for the small calibration shots. Figure 19 shows the local waveforms from SH1 at ranges from 1.2 km (Station TRAN) to 9.4 km (Station WFLD). As expected, the SNR degrades with the increase in range. Cultural noise is observed at stations located close to the roads and structures (e.g. PRDX).

Figures 17 and 18 show the traces from the sensors located along the profiles extending in the north and south direction respectively. The apparent velocity inferred from the first arrivals is approximately 5 km/s. The seismograms from the northern profile show higher *R_g* amplitudes, while the *R_g* phases appear to degrade toward the south. Figure 19 shows the waveforms for all local stations, which demonstrate significant waveform complexities. Higher surface wave attenuation/scattering is likely related to the complexities of the topography and the near-surface geology.

A number of the permanent stations in New England recorded some or all of the shots from the GAS2016 experiment. The SNR is good at Lisbon, New Hampshire (LBNH, United States National Seismic Network, doi:10.7914/SN/US) and low at most of other stations. LBNH waveforms are dominated by high-frequency *P*-wave coda with scattered secondary arrivals as shown in Figure 20.

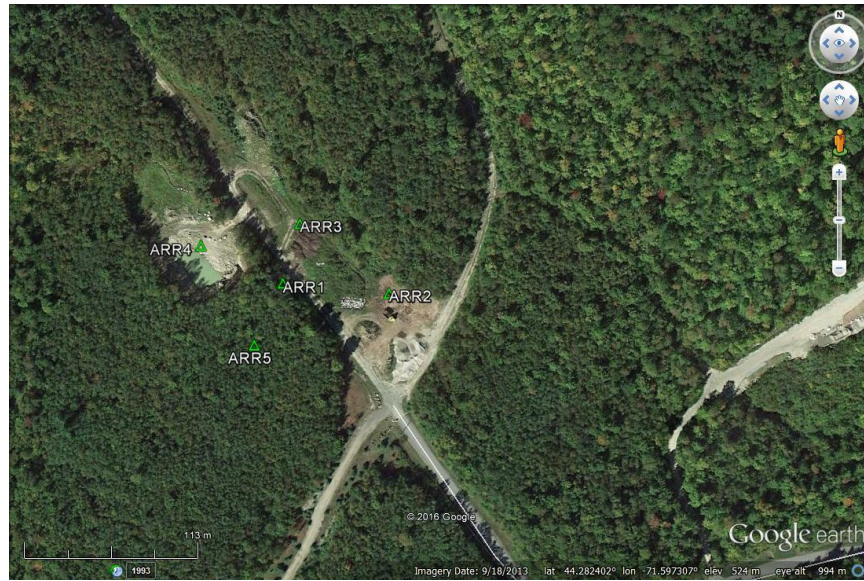


Figure 15. Configuration of the 5-element array.

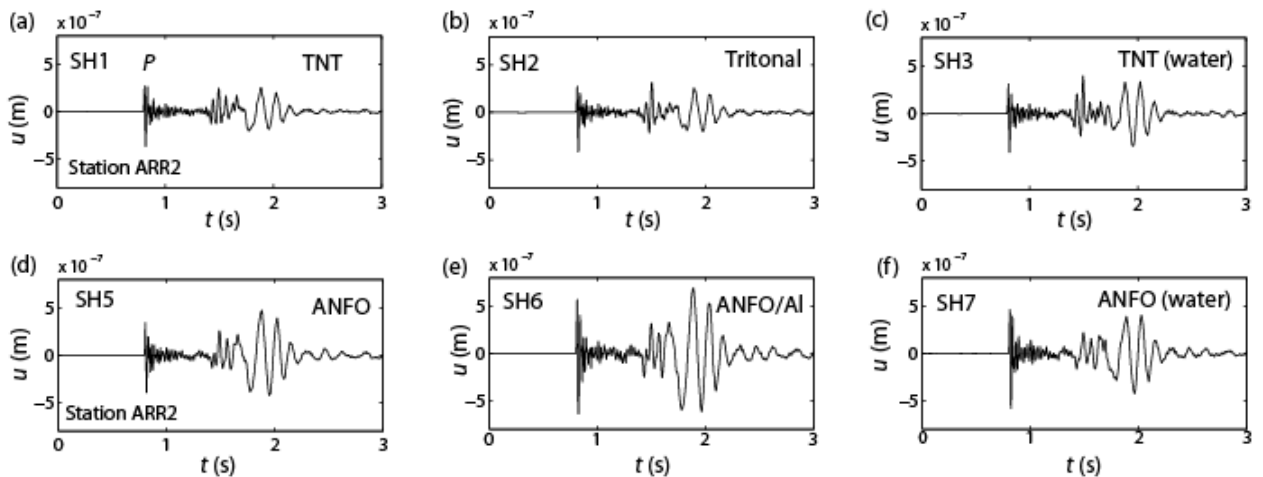


Figure 16. Vertical components of the traces recorded by short period station ARR2 for: (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

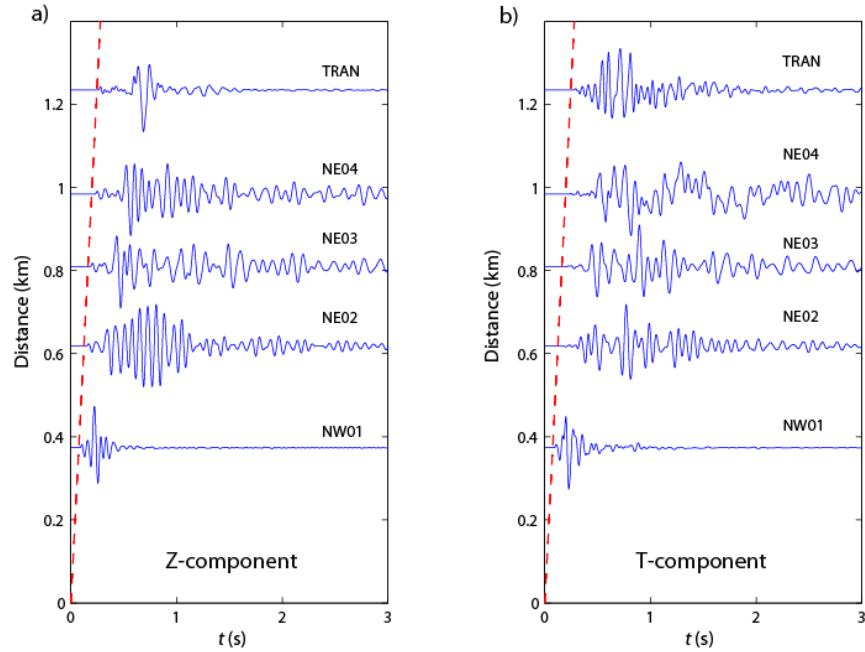


Figure 17. A profile for shot SH1 for the stations located to the north of the shot: (a) vertical components, and (b) transverse components. The red dashed lines correspond to P-velocity of 5 km/s.

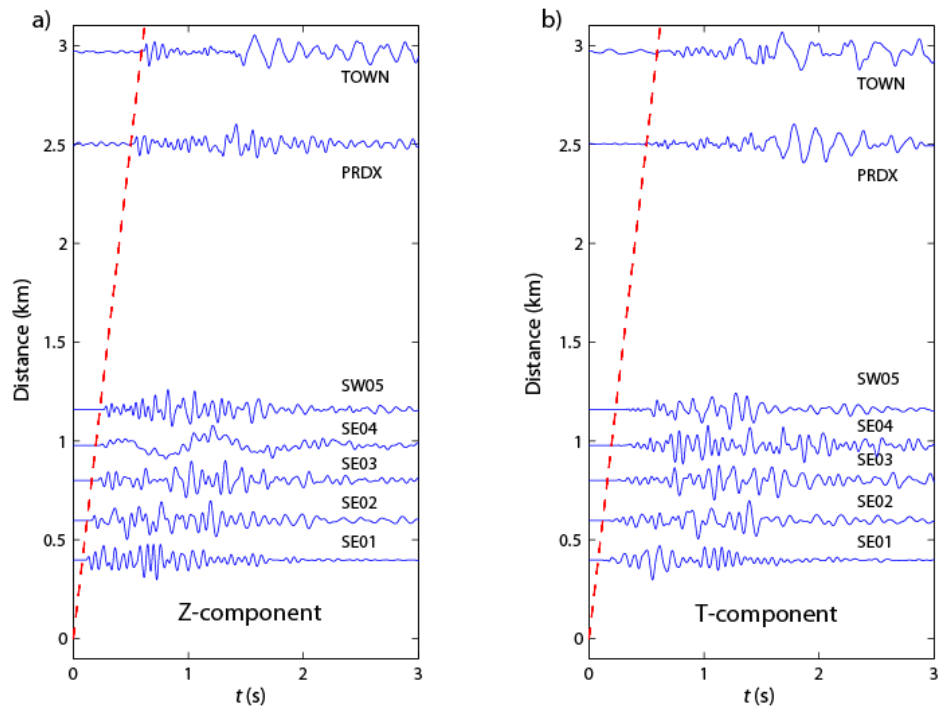


Figure 18. A profile for shot SH2 for the stations located to the south of the shot: (a) vertical components, and (b) transverse components. The red dashed lines correspond to P-velocity of 5 km/s.

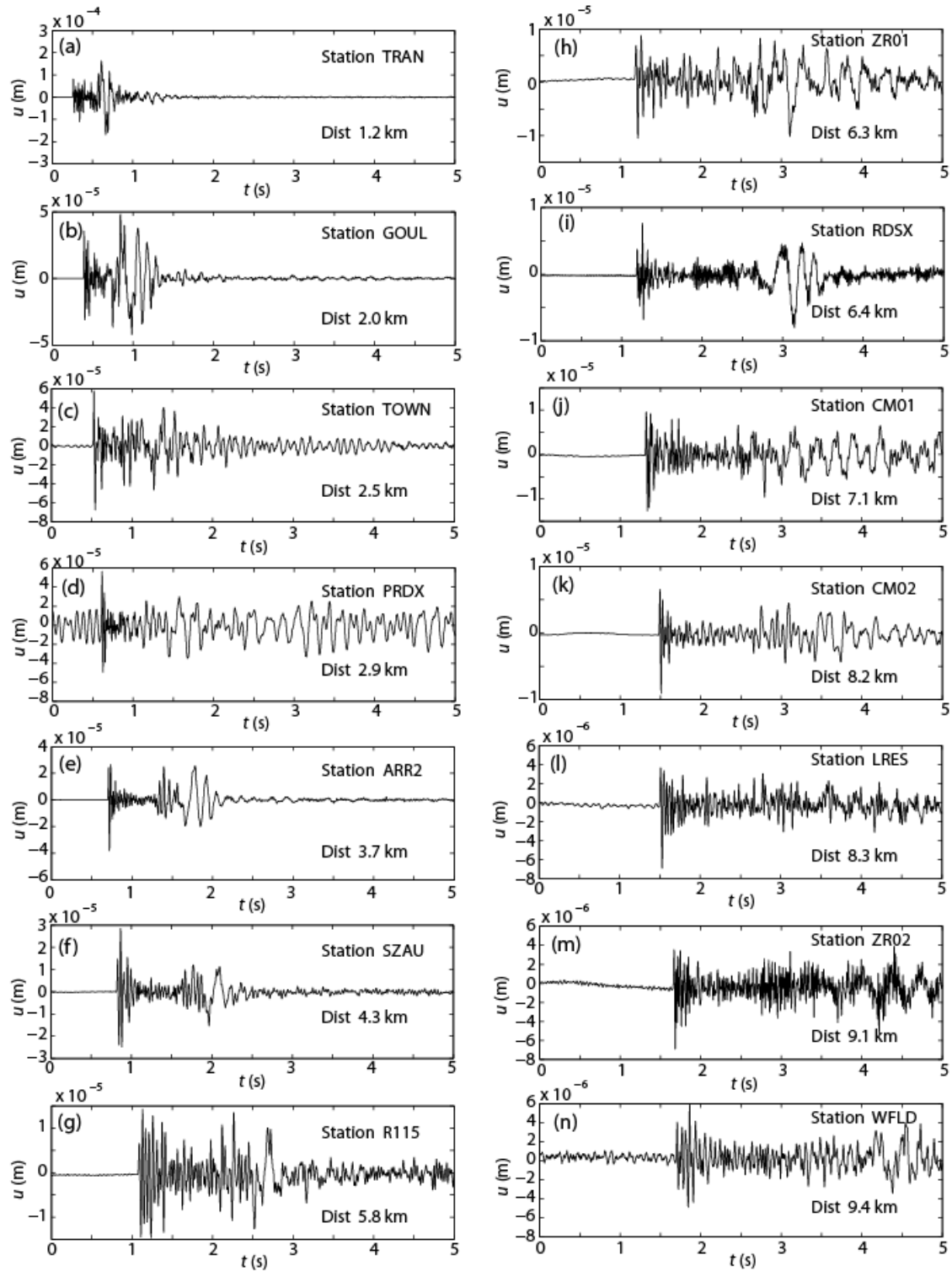


Figure 19. Vertical components of the displacement seismograms for SH1 recorded by the local stations: (a) TRAN, (b) GOUL, (c) TOWN, (d) PRDX, (e) ARR2, (f) SZAU, (g) R115, (h) ZR01, (i) RDSX, (j) CM01, (k) CM02, (l) LRES, (m) ZR02, and (n) WFLD.

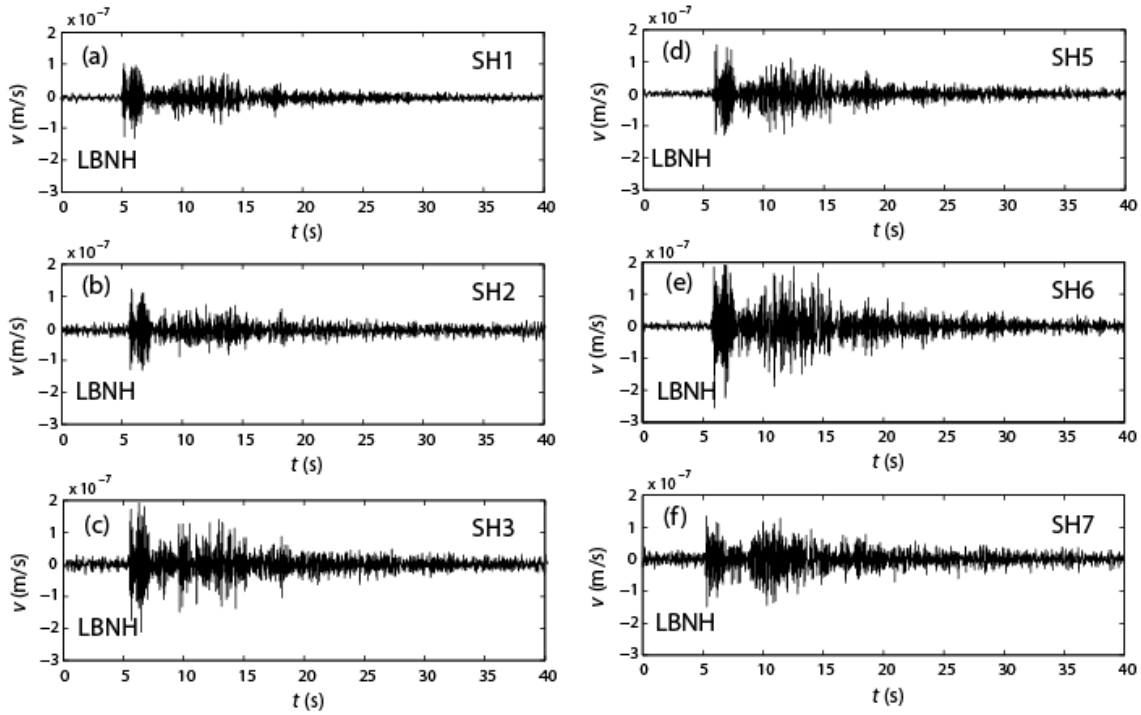


Figure 20. Vertical components of the velocity seismograms recorded by the permanent station LBNH located approximately 30.2 km from the shots in Lisbon, NH for (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

3.7. Conclusions Regarding Deployment

The active source explosion experiment was conducted in New Hampshire in August, 2016. The purpose of the experiment was to study the seismic signatures of the explosion sources using different explosive types that generated different amounts of gaseous products. WGC collected seismic data from 45 stations located between 1.5 m and 9.5 km from the sources. Data from the experiment can be used for explosion source studies, explosion monitoring, seismic event detection, discrimination and yield estimation. In addition, data from this and other explosion experiments, including the New England Damage Experiment in Vermont (Martin et al, 2012) and the Fracture Decoupling Experiment in New Hampshire (Stroujkova et al, 2013), can provide ground truth events for the crustal studies, and velocity calibration in New England.

4. POST-EXPLOSION SITE CHARACTERIZATION

Anastasia Stroujkova, Weston Geophysical Corp.
Mario Carnevale, Hager Geoscience.

4.1. Introduction

This chapter discusses the results of the post-explosion geophysical site characterization conducted as a part of GAS2016 experiment. The well logging survey was conducted in 5 shot boreholes and one analysis borehole. The purpose of the well logging was to characterize the damage created by the underground explosions and to relate it to the radiated seismic waves.

4.2. Drilling Back into the Shot Boreholes

The experiment was conducted in a granite quarry near the town of Carroll, NH (Figures 21 and 22). The quarry is located within the Ordovician gneiss dome, which belongs to Oliverian Plutonic Suite (age 440 ± 40 Ma; Naylor, 1969; Lyons et al, 1997). The rocks are represented by weakly to moderately foliated, biotite gneiss with bands of amphibolite (Naylor, 1969; Bennett et al, 2006). The rocks are cut with fractures dipping toward the NW (dip angles are between 45° and 70°). A prominent fracture zone is extended along the SE boundary of the site (Figure 21a) and represented by highly fractured and oxidized rocks (Figure 21b).

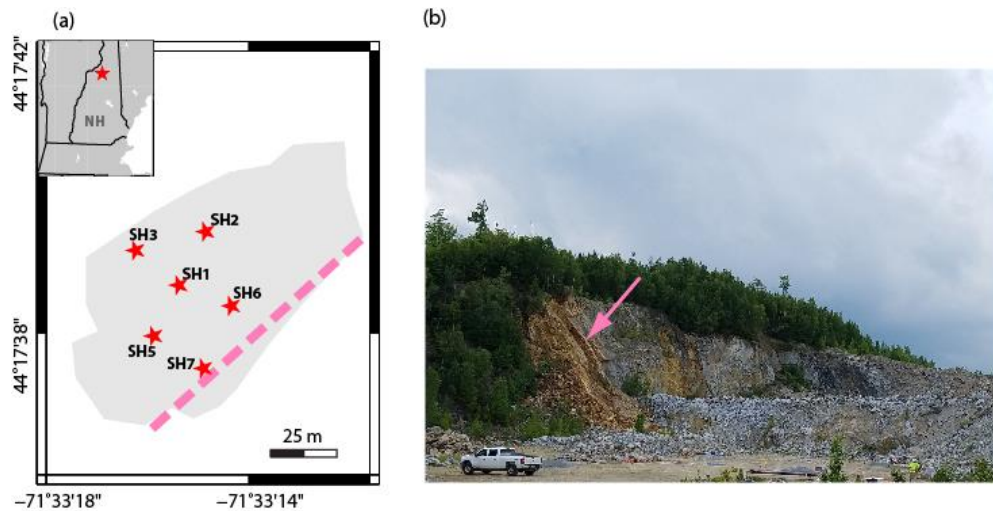


Figure 21. (a) Map of the test site, showing the shot locations (red stars) and strike direction of the fracture zone (pink dashed line). The insert in the upper left shows the map of New England with the experiment location marked as a red star. (b) A photograph of the test site looking from the NE toward the SW. The arrow points to the fracture zone dipping toward the NW marked in (a).

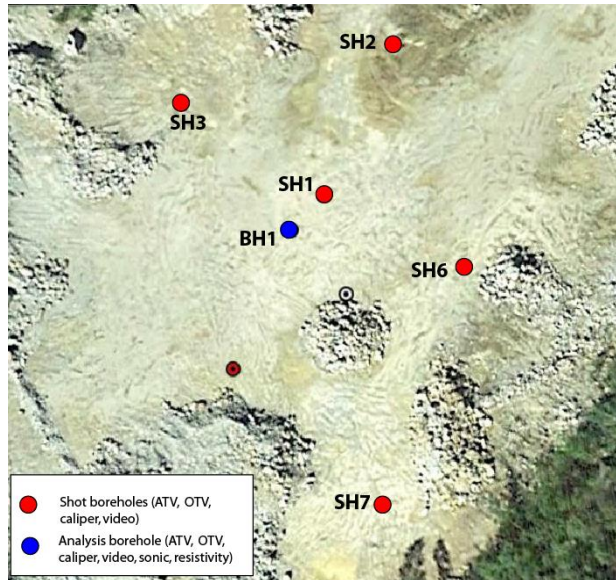


Figure 22. Map of the experiment site in Carroll, NH, showing the locations of the de-stemmed shot boreholes (red circles) and an analysis borehole (blue circle), where geophysical logging was conducted.



Figure 23. Re-drilling SH7 borehole.



Figure 24. Rock samples extracted from the borehole re-drilled after SH2 (Tritonal). The rock fragments are similar to pumice, which indicates that it was molten and quickly solidified.

After completion of the explosive experiment the shot boreholes were evacuated in order to study the damage in the explosive cavities and along the boreholes (Figure 23). Only five out of six boreholes were cleaned. SH5 produced extensive damage in the spall zone and the drillers were unable to drill back into the cavity. Well logging was performed by Hager Geoscience in the five shot boreholes and in an analysis borehole (BH1) located 6 m from SH1 (Figure 22).

We found evidence of melt in the rock samples exhumed from some of the shot boreholes. The fragments had vesicular texture similar to pumice (Figure 24). The largest number of these fragments was found near SH2. This observation is consistent with the expected high pressure and temperature produced during the Tritonal detonation (Table 1, Column 5).

4.3. Well Logging

After the shots stemming was evacuated from five of the shot boreholes (SH1, SH2, SH3, SH6, and SH7). Borehole SH5 had significant rock damage in the spall zone, and it was impossible to drill back into the cavity. Well logging was performed in the five shot boreholes and in an analysis borehole (BH1) located 6 m from SH1 (Figure 25). Logs performed in all shot boreholes included Acoustic Televiwer (ATV), Optical Televiwer (OTV), caliper and video log. The logs performed in the analysis borehole (BH1) included also a full waveform sonic log, a resistivity log and a gamma log. The logging results for the shot boreholes are briefly summarized in Table 4.



Figure 25. Logging of the shot borehole SH1.

The dominant rock type observed in the boreholes is granite with bands of mafic minerals including possible amphibolites at some locations/depths. Full waveform sonic logging of BH1 indicated compressional (*P*) wave velocities of 4300 – 5300 m/s and shear wave velocities of 2500 – 2800 m/s. Normal Formation Resistivity logging of BH1 shows resistivity of 1000 – 2000 Ohm-m between the water table and the depth of approximately 35 ft. Below this depth the resistivity gradually increases to 8000 – 10,000 Ohm-m at a depth of 55 ft (for the electrode spacing of 32-64”).

Table 4. Well logging results

Shot	Charge bottom (m)	Charge top (m)	Cavity top (m)	Fracture azimuths (°)	Fracture apertures (cm)	Rock
SH1	12.95	11.67	10.5	154, 316	0.2 - 1	Granite
SH2	13.0	11.81	10.5	34, 242	0.2 – 1.3	Granite
SH3	12.65	11.37	10.8	68, 247	0.6 – 2.5	Granite/amphibolite
SH6	12.65	10.52	9.3	71, 260	0.6 – 3	Granite
SH7	12.5	8.23	5.7	89, 278	0.8 – 4.8	Granite/foliation/fracture zone

The post-explosion damage observed in the shot holes falls into the following categories:

1. Cavity and the crush zone located in the immediate vicinity of the explosive charge placement (working point).
2. Pre-existing fractures and joints reactivated during explosions.
3. Spall zone damage produced due to the shock wave interaction with the free surface.
4. Vertical or high-angle fractures extending along the boreholes.

The caliper probe produces a continuous record of the borehole diameter using three mechanically coupled arms in contact with the borehole wall. Changes in borehole diameter are related to fracturing or breakout along the borehole wall. Because borehole diameter commonly affects log response, the caliper log is useful in the analysis of other geophysical logs. The sampling interval for the logging was 1.2 cm, at a logging rate of approximately 4.5 meters per minute. The caliper probe was calibrated on-site before each run and re-calibration performed as necessary. The caliper measurements for all shot boreholes are presented in Figure 26.

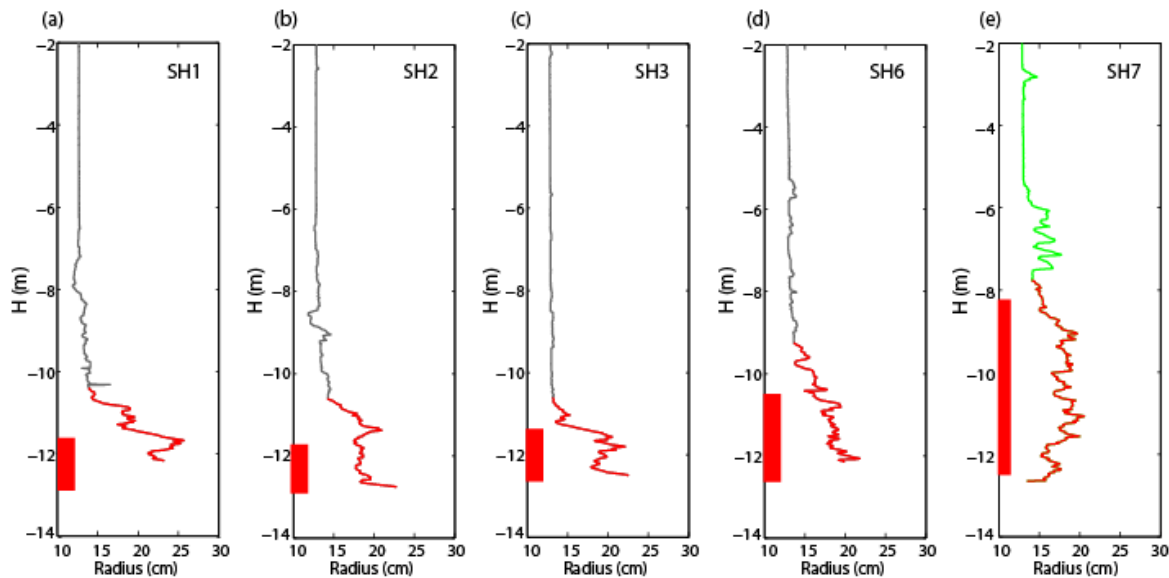


Figure 26. Caliper logs for the shot boreholes SH1, SH2, SH3, SH6 and SH7, showing the borehole radii in cm.

The OTV and ATV logs were used to visualize the surface of the boreholes and the damage caused by the explosions. The OTV produces a continuous oriented 360° image of the borehole wall using an optical imaging system. The OTV produces better results in dry boreholes, while the ATV imaging was used in water-filled boreholes. The results of the OTV logging for all shot boreholes is shown in Figure 27.

Imaging the cavities produced by the explosions was performed by using the ATV and caliper. The ATV is a logging tool that consists of an oriented rotating transducer that emits

ultrasonic pulses and receives their reflections from the borehole walls. The travel times of the acoustic pulses through the borehole fluid are converted into the borehole shape. The velocity of the borehole fluid is calibrated by using the caliper data. The caliper probe produces a continuous record of the borehole diameter using three mechanically coupled arms in contact with the borehole wall with a sampling interval of 1.2 cm. Thus, by combining the ATV and caliper data one can create detailed images of the borehole volume, including the cavities produced by explosions.

Figure 27 shows 2D “unwrapped” OTV images of the borehole surfaces. The OTV tool produces a continuous oriented 360° image of the borehole wall surface using an optical imaging system. The intersections of the borehole with inclined joints and fractures are seen as sinusoids. The predominant dip azimuths for the pre-existing joints and fractures range between 280° - 340° (with corresponding strike azimuths between 190° - 250°), and the mean dip is 53°. Foliation dip angles and dip directions are somewhat variable, with dip angles ranging between 45° and 70°. This fracture/foliation orientation is characteristic for all logged boreholes. Pre-existing foliation and fracturing was likely enhanced during the explosions.

Spall damage, observed down to depths of approximately 3 m, appears to be controlled by the pre-existing fracture orientation. Larger shallow fractures following the predominant fracture orientation (Figure 27) appear to be enhanced during the shock wave reflection from the free surface. Shallow fractures with different strike and dip angles are observed in SH2 and SH7.

The ATV tool generates an image of the borehole wall by transmitting ultrasound pulses from a rotating sensor and recording the amplitude and travel time of the signals reflected at the interface between the borehole fluid and formation (borehole wall). Using high frequency acoustic energy, the ATV measures the acoustic impedance of the borehole wall and the two-way travel time of the transmitted signals. Differences in travel time and reflection amplitudes from background values are seen as anomalous features. Borehole deviation data, recorded from a three-component magnetometer and two accelerometers, are used to provide the corrected orientation and shape of the imaged features. As a result, it is possible to calculate the dip direction and dip angle of imaged planar features. Discontinuities imaged with the ATV include open or filled fractures, foliation, mineralization, weathered zones, and other rock fabric. Images created by the ATV tool can be used to determine the volume of the cavity.

The ATV log also provides 3D caliper/borehole geometry via the 2-way travel time data and is immune to turbidity and other borehole fluid characteristics, which degrade the quality of OTV logs. High-resolution imaging was achieved using a vertical sampling interval of 0.01 foot and 360 measurements per revolution in the uncased portion of the borings. An average logging rate of 1.5 – 1.6 meter per minute was used. Caliper data were combined with ATV data to produce 3D “virtual cores” and acoustic caliper logs. Figure 28 shows the 3D rendering of the cavity for shot SH1 created by using the ATV caliper overlayed by the OTV image to highlight the relief. The cavity volumes for SH1, SH2, SH3, SH6 and SH7 calculated using the ATV logs are provided in Table 4.

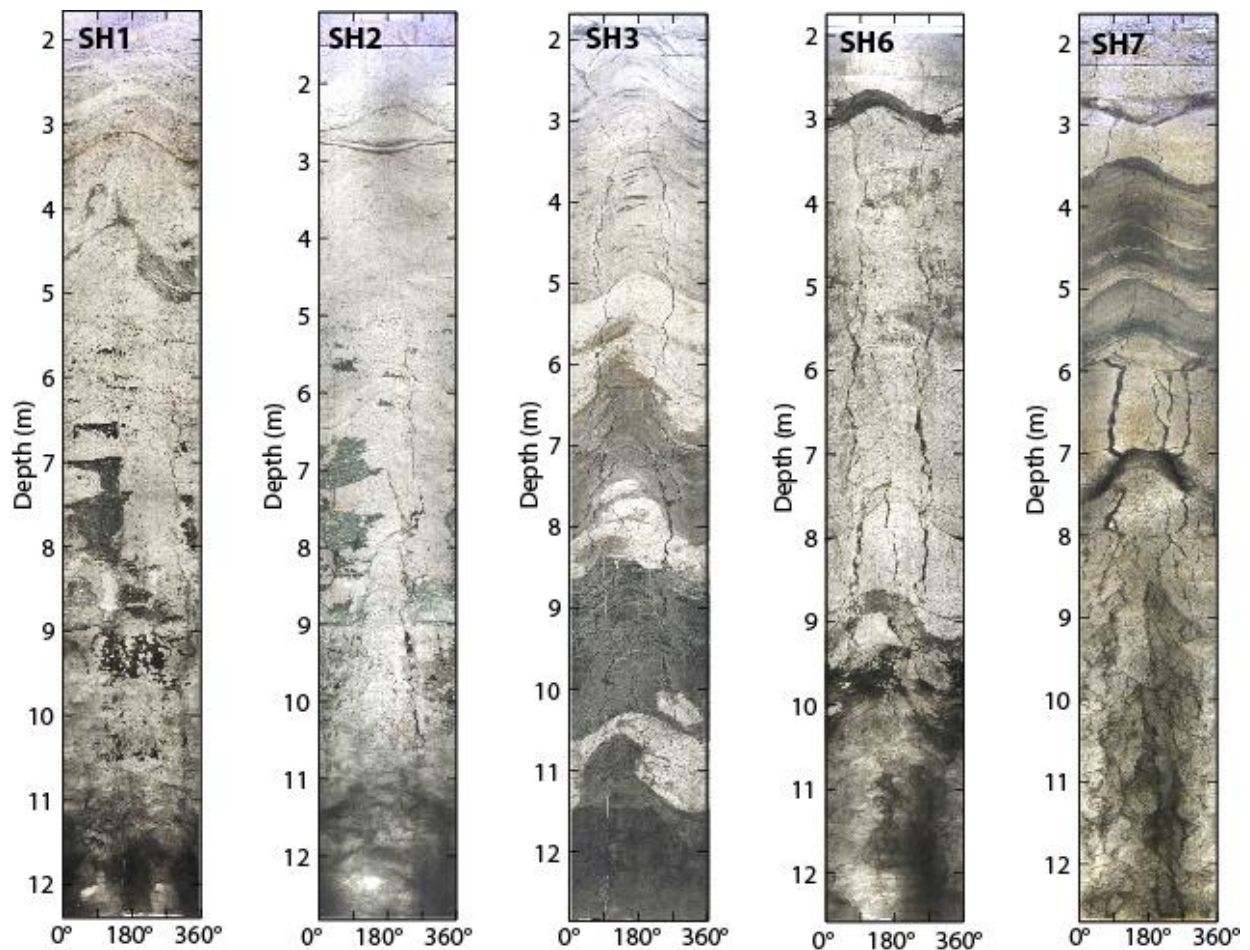


Figure 27. OTV logs for the shot boreholes SH1, SH2, SH3, SH6, and SH7

Vertical or near-vertical fractures extend above the blast cavities in all boreholes. The intensity and concentration of vertical fractures are zonal, diminishing or terminating upward at distinct boundaries defined by horizontal or sub-horizontal discontinuities. Some of these boundaries may be blast-related. The apertures of the largest fractures are shown in Table 4. As expected, the ANFO-based explosions produced larger fracture apertures (SH6 and SH7). Shot SH3 conducted in a water-filled borehole also resulted in larger fractures than the TNT-based shots in dry boreholes. Notice that the orientations of the largest vertical fractures are in the same quadrants for SH2, SH3, SH6 and SH7, while the fracture orientation for SH1 is very different. Brief description of the well logging results for each individual borehole is presented below.

SH1: 63.2 kg TNT in a dry borehole. Figures 26a and 27a show the OTV and a caliper logs for SH1. The rock is fine-grained granite with quartz-dominated veins near the surface. Multiple tight fractures are present. Vertical fractures extending down to the area of the cavity are probably blast-related. The cavity appears at 30 feet and widens toward

the bottom of the hole. The SH1 blast cavity is slightly asymmetric in cross section. The cavity increases in size from 32-foot depth to the widest point between 38 and 39 feet, with radius values approximately 8 to 10 inches. The majority of the cavity is at a depth of 32 to 40 feet. The estimated cavity volume is $\sim 0.373 \text{ m}^3$ (Table 4).

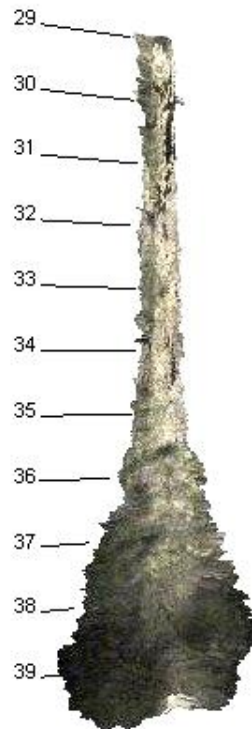


Figure 28. Cavity produced by SH1. The image was created by combining the results of ATV and OTV logging. The numbers on the left show depth in ft.

Structure classifications and orientations for BH1 are shown in Figure 29 as a stereonet (polar plot, Figure 29a) and a rose diagram (Figure 29b) depicting the fractures in the entire logged interval. The stereonets were constructed using a southern hemisphere equal area Schmidt polar projection showing dip direction (azimuth) and dip angle. The predominant fracture dip azimuths range between 285° - 315° , and the mean dip is 53° . Foliation dip angles and dip directions are somewhat variable, with 45- to 70-degree dip angles and northwest dip direction. This fracture/foliation orientation is characteristic for all logged boreholes. As discussed later, foliation and fracturing likely influenced the blast-induced fracture orientations and may have affected the radiation patterns of the seismic waves.

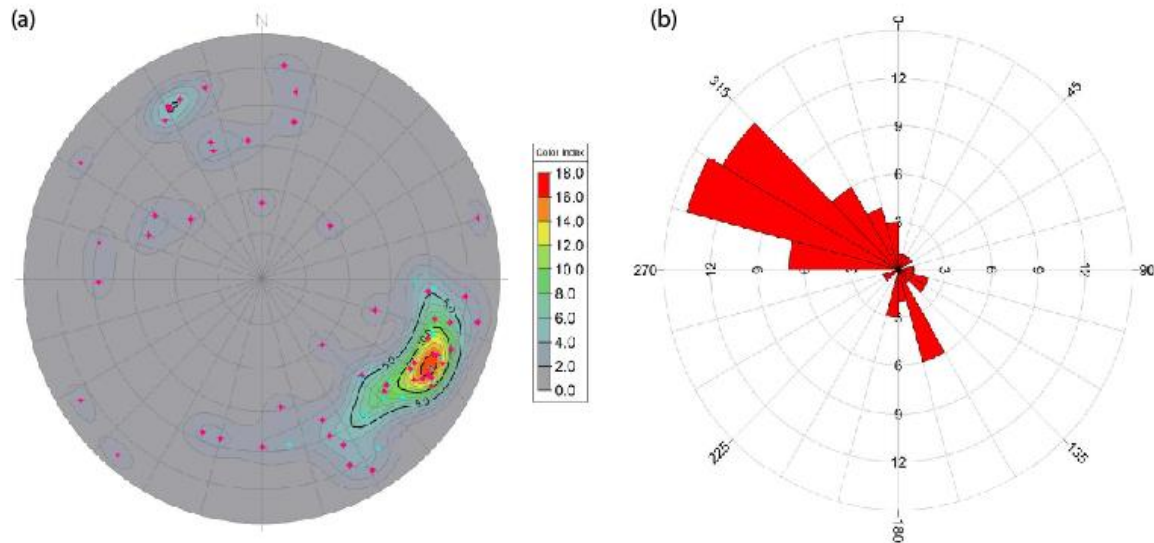


Figure 29. Dip direction and azimuths in BH1 based on the well logging results: (a) stereonet, and (b) rose diagram.

SH2: 63.2 kg of Tritonal in a dry borehole (96.2 kg TNTe). OTV and caliper logs for SH2 are shown in Figures 26b and 27b respectively. The rock is fine-grained granite, dominated by quartz and feldspar. Small to tight fractures were noted around 9 feet. Blast material is present on the walls at 24 feet, including blast wire and a black-green coating. Vertical fractures extending from the surface to the cavity are likely blast related. The cavity appears below 30 feet; it becomes wider and is highly fractured. The SH2 cavity appears to have a smaller diameter and almost the same volume (0.377 m^3) as SH1 (0.373 m^3). However, judging from the plot, SH1 may not have been completely evacuated (the charge bottom appears to be below the evacuated cavity). The cavity, at a depth of 30 to 41 feet, is not as tightly tapered, and extends two feet closer to the surface.

SH3: 63.2 kg of TNT in water-filled borehole. OTV and caliper logs for SH3 are shown in Figures 26c and 27c respectively. The rock is fine-grained granite with moderate metamorphism with biotite and pyrite incorporated into the foliation planes. Tight fractures exist on the foliation planes. Blast-induced vertical fractures are significant and extend to the surface. The increased percentage of mafic banding signals a shift in rock type at $\sim 6.5 \text{ m}$ into a possible amphibolite. The SH3 cavity extends from 10.8 m to the bottom at 12.7 m and is more symmetrical in cross section than those in the previous boreholes. The cavity appears to start near the contact between the granite and amphibolites; it is somewhat smaller than the other cavities. The SH3 cavity is smaller than the ones created by SH1 and SH2 (0.353 m^3), possibly because the working point was below the contact with amphibolites. Shock reflection from the contact (or fractures associated with it) may have resulted in more damage below the contact and less damage on the other side.

SH6: ANFO/AI 80/20 in a dry borehole (94.1 kg TNTe). Figures 26d and 27d show the OTV and a caliper logs for SH6. The rock is fine-grained granite, dominated by quartz

and feldspar, with some areas of moderate metamorphism. Tight fractures are present, as well as blast-induced vertical fracturing extending from the blast area to the surface. A contact exists around 30 feet, and the rock is banded and fractured in the same orientation. Below that contact, the cavity becomes very wide and is highly fractured. In some areas the SH-6 cavity widens along what appear to be fracture/foliation planes. The cavity created by SH6 is larger than the ones created by SH1-SH3, possibly because the charge is longer.

SH7: Water-resistant ANFO in a water-filled borehole (63.1 kg TNTe). Borehole SH7 was drilled through the fracture zone shown in Figure 21. The rock is fine-grained granite, dominated by quartz and feldspar, with some areas of foliation. The logs for SH7 are shown in Figure 26e and 27e. Extensive blast-induced vertical fracturing extends to the surface. A contact is present at 12 feet and the rock is foliated. Below the contact, the vertical fractures become larger leading to the cavity. The SH7 cavity is extremely asymmetric. The cavity created by SH7 extends from 19 to 41 feet and has the largest volume in the dataset. The cavity is highly fractured internally, and vertical fractures extend from the cavity to the surface. Apparently the charge length plays a role.

4.4. Conclusions Regarding Post-explosion Site Characterizations

Well logging was performed in the shot boreholes following the explosion experiment GAS2016. The well logging included down-hole camera, ATV, OTV, and caliper logs.

All explosions produced cavities (voids) around the working points. Well logging has shown that the sizes of the cavities do not necessarily correlate with the seismic amplitudes. For instance, the size of the cavity produced by SH3 is slightly smaller than the cavity produced by SH1, while the amplitudes generated by SH3 are higher by a factor of 1.5 due to a presence of water in the shot borehole.

In addition to creating cavities around the working point, the explosions created extended macro-fractures. Low-angle shallow fractures, possibly related to spall, are observed in all boreholes. Other fractures related to the pre-existing fractures are also common. In addition to reactivating pre-existing fractures, vertical or near-vertical fractures extend above the blast cavities. Our previous experiments (e.g. NEDE) show that fractures along the borehole are ubiquitous for small chemical explosions. The fractures observed during NEDE, however, terminate at greater depth due to the presence of large sub-horizontal joints, which tend to arrest the propagating fractures. The site used in GAS2016 experiment did not have the large sub-horizontal joints, therefore the explosion-related fractures in some cases extended to the surface. ANFO-based explosions produced longer fractures with larger apertures. Shot SH3 conducted in a water-filled borehole also resulted in larger fractures than the TNT-based shots in dry boreholes (SH1 and SH2). The increase in the loading rate for the explosives with high velocity of detonation with subsequent increase in dynamic strength (e.g. Ashby and Sammis, 1990) as well as the increase of the pore pressure due to larger volume of the gaseous products are the main factors responsible for

the larger apertures and the extent of the explosion-related fractures for the ANFO-based explosives.

The fractures along the borehole walls are created when stresses from the passing wave interact with the borehole surface. At low loading rate the wall fractures are controlled by the in situ stress and grow perpendicular to the minimum horizontal stress direction (e.g., Bell and Gough, 1982). A high dynamic loading rate created by stress waves from explosions can overcome the in situ stresses; therefore explosions can generate borehole-parallel fractures with arbitrary orientations (e.g. Settgaest et al, 2017). As illustrated in Figure 27, the vertical fractures generated by ANFO-based explosions have more consistent orientations and larger apertures than the fractures generated by the TNT-based explosives. A high loading rate for the explosives with high velocity of detonation with subsequent increase in dynamic strength (e.g. Ashby and Sammis, 1990) could be one of the factors responsible for the larger apertures and the extent of the explosion-related fractures for the ANFO-based explosives. Another possible explanation is the sustained high fluid or gas pressure in the cavity and in the stemmed borehole due to larger volume of the gaseous products released by ANFO-based explosives.

5. SEISMIC DATA ANALYSIS

5.1. Introduction

Weston Geophysical Corp. conducted a series of chemical explosions using aluminized and non-aluminized explosive pairs in order to investigate the effect of gaseous detonation products on seismic signatures. Previous experimental data (NEDE, e.g. Martin et al, 2012) suggest that low-frequency *P*-wave amplitudes are affected by the explosive velocity of detonation (VOD) and by the thermodynamic characteristics of gaseous explosive products (Stroujkova, 2015). The new experiment was conducted in New Hampshire in 2016 using pairs of explosions with similar VOD while producing different volumes of gas.

The excess gas in the cavity can potentially affect seismic radiation by: a) increasing the static displacement (RDP) due to higher residual pressure and b) late time damage due to opening gas-driven fractures. The main objective of this study is to quantify the amplitude and spectral differences between the explosions.

In this section we discuss the analysis of the dataset collected during the experiment. The dataset consists of the records from 6 large explosions and 3 calibration shots recorded with a network of 45 3C seismic instruments deployed from near field to local distances. In this section we show our preliminary findings, including the waveform analysis, spectral ratios and the azimuthal radiation patterns for the explosions of the experiment.

5.2. Seismic Waveform Analysis

The objective of GAS2016 experiment was to document the differences of the waveforms and spectra due to differences in the explosive gaseous products. Six explosions were

conducted in a course of the experiment (Table 2). Four of the explosions conducted using non-aluminized explosives had similar TNT equivalent yields (Table 3). The remaining two shots conducted using aluminized explosives had the same weights of the explosives as their non-aluminized counterparts (TNT and Tritonal, ANFO and aluminized ANFO), but their TNT equivalent yields are higher due to the addition of aluminum. The maps of the shot and station locations are shown in Figure 9 a-d.

Figure 30 shows the displacement seismograms for all six shots recorded by Station GOUL, located approximately 2 km from the explosions. Vertical component waveforms are shown in the left column, while the right column shows the transverse waveforms. Notice that the *P* wave amplitudes for SH1 (TNT) and SH2 (Tritonal) are nearly identical (Figure 30 a and c), despite the fact that SH2 has a larger yield by a factor of 1.53. The amplitudes produced by aluminized ANFO (SH6) are, however, higher than the amplitudes from the ANFO shot (SH5). SH6 shows the highest amplitudes for both *P* and *Rg*. The amplitude ratios between the shots recorded at other stations are consistent with the ratios observed at Station GOUL. The averaged amplitude ratios and their standard deviations are shown in Table 5 in columns 3 and 4 respectively.

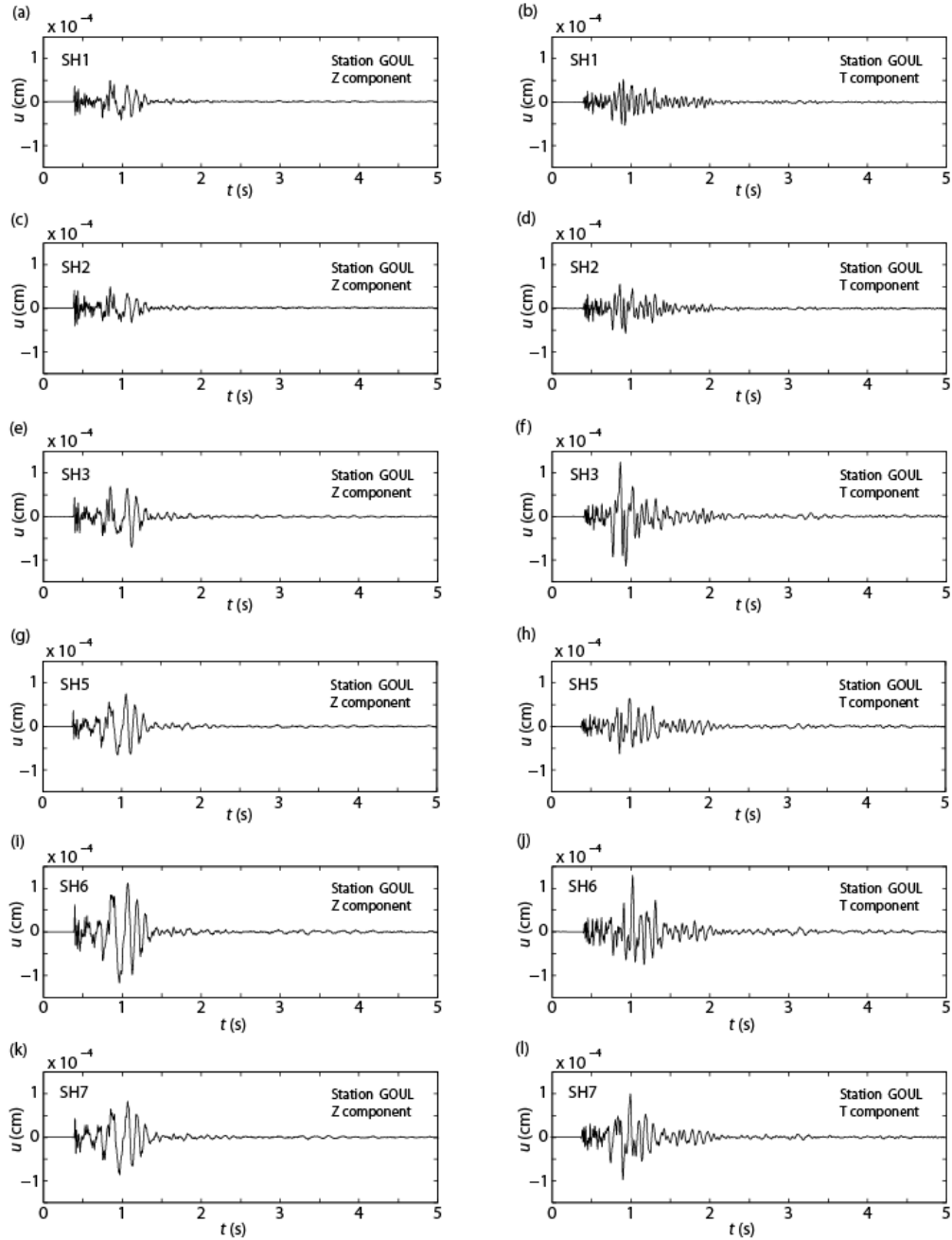


Figure 30. Vertical (left column) and transverse (right column) components of the seismograms from Station GOUL located at a range of 2 km from the explosions: (a) SH1 – Z component, (b) SH1 – T component, (c) SH2 – Z component, (d) SH2 – T component, (e) SH3 – Z component, (f) SH3 – T component, (g) SH5 – Z component, (h) SH5 – T component, (i) SH6 – Z component, (j) SH6 – T component, (k) SH7 – Z component, (l) SH7 – T component.

Table 5. *P*-wave amplitude ratios

Shots	Explosive Type	Amplitude Ratios		Yield Ratio
		Mean	σ	
SH2/SH1	Tritonal / TNT (dry)	1	0.12	1.53
SH3/SH1	TNT (water) /TNT (dry)	1.55	0.17	1
SH5/SH1	ANFO (dry) / TNT (dry)	1.3	0.34	1
SH6/SH5	(ANFO/Al) / ANFO (dry)	1.46	0.17	1.5
SH7/SH5	ANFO (water) / ANFO (dry)	1.25	0.22	0.97

Seismic amplitudes from the near-source stations (less than 1.2 km) are shown in Figure 13 and 14. The amplitudes observed at these stations show the same characteristics as the local amplitudes. SH1 and SH2 amplitudes are nearly the same. SH6 shows the largest amplitudes among all shots for most of the stations. However, the example in Figure 14 shows that SH3 amplitude recorded at NE03 is higher, which may potentially indicate non-isotropic radiation pattern.

Shear wave amplitudes from the transverse components do not always correlate with the *P* wave amplitudes. For instance, the highest *S*-wave amplitude recorded by Station GOUL is observed for SH3 (TNT in water-filled hole, Figure 20f), which significantly exceeds the amplitude from SH1 (TNT in dry BH). The highest amplitudes for *P* and *R_g* are observed for SH6 (Figure 20i). Shear wave amplitude from SH7 (ANFO in the water filled BH) is also greater than from SH5 (dry ANFO). Shear wave amplitude variations are most likely caused by the differences in the event source mechanisms. For instance, water in the borehole promotes hydrofracturing during explosions, which potentially leads to non-isotropic source radiation and higher shear wave amplitudes.

5.3. Spectral Analysis of the Data

The results from the New England Damage Experiments (NEDE) suggest that different explosives generate different seismic signatures. For instance, ANFO explosions generate higher amplitudes in the low-frequency part of the spectra than the COMP B explosions of the same yield (e.g. Stroujkova, 2015).

Figure 31 shows the spectral ratios between the shots conducted as a part of this project. The spectral ratios between SH2 (Tritonal) and SH1 (TNT) are close to 1 for all frequencies. The ratio between the TNT in water-filled and dry boreholes (SH3/SH1) is close to 2 at low frequencies, then decreases to 1.1 – 1.2 around the corner frequency, with a slight increase toward higher frequencies. The ratios between ANFO and TNT shots (SH5/SH1) show similar features; however, they decrease even lower to less than 1 around the corner frequency.

Thus, we observe an amplitude increase at low frequencies for explosions with slower VOD and higher gas volume, which is similar to the amplitude increase in water-filled boreholes. These observations support the previous findings from New England Damage Experiment (e.g. Stroujkova, 2015) suggesting an increase in the low frequency amplitudes for the explosions with higher amount of the gaseous products.

Unfortunately, the detonation pressure from the aluminized ANFO (SH6) could not be determined, because we did not determine the density of the ANFO/Al, which was mixed in the field. Interestingly, the aluminized ANFO produced seismic amplitudes proportional to the yield increase compared to ANFO, which is different for the TNT. This observation needs further investigation.

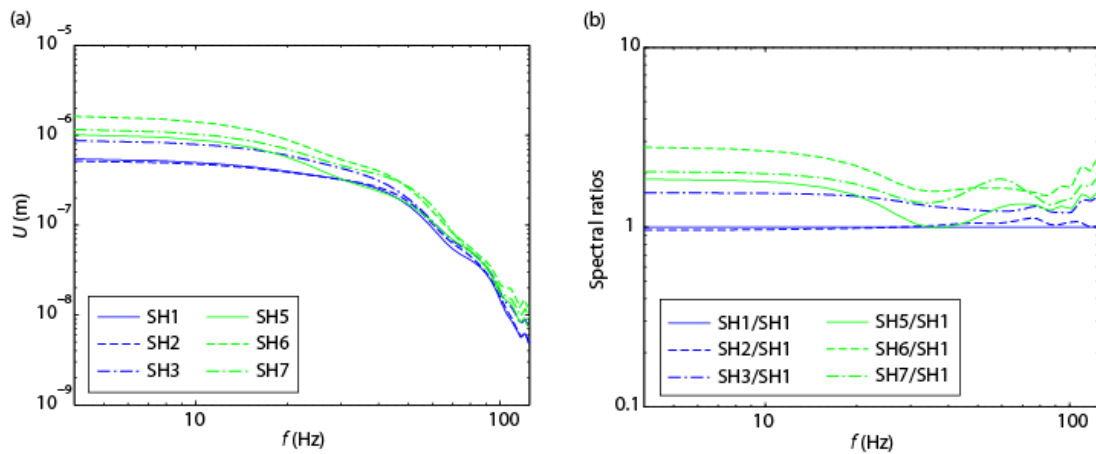


Figure 31. a) Displacement spectra for the explosions SH1, SH2, SH3, SH5, SH6, and SH7. B) Spectral ratios between the explosions shown in (a) and SH1. Notice similar amplitude increase in the low-frequency part of the spectra for both ANFO shot and the TNT shot in the water-filled hole (compared to the TNT shot in a dry borehole).

5.4. Radiation Pattern Analysis

It was shown in the previous section that a TNT explosion in a water-filled borehole (SH3) produced higher seismic amplitudes than an explosion conducted using the same charge in a drained borehole (SH1). It was also shown that the amplitude increase is higher in the low frequency part of the spectrum. The ANFO shot of the same yield (SH5) produced similar amplitudes as SH3 and higher than SH1. An important question is what mechanism is responsible for the amplitude increase.

P -wave amplitudes were measured from the first positive peaks (Figure 32) because this phase is the least affected by the interactions with the medium. Figure 33 shows the amplitude ratios between different pairs of explosions plotted as a function of azimuth. P -wave ratios between SH1 and SH2 are close to 1 at all azimuths. The ratios for other explosions show systematic azimuthal variations. Thus, these two explosions appear to

have the smallest non-isotropic components among the events of the set. This is why the use of the TNT and Tritonal shots as the reference was justified.

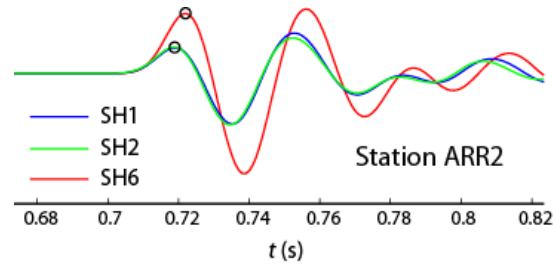


Figure 32. An illustration of the first peak amplitudes extraction to find the amplitude ratios between the events. *P-wave amplitude ratios were calculated with respect to SH1, SH2 and the average between SH1 and SH2 traces.*

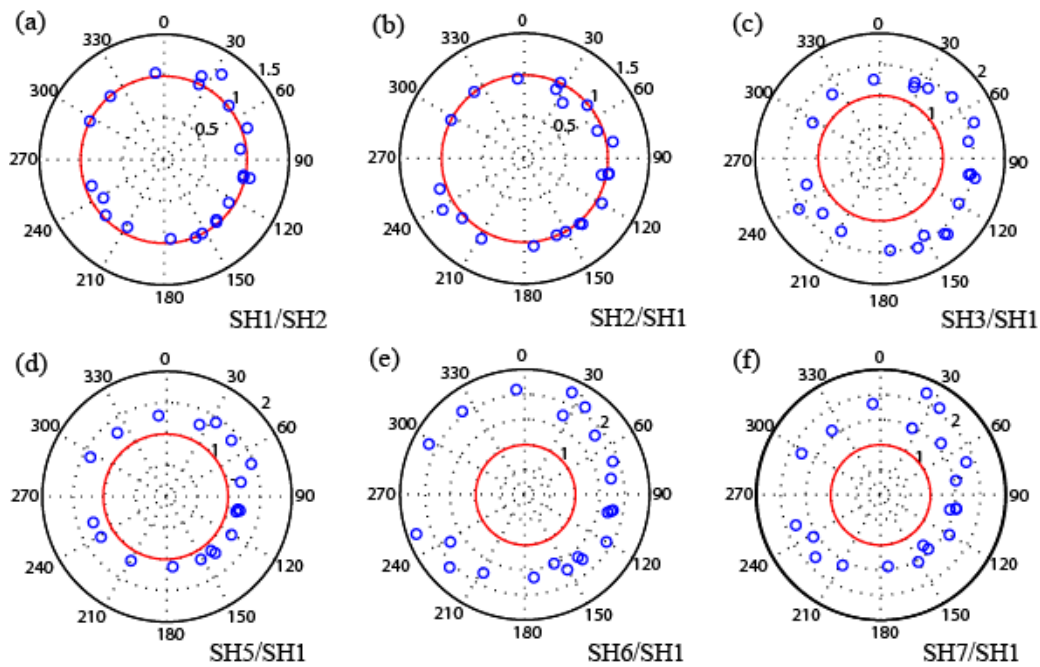


Figure 33. *P-wave amplitude ratios between the first positive peaks plotted as a function of the station azimuths for the event pairs: (a) SH1/SH2, (b) SH2/SH1; (c) SH3/SH1, (d) SH5/SH1, (e) SH6/SH1, and (f) SH7/SH1. The data were filtered between 1 and 100 Hz. The unit circles are highlighted in each plot for scale.*

5.5. Seismic Radiation Pattern and the Rock Damage

It follows from the analysis of the amplitudes that adding water or increasing the amount of gas products during underground detonation results in improved coupling and higher

seismic amplitudes, particularly in the low-frequency part of the spectrum. For instance, a TNT explosion in a water-filled borehole (SH3) produced higher seismic amplitudes than an explosion conducted using the same charge in a drained borehole (SH1). The ANFO shot of the same yield (SH5) produced similar amplitudes as SH3 and higher than SH1. It was also shown that the improved coupling is accompanied by formation of larger fractures, while the cavity sizes stay approximately the same.

To identify the mechanism of the improved coupling we need to look at the radiation pattern, because azimuthally varying seismic amplitudes may provide insight into additional radiation by fractures. Figure 33 shows the amplitude ratios between different pairs of explosions plotted as a function of azimuth. *P*-wave amplitudes were measured from the first positive peaks because this phase is the least affected by the interactions with the medium. The seismograms were filtered between 1 and 100 Hz. *P*-wave ratios between SH1 and SH2 are close to 1 at all azimuths. The ratios for other explosions show systematic azimuthal variations with respect to SH1. In addition, SH1 produced the least amount of damage (macro-fractures) in the post-shot well logging images (Figure 2). Also, SH1 was detonated in the middle of the source array. This is why the TNT shot (SH1) was used as a baseline to quantify the radiation patterns for the other shots. The estimated take-off angles for all stations used in this study vary between 45° and 51°, therefore the amplitude ratio dependence on the take-off angle can be neglected for the purposes of this approximate radiation pattern analysis.

Figure 34 shows the amplitude ratios with respect to SH1 extracted from the waveforms filtered in two different frequency bands: a) low-frequency band 1 – 15 Hz, and b) high-frequency band 15 – 100 Hz. The frequency bands were chosen based on the spectral ratios and the corner frequencies (Figure 31). Frequencies below 15 Hz belong to the flat portion of the spectra, while frequencies above 15 Hz cover the corner frequency and the roll-off. The amplitude ratios for all shots with respect to SH1 are consistently higher in the low-frequency range (1 – 15 Hz) than in the high-frequency range (15 – 100 Hz). It can be observed in Figure 34 that the radiation patterns are different between the frequency bands. The differences in the radiation patterns indicate that they may have been produced by different processes.

To identify the mechanism that causes the observed radiation pattern we assume that the radiation pattern was created by multiple fractures, therefore the final result is a superposition of the individual radiation patterns and the fault strike parameters represent an effective strike for the superposition.

Far-field *P*-wave amplitudes from an arbitrary moment tensor source can be represented on a focal sphere as an expansion in surface harmonics (e.g. Knopoff and Randall, 1970):

$$A_P(\theta, \phi) = \frac{1}{(4\pi)^{1/2}} \{c_0 + c_1(3 \cos^2 i - 1) + c_2 \sin 2i \cos \phi + c_3 \sin 2i \sin \phi + c_4 \sin^2 i \cos 2\phi + b_2 \sin^2 i \sin 2\phi\}, \quad (3)$$

where i and ϕ are the polar angles shown in Figure 35b. The first term of the series represents a monopole, while the remaining terms represent a complete set of surface

harmonics of the second order (Knopoff and Randall, 1970). This reflects the fact that the radiation pattern from a general moment tensor source has six degrees of freedom.

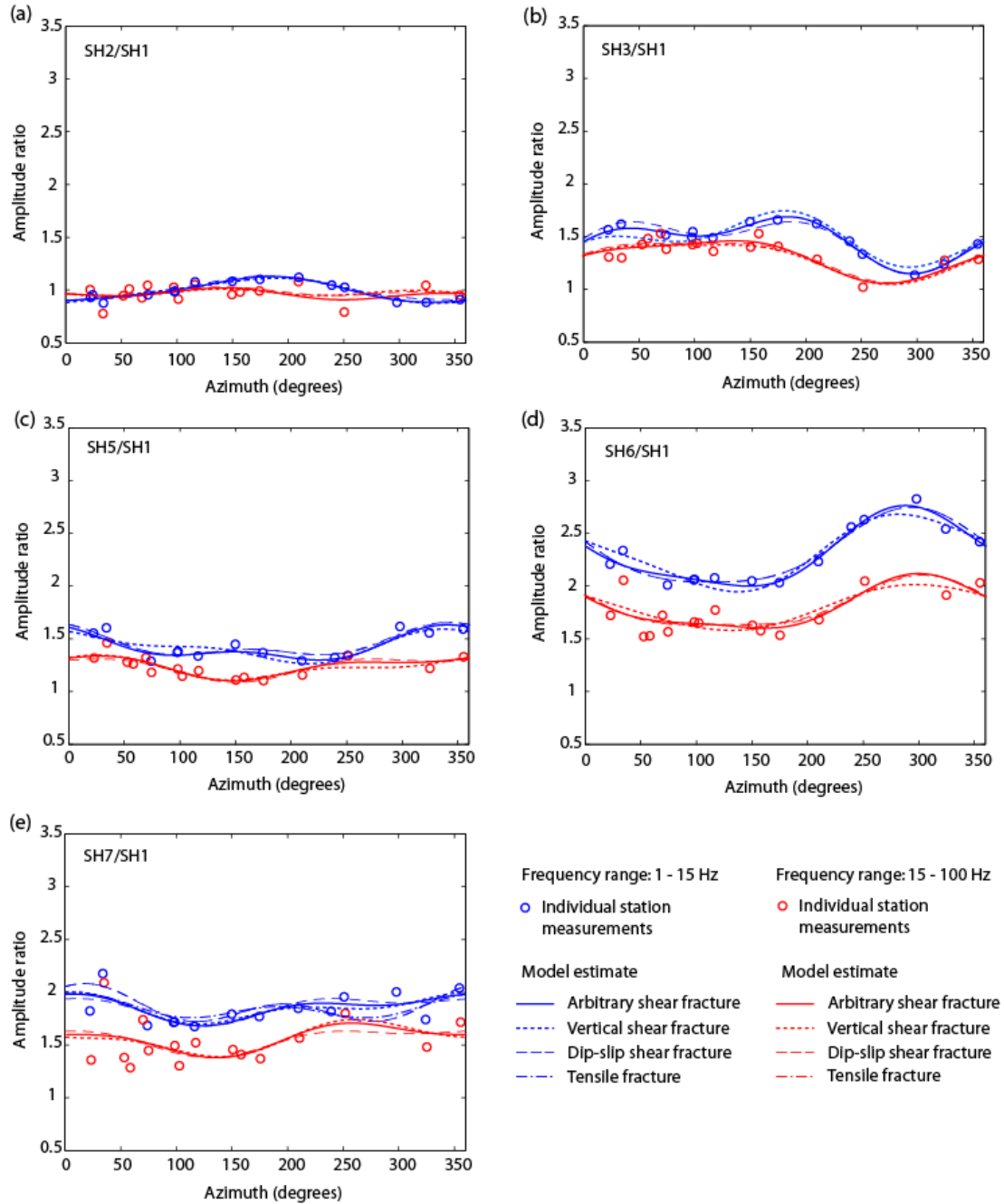


Figure 34. Amplitude ratios between the P -wave amplitudes of the first positive peak plotted as a function of the station azimuths for the event pairs: (a) SH2/SH1; (b) SH3/SH1, (c) SH5/SH1, (d) SH6/SH1, and (e) SH7/SH1. The amplitudes were extracted from the waveforms filtered between 1 – 15 Hz (blue symbols) and 15 – 100 Hz (red symbols). The dashed lines show the best model estimates.

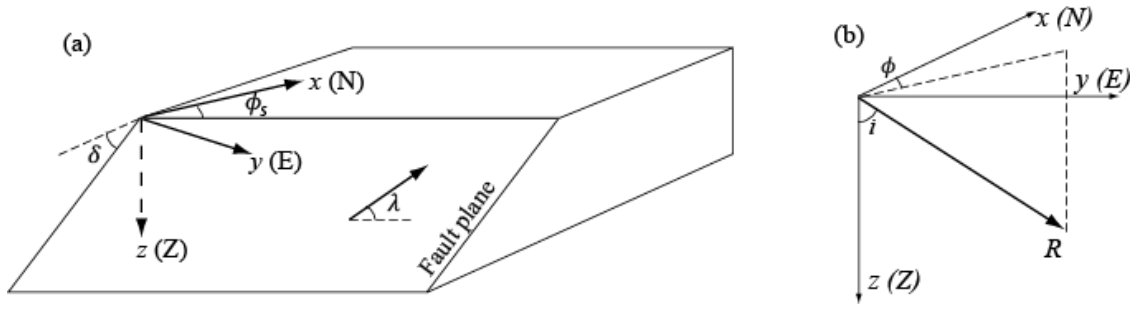


Figure 35. (a) Cartesian coordinates (x, y, z) used to describe the fault zone. In this coordinate system the vertical axis z points downward, indicating depth, x coincides with the north, and y points to the east. Azimuth is measured clockwise from the north. (b) Cartesian coordinates associated with the ray (R). The incidence angle i is measured from z direction.

Let us consider radiation by a fault with a strike ϕ_s and a dip angle δ failing in either shear or tensile regime. For a fixed incidence angle i the radiation pattern can be expressed as a function of the azimuth ϕ with 5 degrees of freedom (e.g. Ben-Menahem and Singh, 1981):

$$A_P = a_0 + a_1 \cos(\phi - \phi_s) + b_1 \sin(\phi - \phi_s) + a_2 \cos 2(\phi - \phi_s) + b_2 \sin 2(\phi - \phi_s), \quad (4)$$

where ϕ_s is the fault strike, ϕ - azimuth to the station. For shear dislocation the coefficients a_i^s and b_i^s are given by (e.g. Ben-Menahem and Singh, 1981; Aki and Richards, 2002):

$$a_0^s = \frac{1}{2} \sin \lambda \sin 2\delta (3 \cos^2 i - 1), \quad a_1^s = -\cos \lambda \cos \delta \sin 2i, \quad b_1^s = 3 \sin \lambda \cos 2\delta \sin 2i, \quad (5)$$

$$a_2^s = \frac{1}{2} \sin \lambda \sin 2\delta \sin^2 i, \quad b_2^s = \cos \lambda \sin \delta \sin^2 i$$

For a tensile fracture the coefficients are given by:

$$a_0^t = 2 s_0 + 2 \cos^2 \delta \cos^2 i + \sin^2 \delta \sin^2 i, \quad a_1^t = b_2^t = 0, \quad (6)$$

$$b_1^t = -\sin 2\delta \sin 2i, \quad a_2^t = -\sin^2 \delta \sin^2 i,$$

where $s_0 = \sigma/(1 - 2\sigma)$, and σ is a Poisson's ratio. To find the radiation pattern from a shear fracture (A_P^s) we substitute (5) into (4) yielding:

$$A_P^s = \frac{1}{2} \sin \lambda \sin 2\delta (3 \cos^2 i - 1) - \cos \lambda \cos \delta \sin 2i \cos(\phi - \phi_s) + \sin \lambda \cos 2\delta \sin 2i \sin(\phi - \phi_s) + \frac{1}{2} \sin \lambda \sin 2\delta \sin^2 i \cos 2(\phi - \phi_s) + \cos \lambda \sin \delta \sin^2 i \sin 2(\phi - \phi_s). \quad (7)$$

Equation 7 is equivalent to Equation 4.89 of Aki and Richards (2002).

The radiation pattern from a tensile fracture (A_P^t) is found by substituting (6) into (4) yields:

$$A_P^t = (2 s_0 + 2 \cos^2 \delta \cos^2 i + \sin^2 \delta \sin^2 i) + \sin 2\delta \sin 2i \sin(\phi - \phi_s) + \sin^2 \delta \sin^2 i \cos 2(\phi - \phi_s). \quad (8)$$

Notice that the radiation pattern for the tensile fracture has terms containing $\sin(\phi - \phi_s)$ and $\cos 2(\phi - \phi_s)$, while the expression for the shear fracture also has terms containing $\cos(\phi - \phi_s)$ and $\sin 2(\phi - \phi_s)$. The radiation pattern from a tensile fracture has only 3 degrees of freedom.

Equation 4 can be further simplified if we recall that (Gradshteyn and Ryzhik, 2007):

$$b \sin x \pm a \cos x = \sqrt{a^2 + b^2} \sin \left[x \pm \arctan \left(\frac{a}{b} \right) \right], b \neq 0. \quad (9)$$

$$b \sin x \pm a \cos x = \sqrt{a^2 + b^2} \cos \left[x \mp \arctan \left(\frac{b}{a} \right) \right], a \neq 0. \quad (10)$$

After inserting Equations 9 and 10 into Equation 4 we obtain:

$$A_P = a_0 + \sqrt{a_1^2 + b_1^2} \sin \left[(\phi - \phi_s) - \arctan \left(\frac{a_1}{b_1} \right) \right] + \sqrt{a_2^2 + b_2^2} \cos \left[2(\phi - \phi_s) + \arctan \left(\frac{b_2}{a_2} \right) \right] \quad (11)$$

It is convenient to define:

$$\hat{b}_1 = \sqrt{a_1^2 + b_1^2}, \quad \hat{a}_2 = \sqrt{a_2^2 + b_2^2}, \quad \phi_1 = \phi_s + \arctan \left(\frac{a_1}{b_1} \right), \\ \text{and } \phi_2 = \phi_s - \frac{1}{2} \arctan \left(\frac{b_2}{a_2} \right). \quad (12)$$

Then

$$A_P = a_0 + \hat{b}_1 \sin[\phi - \phi_1] + \hat{a}_2 \cos[2(\phi - \phi_2)]. \quad (13)$$

Thus, the radiation pattern for an arbitrary moment tensor source can be written as a sum of $\sin(\phi - \phi_s)$ and $\cos 2(\phi - \phi_s)$ terms with phases ϕ_1 and ϕ_2 depending on geometry. In case ϕ_1 or ϕ_2 equal zero, the radiation pattern has fewer degrees of freedom.

It follows from Equation 13 that the radiation pattern from an arbitrary shear fracture can be expressed in the same form as for the tensile fracture, however the terms containing $\sin(\phi - \phi_s)$ and $\cos 2(\phi - \phi_s)$ will in general have different phases, while dipole sources (inclined) or shear dip-slip sources would have the same phase for both terms. Vertical or horizontal dipole sources will not have $\sin(\phi - \phi_s)$ terms. Notice that the notation $\hat{b}_1$ and $\hat{a}_2$ is used for the general case described in Equation 13. For the tensile fractures and other special cases, for which $\phi_1 = \phi_2 = \phi_s$, the coefficients are denoted b_1 and a_2 .

For a vertical tensile fracture ($\delta = \frac{\pi}{2}$) the term containing $\sin(\phi - \phi_s)$ vanishes, which reduces the number of the degrees of freedom to two:

$$A_p^t = (2 s_0 + 2 \cos^2 \delta \cos^2 i + \sin^2 \delta \sin^2 i) + \sin^2 \delta \sin^2 i \cos 2(\phi - \phi_s). \quad (14)$$

For a horizontal tensile fracture ($\delta = 0$) both azimuth dependent terms ($\sin(\phi - \phi_s)$ and $\cos 2(\phi - \phi_s)$) vanish and the radiation pattern becomes azimuth independent (one degree of freedom).

Some types of shear fractures also allow for a reduction in the number of the degrees of freedom. For a dip-slip fault ($\lambda = \pi/2$ or $\lambda = 3\pi/2$) the terms containing $\cos(\phi - \phi_s)$ and $\sin 2(\phi - \phi_s)$ vanish:

$$A_p^s(\text{dip slip}) = \frac{1}{2} \sin \lambda \sin 2\delta (3 \cos^2 i - 1) \pm \cos 2\delta \sin 2i \sin(\phi - \phi_s) \pm \frac{1}{2} \sin 2\delta \sin^2 i \cos 2(\phi - \phi_s). \quad (15)$$

The expression in Equation 15 has the same symmetry as Equation 8 for the tensile fracture with different coefficients before the second and the third terms. The signs before the second and the third terms are determined by the sign of $\sin \lambda$. Notice that the coefficients for the tensile fracture are always positive (because $0 \leq i \leq \pi/2$ and $0 \leq \delta \leq \pi/2$), while the coefficients for the dip-slip fracture can be either positive or negative.

For a vertical shear fracture with an arbitrary rake ($\delta = \pi/2$) the terms containing $\cos(\phi - \phi_s)$ and $\cos 2(\phi - \phi_s)$ vanish, which yields:

$$A_p^s(\text{vert}) = \frac{1}{2} \sin \lambda \sin 2\delta (3 \cos^2 i - 1) - \sin \lambda \sin 2i \sin(\phi - \phi_s) + \cos \lambda \sin^2 i \sin 2(\phi - \phi_s). \quad (16)$$

If a sufficient number of the amplitude measurements is available from an event, the coefficients a_0 , b_1 , and a_2 and the phases ϕ_1 and ϕ_2 (or ϕ_s in special cases) can be found by solving an inverse problem. In this study the equations were solved using the simplex search method (Lagarias et al., 1998).

To study the radiation patterns the amplitude ratios with respect to SH1 instead of the absolute amplitudes were used. The amplitude ratios cancel out the effects of the propagation paths, while keeping the non-linear effects in the near-source zone. Figure 34 shows the amplitude ratios for each event and the theoretical radiation patterns. The inversion results show that the radiation patterns for all explosions are consistent with the general model described in Equation 11 with 5 degrees of freedom. Examination of the coefficients and the strike angles provided in Table 6 shows that for some of the events the strike angles ϕ_1 and ϕ_2 are within 30° from each other, which indicates the potential for the reduction of the number of the degrees of freedom. For SH2 the difference between ϕ_1 and ϕ_2 is greater than 30° , however the coefficient a_2 is small. The waveforms for SH7 show higher noise level in the high frequency range (Figure 34e) and therefore the uncertainty is higher in this case. Using the similarity of the strike angles, we may try to reduce the number of the degrees of freedom by fitting the expressions for the special cases discussed above.

Using the dip-slip model (Equation 15) the recovered strike azimuths for SH2, SH5, SH6 and SH7 are between 201° and 268°. Based on the well logging results the predominant strike azimuths for the pre-existing joints are between 190° and 250°. The approximate directions of the shear fracture orientations (Table 7) are in this range for SH5, SH6, and SH7. The strike azimuths estimated for SH2, SH5, SH6 and SH7 from their radiation patterns presented in Table 3 roughly agree with the direction of the joints. Thus, the radiation patterns for some of the events can be explained by sliding on the pre-existing joints or fractures.

The strike azimuths estimated using a vertical shear fracture model are trending in the NE direction (Table 8). The vertical fractures observed in the well logs are oriented in the same general direction. However, the differences between the individual observed and estimated strike directions vary between 12° and 50°. Therefore there is a possibility that shear failure on the vertical fractures affected the radiation patterns, however it is difficult to say definitively whether it is really the case.

Table 6. Coefficients a_0 , b_1 , a_2 and the effective strike angles ϕ_1 and ϕ_2 calculated for explosions SH2, SH3, SH5, SH6 and SH7 using an arbitrary fracture model (Equation 13).

Shot	Frequency band 1 – 15 Hz						Frequency band 15 – 100 Hz					
	a_0	b_1	a_2	ϕ_1 (°)	ϕ_2 (°)	rms	a_0	b_1	a_2	ϕ_1 (°)	ϕ_2 (°)	rms
SH2	0.99	0.12	0.02	85.5	34.5	0.021	0.97	0.03	0.03	23.2	299.8	0.078
SH3	1.47	0.19	0.15	36.1	42.5	0.021	1.30	0.19	0.06	9.6	350.3	0.063
SH5	1.44	0.13	0.08	258.8	315.6	0.052	1.23	0.09	- 0.05	251.1	281.7	0.054
SH6	2.32	0.36	0.10	205.0	199.5	0.060	1.81	0.24	0.07	215.0	229.3	0.122
SH7	1.85	0.11	- 0.07	230.9	231.6	0.106	1.56	0.13	0.06	206.6	110.8	0.186

Finally, the coefficients and the strike angles estimated using a tensile fracture model are shown in Table 9. It follows from Equation 14 that, in order to be consistent with a tensile fracture model, the coefficients b_1 and a_2 should be positive, because both take-off angle i and the dip angle δ do not exceed $\pi/2$. Therefore the quantities $\sin 2\delta$, $\sin 2i$ as well as $\sin^2 \delta$ and $\sin^2 i$ should be positive. It follows from Table 9 that, in the frequency band 1 – 15 Hz, all explosions except SH3 are consistent with tensile failure, while in the frequency band 15 – 100 Hz only SH5 and SH6 are consistent. Also notice, that for a vertical tensile fracture the coefficient b_1 should be close to zero, which is not the case for all explosions. Therefore, the radiation patterns are inconsistent with radiation by the nearly vertical fractures that extend along the boreholes.

Table 7. Coefficients a_0 , b_1 , a_2 , and the strike angle ϕ_s for explosions SH2, SH3, SH5, SH6 and SH7 using a dip-slip fracture model (Equation 15).

Shot	Frequency band 1 – 15 Hz					Frequency band 15 – 100 Hz				
	a_0	b_1	a_2	ϕ_s (°)	rms	a_0	b_1	a_2	ϕ_s (°)	rms
SH2	0.99	-0.12	-0.02	267.8	0.023	0.97	0.02	-0.03	231.3	0.079
SH3	1.47	0.18	0.14	25.7	0.034	1.30	0.19	0.05	7.5	0.066
SH5	1.44	0.13	-0.08	252.3	0.054	1.24	-0.10	0.05	241.3	0.055
SH6	2.32	0.36	-0.09	201.8	0.067	1.81	-0.24	-0.06	213.5	0.124
SH7	1.85	0.11	0.06	215.9	0.109	1.54	-0.11	0.05	220.4	0.187

Table 8. Coefficients a_0 , b_1 , b_2 , and the strike angle ϕ_s for explosions SH2, SH3, SH5, SH6 and SH7 using a vertical shear fracture model (Equation 16).

Shot	Frequency band 1 – 15 Hz					Frequency band 15 – 100 Hz				
	a_0	b_1	b_2	ϕ_s (°)	rms	a_0	b_1	b_2	ϕ_s (°)	rms
SH2	0.99	0.12	0.02	84.5	0.023	0.97	0.01	-0.03	92.1	0.080
SH3	1.48	0.18	0.13	56.5	0.059	1.31	0.17	0.03	12.7	0.069
SH5	1.43	-0.13	-0.06	96.2	0.069	1.22	-0.09	0.05	85.1	0.056
SH6	2.32	-0.35	-0.06	29.5	0.081	1.79	-0.22	-0.01	34.4	0.129
SH7	1.85	-0.11	0.07	63.0	0.124	1.56	-0.14	-0.06	20.3	0.187

Table 9. Coefficients a_0 , b_1 , a_2 , and the strike angle ϕ_s for explosions SH2, SH3, SH5, SH6 and SH7 using a tensile fracture model (Equation 14).

Shot	Frequency band 1 – 15 Hz					Frequency band 15 – 100 Hz				
	a_0	b_1	a_2	ϕ_s (°)	rms	a_0	b_1	a_2	ϕ_s (°)	rms
SH2	0.99	0.12	0.02	267.8	0.023	0.97	-0.01	-0.04	324.2	0.080
SH3	1.47	0.18	-0.14	205.7	0.034	1.30	0.19	-0.05	187.5	0.066
SH5	1.44	0.13	0.08	72.3	0.054	1.21	0.08	0.05	116.1	0.067
SH6	2.32	0.36	0.09	21.8	0.067	1.81	0.24	0.06	33.5	0.124
SH7	1.84	0.06	0.08	102.2	0.124	1.52	-0.02	0.09	131.8	0.187

It is important to note that the terms in $\sin \phi$ and $\cos \phi$ are excited only by M_{xz} and M_{yz} (e.g. Aki and Richards, 2002). These terms are often considered insignificant for shallow sources with depth less than the wavelength (e.g. Julian et al, 1998) because of the vanishing traction at the free surface. *One of the important results of this study is the observation that these terms are significant* as well as the estimate of their relative amplitudes. According to Table 6, the coefficients in front of the $\sin \phi$ terms (b_1) are larger than the coefficients corresponding to $\cos 2\phi$. The relative amplitudes of the coefficients b_1 with respect to a_o (the constant terms) are between 6 and 16% in the low-frequency band and between 3 and 15% in the high-frequency band.

The results of this study show that the medium damage created by explosions increases with the increase in the amount of gas and other volatile components in the cavity during the detonation. The extent of macro-fracturing correlates with improved seismic coupling and increase in low-frequency P and Rg amplitudes. Our observations do not show evidence of the CLVD damage model proposed by Patton and Taylor (2011). The observed radiation patterns can be explained by sliding along the pre-existing fractures.

5.6. Conclusions Regarding Seismic Data Analysis

The results of the experiment show that the amount of explosive gas or water in the cavity improves seismic coupling resulting in higher seismic amplitudes. The analysis of seismic amplitudes show that the TNT and Tritonal (TNT with 20% of aluminum) charges of the same weight generated very similar amplitudes, despite the fact that the Tritonal charge had higher yield by a factor of 1.53 and released less gas. Addition of aluminum to the explosive causes temperature increase and decrease in the “specific particle density” (due to the lower amount of gas) during the detonation. However, the detonation pressure P_{CJ} reached during the explosion is very similar between the TNT and Tritonal as shown in Table 1. Thus, the shock waves generated by these two explosive charges are similar, despite the differences in the yield. According to Mader (1998), for high-temperature and low particle density detonation, a larger portion of energy is present in the form of thermal energy, rather than intermolecular potential energy. This energy may only become available after expansion to very low pressures. Thus, despite significant increase in the heat of detonation, addition of aluminum reduces the VOD, detonation pressure and performance of aluminized explosives. Another possible explanation for lower than expected amplitudes for the Tritonal but not for ANFO/Al is the fact that both TNT and Tritonal have low oxygen balance. Maienschein (2002) predicts that if low quantities of oxygen are available during the detonation, then only a fraction of aluminum would react with oxygen to produce aluminum oxide, causing lower than predicted yield. This observation requires further investigation.

Post-shot well logging survey confirmed that the amount of gas or water in the cavity causes an increase in the length and aperture of the explosion-generated macro-fractures. In addition, well logging has shown no correlation between the cavity size and the seismic amplitudes. Therefore, the amplitude increase is attributed to the rock damage rather than the increase in the static moment during the initial shock wave passage. Increase in Rg

amplitudes with the increase of the rock damage suggests that the CLVD component proposed by Patton and Taylor (2011) is not a significant factor for the explosions described in this report, possibly because these are small overburied explosions in hard rock. This may not be the case for the explosions conducted with normal DOB in different rock types.

The radiation patterns are different between the signals band-passed in a low frequency range (1–15 Hz) and a high frequency range (15–100 Hz). The strength of the non-isotropic components is higher in the low frequency range. Seismic radiation related to the off-diagonal moment tensor elements, expressed as the radiation pattern terms proportional to $\sin \phi$ and $\cos \phi$, is between 3 and 16% of the azimuthally-independent component. For four out of five explosions, the radiation pattern is consistent with shear failure along the natural fracture set observed in the televiewer. Shear failure along the vertical borehole-parallel fractures is also possible, although the *rms* errors are higher in this case.

6. PRINCIPAL COMPONENT ANALYSIS

6.1. Introduction

Discriminating between different types of seismic sources often requires finding common features and differences between similar waveforms. For instance, such data sets may include waveforms from closely located earthquakes with different focal mechanisms or depths, earthquakes and explosions from the same general area etc. In some cases explosion waveforms from the same test site can be very similar; however, subtle variations may exist due to the differences either in the source processes or in the emplacement medium. Using Principal Component Analysis (PCA) can help with the separation of the events with similar path effects but different source processes. The objective of this analysis was to determine whether PCA can be used to discriminate between explosions of different types. The differences between such explosions are more subtle than, for instance, the differences between earthquakes and explosions. Therefore the analysis is intended to identify very small differences between similar well-correlated waveforms.

As a part of this project, PCA was applied to the waveform data from the GAS2016 experiment. The technique was applied using two different input data types: a) full waveforms and b) amplitudes from different seismic phases extracted from filtered waveforms. The analysis shows that the sign of the second principal component can, with a high degree of accuracy, predict the type of the explosive (TNT vs ANFO).

6.2. Using Principal Component Analysis for Explosion Characterization

PCA is a statistical technique that transforms a set of correlated variables (or functions) into an orthonormal basis. PCA can find the most informative components in a series of waveforms and divide the waveforms into groups based on their principal components. Keeping the important components and neglecting the least important components can help

reduce the dimensionality of the observed data and express the data in terms of a small number of principal components.

Data representation is an important issue to consider when performing PCA. Most previous studies applied PCA to data derived from the waveforms (e.g. spectra, spectrograms, sonograms) because of low SNR. Sick et al (2015) applied PCA to spectrograms or sonograms (e.g. Joswig, 1993) for event characterization. Sick and Joswig (2013) applied PCA as a first step in a pattern recognition technique in order to detect and characterize low SNR events in an on-site inspection (OSI) scenario. This ability to extract important features from the data is often used for unsupervised pattern recognition (e.g. Sick and Joswig, 2013).

In this study PCA was applied to raw time domain seismograms to quantify the differences in the waveforms from six chemical explosions detonated using different explosive types. The explosions were detonated using different types of explosives, including trinitrotoluene (TNT), aluminized TNT (Tritonal), Ammonium Nitrate and Fuel Oil (ANFO) and aluminized ANFO. One of the principal differences between TNT and ANFO is the velocity of detonation. Higher VOD for the TNT-based explosives results in faster pressure buildup and higher detonation pressure.

Analysis of the local seismic data revealed subtle but systematic differences between the waveforms from TNT-based and ANFO-based explosives. This was possible because of the high correlation between the waveforms coming from closely located sources.

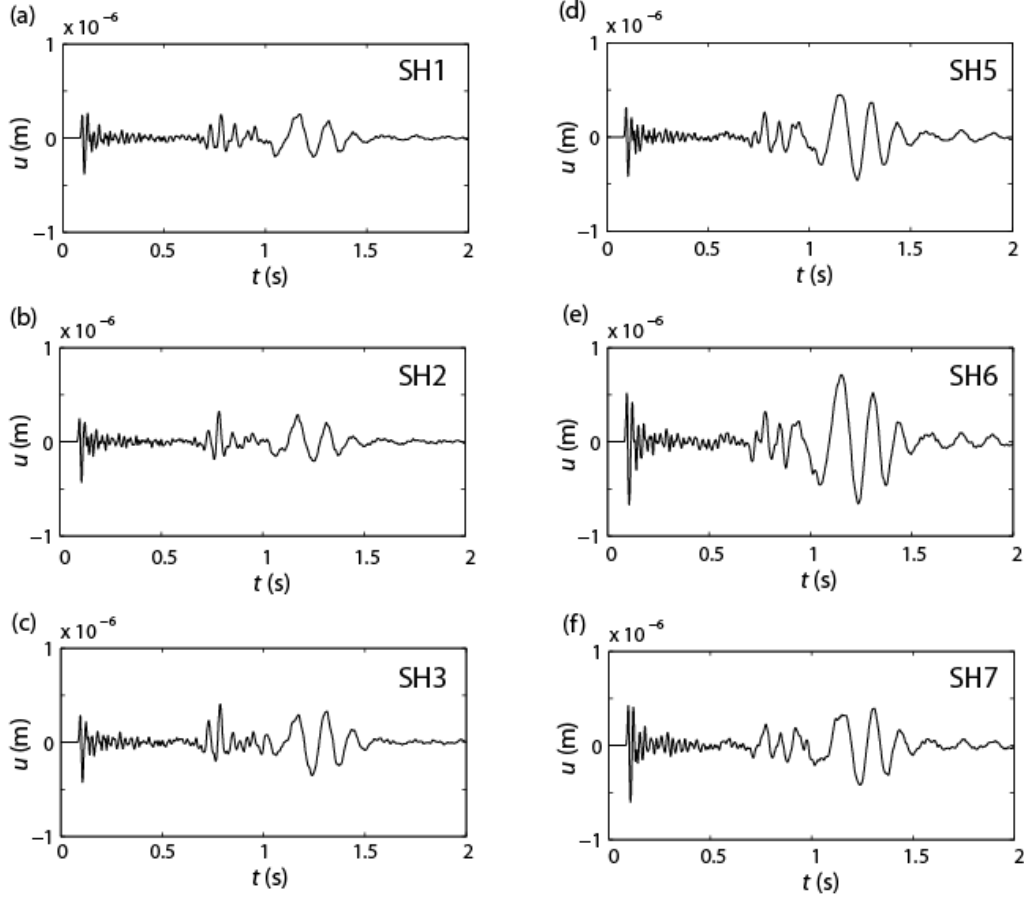


Figure 36. Vertical components of the displacement seismograms recorded by short period station ARR2 for: (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

The method was applied to the waveforms from local stations located between distances of 1.2 and 9 km from the sources. The examples of the local waveforms, converted to displacements from Station ARR2 for all six explosions, are shown in Figure 36. While the waveforms produced by the explosions at local stations were very similar, there are subtle variations in the waveforms and in the spectra, which may be attributed to differences in the source processes. SH1 (TNT) and SH2 (Tritonal) amplitudes are nearly identical for this station (Figure 36 a-b), as well as for other stations of the network, while SH2 has a larger yield by a factor of 1.53. The amplitudes produced by aluminized ANFO (SH6) are, however, higher than the amplitudes from the ANFO shot (SH5). SH6 shows the highest amplitudes at ARR2 for both P and Rg .

The amplitude ratios in the spectral domain using the SH1 spectrum as the denominator were shown in Figure 31b. The ratios were averaged over the local stations. The ratios between SH2 and SH1 (Tritonal/TNT) amplitudes are close to 1, while the ratios for other shots exhibit a characteristic increase toward low frequencies. Similar observations of amplitude increase toward lower frequency was made earlier in Stroujkova (2015) for the NEDE dataset. The amplitude increase is less pronounced for SH3 (TNT shot in a water-filled borehole) and higher for the ANFO-based explosives (SH5, SH6 and SH7). Low-frequency P amplitudes also correlate with the Rg amplitudes as was shown in Stroujkova

(2015). Thus, subtle waveform features, often masked by propagation effects, may potentially be used for discrimination between different types of explosions.

6.3. Principal Component Analysis Using Full Waveforms

The waveforms produced by different explosions observed at each station are similar, because the explosions are located closely in space and therefore the waves travel along very similar trajectories. However, some differences between the waveforms are expected due to the source effects. Principal component analysis (PCA) can be used to separate the subtle differences between the waveforms caused by the variable sources. The PCA is a procedure that uses an orthogonal transformation to convert a set of observations into a set of orthogonal vectors called principal components. Let us assume that we have a set of measurements or signals $S = [s_i]$, ($i = 1, \dots, n$). In our case each vector s_i corresponds to an individual seismic trace. The set of signals can be represented by a linear combination of principal components $X = [x_j]$, so that

$$s_i = \sum_{j=1}^n a_{ij} x_j, \quad (17)$$

where a_{ij} are some coefficients to be determined. In matrix notation Equation 17 can be rewritten as

$$S = A^T X. \quad (18)$$

The covariance matrix of the signals is defined as:

$$C = S^T S. \quad (19)$$

The principal components of the signal set S are given by the eigenvectors of the covariance matrix C , which satisfy the equation:

$$CX = \Lambda X, \quad (20)$$

where Λ is a diagonal $n \times n$ matrix with the eigenvalues λ_i along the diagonal.

The number of principal components is less than or equal to the number of original variables. The first principal component represents the largest possible variance (that is, accounts for as much of the variability in the data as possible), and each succeeding component, in turn, has the highest variance possible under the constraint that it is orthogonal to the preceding components. The resulting vectors are an uncorrelated orthogonal basis set. For example, for a system of two signals, the first principal component is their average, and the second principal component is the difference between each signal and the average.

PCA is sensitive to the relative scaling of the original variables; therefore each data vector S was normalized to satisfy the condition:

$$\bar{S}^T \bar{S} = 1, \quad (21)$$

where $\bar{S}$ is the normalized data vector. In this case, the covariance matrix represents a correlation matrix for the original signals.

PCA can be interpreted geometrically as rotation of the original coordinate system into the system determined by the eigenvectors. The component of each vector in a signal, a_{ij} , can be calculated as the scalar product between the signal and the eigenvector x_j . The projections normalized by the vector length represent directional cosines also called loadings (similar to factor loadings in factor analysis). If two largest PCs are selected, their loadings are located within a unit circle. The closer the points are to the unit circle, the better they are represented by the two principal components. Matrix X can also be used to find projections for observations that were not used for the eigenvector calculations. These observations are called *supplementary*, while the observations used to compute the principal components are called *active* (e.g. Abdi and Williams, 2010).

An illustration of the principal component computation for Station ARR2 is provided here. The covariance matrix is calculated by computing the scalar product between the data vectors (seismic traces) from the explosions in the following order (SH1, SH2, SH3, SH5, SH6, SH7). The first three explosions in that ordered list were conducted with either TNT or Tritonal, while the last three explosions on this list are either ANFO or aluminized ANFO. The covariance matrix for station ARR2 is:

$$C_{ARR2} = \begin{bmatrix} 1.00 & 0.87 & 0.87 & 0.92 & 0.91 & 0.88 \\ 0.87 & 1.00 & 0.89 & 0.77 & 0.76 & 0.74 \\ 0.87 & 0.89 & 1.00 & 0.84 & 0.81 & 0.81 \\ 0.92 & 0.77 & 0.84 & 1.00 & 0.98 & 0.95 \\ 0.91 & 0.76 & 0.81 & 0.98 & 1.00 & 0.96 \\ 0.88 & 0.74 & 0.81 & 0.95 & 0.96 & 1.00 \end{bmatrix}$$

The eigenvalues of this covariance matrix are:

$$\lambda_i = (5.323, 0.418, 0.122, 0.076, 0.045, 0.016).$$

The eigenvectors (principal components) represent an orthonormal set. In some respect the decomposition is similar to a Fourier transform which decomposes a function into an orthonormal set of predefined functions (sines and cosines). In contrast, PCA transforms each waveform of the dataset into an orthonormal set of functions derived directly from the data set.

It should be pointed out that each of the two smallest eigenvalues is less than 1% of the largest eigenvalue. This means that the portion of the eigenvectors corresponding to these eigenvalues in the total signal is small. Therefore, only the four largest eigenvectors (principal components) are shown in Figure 37. The largest eigenvector (Figure 37a) represents the most common signal between all the explosions (compare with the traces in Figure 36).

A close look at the first and the second principal components for Station ARR2 (Figure 37 a and b) shows that adding the second vector to the first one with a positive sign would increase the signal amplitude in the P and S wave windows, and reduce the amplitude in the R_g window. Thus, positive a_{i2} corresponds to an increase in the P and S amplitudes compared to the R_g amplitudes. This feature can be observed in the raw traces in Figure 36; however, the principal component analysis helps to quantify this observation.

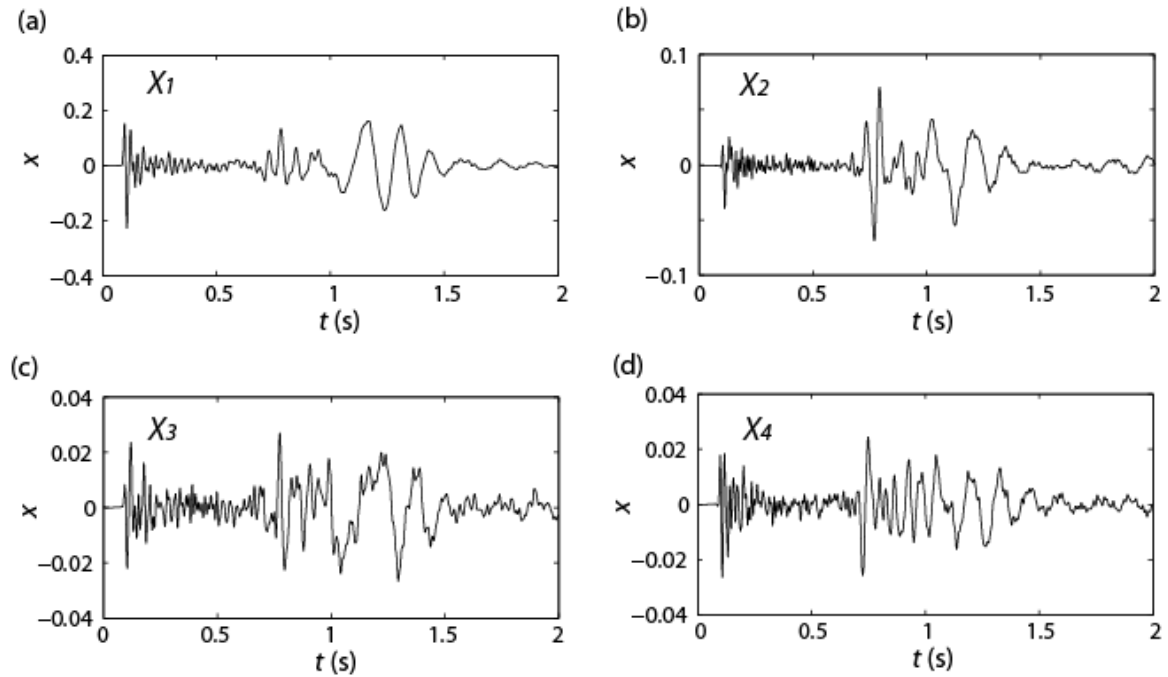


Figure 37. Eigenvectors for the data from station ARR2: (a) x_1 , (b) x_2 , (c) x_3 , and (d) x_4 .

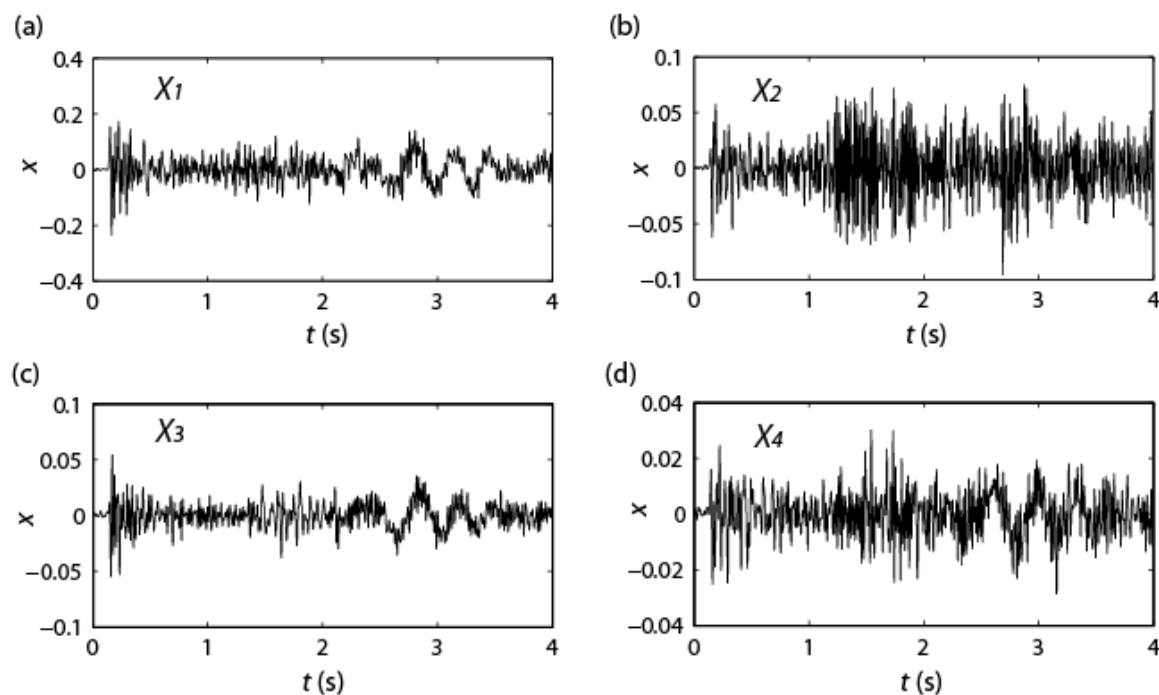


Figure 38. Eigenvectors for the data from station ZR02: (a) x_1 , (b) x_2 , (c) x_3 , and (d) x_4 .

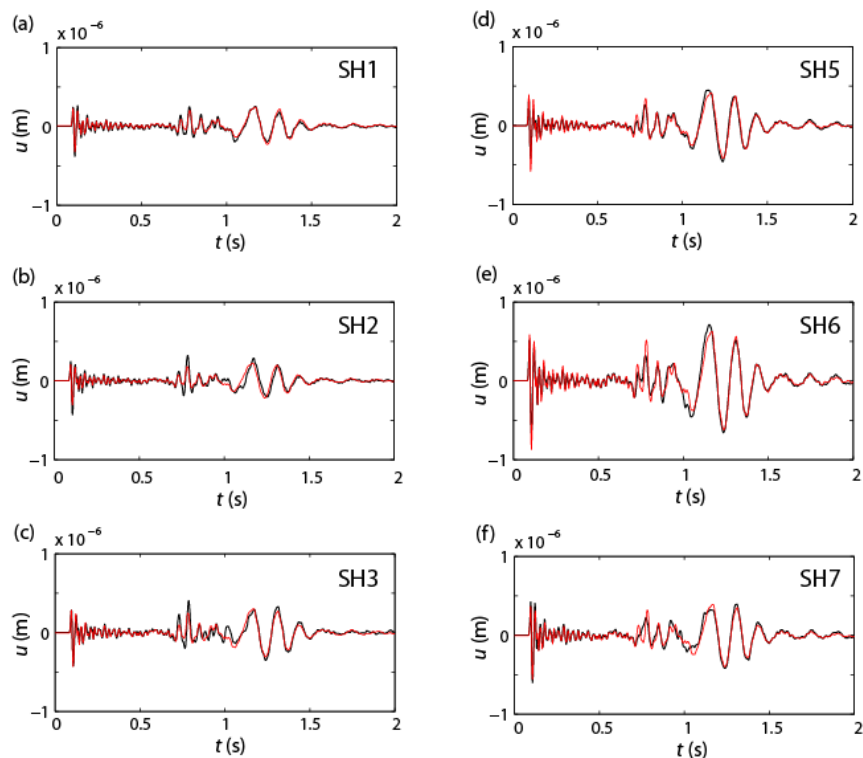


Figure 39. The data from station ARR2 and the contribution from the first principal component for (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7.

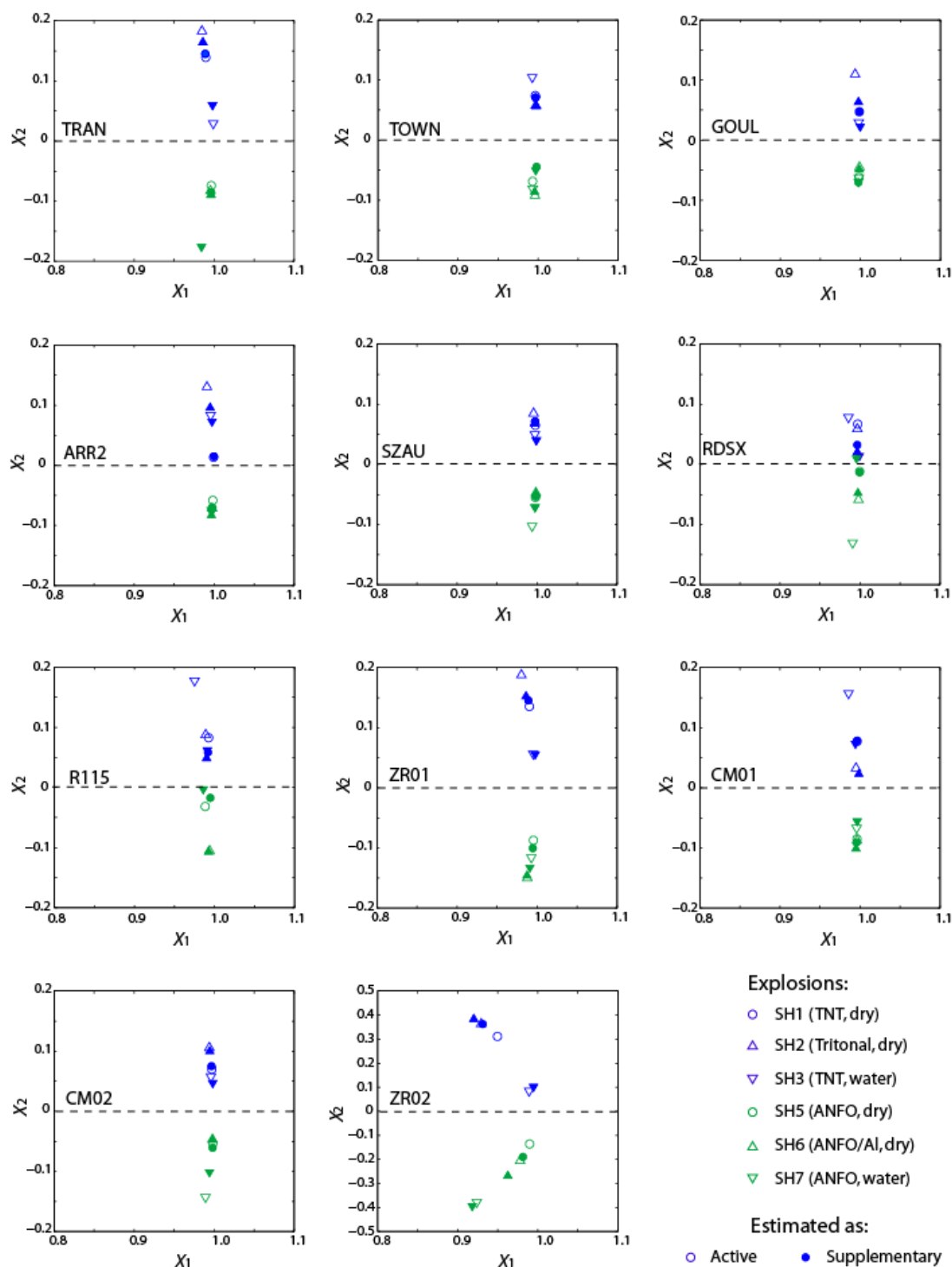


Figure 40. Principal components 1 and 2 calculated for the local stations: TRAN, TOWN, GOUL, ARR2, SZAU, RDSX, R115, ZR01, CM01, CM02, ZR02. For each station and event pair both active (open symbols) and supplementary (solid symbols) variable estimates are shown.

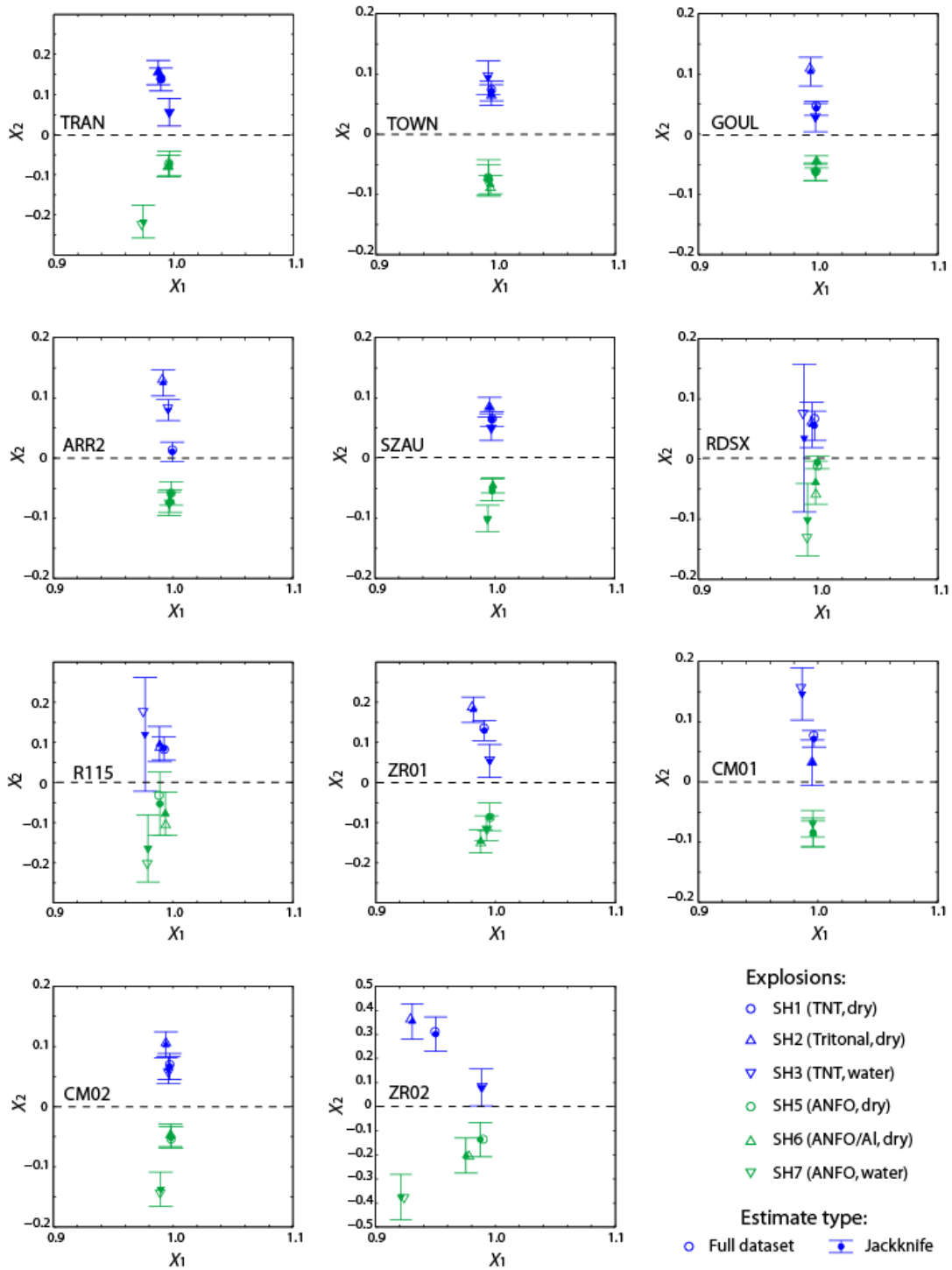


Figure 41. Cross-plot between the first and the second principal components calculated for the local stations using full waveforms: TRAN, TOWN, GOUL, ARR2, SZAU, RDSX, R115, ZR01, CM01, CM02, ZR02. The solid symbols and the error bars show the mean and the standard deviation calculated using a jackknife technique.

PCA results for Station ZR02 are shown in Figure 38. Unlike ARR2, Station ZR02 is located in the wooded area near a creek more than 9 km from the explosions. As a result, the noise level is higher for ZR02. In addition, the secondary seismic phases (e.g. R_g) are significantly degraded due to scattering. The first principal component is dominated by P -wave coda with a visible R_g phase. The second principal component is represented by P -wave coda and a very strong high-frequency signal beginning in the S-wave window, possibly scattered S-coda. In addition, the high-frequency signal also strengthens in the R_g window, which possibly represents R_g scattered from topography and other lateral heterogeneities. Despite considerable differences between ARR2 and ZR02 waveforms, the principal components also change sign between the TNT-based and ANFO-based explosions. As this example shows, the PCA pinpoints some latent similarities between the waveforms that are not obvious in the raw data. Overall, the second principal component in this dataset tends to amplify the high-frequency body waves (P and S), and in some cases degrade the low-frequency R_g phase for the TNT based explosives. This result is in agreement with the observations of Stroujkova (2015) that ANFO explosions radiate more energy in the low-frequency part of the spectrum than the explosives with higher VOD and lower volume of gaseous products.

Table 10. Results of the eigenvalue computations for 11 local stations using full waveforms. The “+” signs in column 6, indicate that the sign of the 2nd principal component is different between the TNT-based and ANFO-based shots, while the “-” signs indicate that at least one shot does not follow this pattern. The “+” signs in column 7 indicate that the sign of the 3rd principal component is different between the shots in dry and water-filled boreholes, while the “-” signs indicate that at least one shot does not follow this pattern. The question marks in column 7 show that the value of the 3rd principal component is close to zero for at least one of the shots.

Station	Distance (km)	Full waveform PCA				
		Principal component loadings (%)			PC sign change	
		1 st	2 nd	3 rd	2 nd	3 rd
TRAN	1.2	81.7	10.8	2.7	+	-
GOUL	2.0	89.7	5.7	2.5	+	-
TOWN	2.5	84.6	6.8	3.9	+	+
ARR2	3.7	88.7	7.0	2.0	+	-
SZAU	4.3	88.0	6.2	2.5	+	-
R115	5.8	77.8	9.9	7.6	+	+
ZR01	6.3	82.4	10.6	3.6	+	-
RDSX	6.4	85.7	6.4	5.5	+	+
CM01	7.1	85.0	7.7	4.3	+	?
CM02	8.2	86.7	7.4	3.2	+	-
ZR02	9.1	72.0	19.6	4.3	+	?
All	-	84.3	8.3	3.6	+	-

Figure 39 shows the data from Station ARR2 (shown with the black lines) and the portion explained by the first principal component (shown in red). As expected, the first principal component recovers a significant part of each seismic trace. The residuals, which represent the sum of all remaining principal components, mainly contribute to the relative amplitudes of the phases. For instance, P and S amplitudes for the TNT-based explosives are higher than predicted by the first principal component, while for the ANFO-based explosives P and S amplitudes are lower.

The component of each vector in a signal a_{ij} can be calculated as the scalar product between the signal and the eigenvector x_j . The projections normalized by the vector length represent directional cosines. If two largest principal components are selected, the variables are located within a unit circle.

Figure 40 shows the cross-plots between the first and the second principal components loadings a_{i1} and a_{i2} for eleven local stations. The blue symbols represent SH1 through SH3 (TNT-based explosives), while the green symbols show SH5 through SH7 (ANFO-based explosives). The first principal component is positive for all shots and it accounts for over 90% of the total signal energy. The second principal component is positive for the TNT-based explosions and negative for the ANFO-based explosions. The first principal component is positive for all events for each station because all events have large positive correlation coefficients, while the second principal components have different signs for the TNT and the ANFO shots. This holds for all stations shown in Figure 40.

Calculating the principal components using 5-event subsets to predict the loadings for supplementary variables also enables us to perform an error estimate using the jackknife method (e.g. Abdi and Williams, 2010). Figure 41 shows the mean estimated values of each principal component and their standard deviations. According to Figure 41, the only incorrectly classified data point was Shot SH7 recorded at Station RDSX. The principal components calculated using the full set of six events are shown with open symbols. The difference between Figures 40 and 41 is that in Figure 40 the estimates were made as supplementary events with five event subsets, while in Figure 41 the estimates were made with each event as an active variable using the jackknife method. Notice that all the mean values are close to the estimated value using the complete set. However, the confidence intervals determined by the standard deviation suggest that for some stations errors are possible. This analysis shows that despite the small size of the dataset, PCA can correctly identify the type of the explosive, provided the explosive type to be classified is similar to the ones used for the principal component computations.

For the data set presented in this report only two different mechanisms could be separated using principal components. If more principal components are necessary to characterize the features of the data vectors, PCA can be used as a first step before performing a cluster analysis or neural network analysis. In those cases event classification can be performed by finding the regions in a multidimensional space.

6.4. Principal Component Analysis Using Phase Amplitudes

In the previous section the PCA was applied to the entire waveforms. Thus the dimensionality of the data vectors equaled the number of the samples in the traces. The results for some stations show that the 1st principal component represents the averaged trace, while the second principal component describes the differences between the average and the individual traces. In many cases, the major differences are expressed as the increase or the reduction of relative amplitudes for different phases (e.g. Figure 36). For instance, for Station ARR2 the first principal component underestimates the body wave amplitudes (*P* and *S*) for the TNT-based explosions, and overestimates the body waves for the ANFO-based explosions with respect to *Rg*. Thus, instead of using the entire trace, we can use some features extracted from each trace, in this case the amplitudes of *P*, *S* and *Rg* phases. Figure 42 shows waveforms from Station ARR2 band-pass filtered between 1 and 20 Hz. The same waveforms are shown unfiltered in Figure 36. The envelopes (Hilbert transforms) are shown in red. The amplitudes for each phase were calculated as the maximum envelope in each window marked in Figure 30.

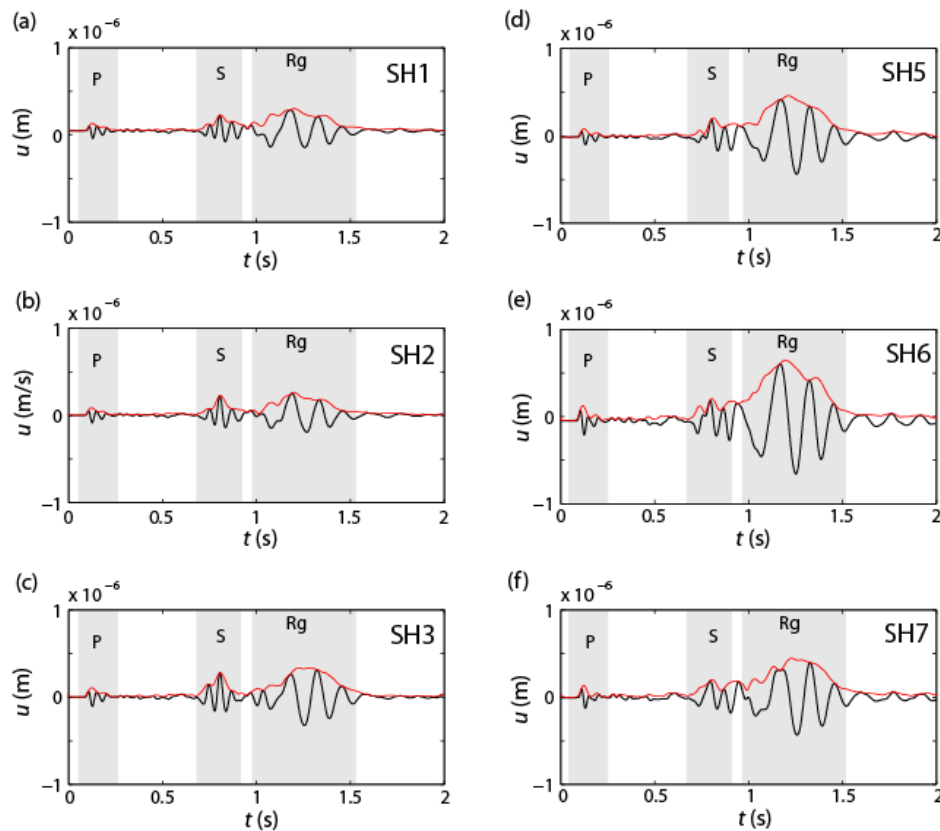


Figure 42. Seismic traces from station ARR2 bandpass filtered between 1 and 20 Hz for (a) SH1, (b) SH2, (c) SH3, (d) SH5, (e) SH6, and (f) SH7. The red lines show amplitude envelopes computed using a Hilbert transform. The time intervals used for maximum phase amplitude calculation are shaded.

It follows from Figure 42 that P -wave amplitudes below 20 Hz are lower for the TNT-based explosions than for ANFO-based explosions. Thus, the relationship between P wave amplitudes at high and low frequencies can have discriminating power of its own. The amplitudes can be calculated separately for high and low frequencies and both values can be used as a part of the data vector. The high-frequency P amplitudes were calculated as maxima of the envelopes of the traces filtered above 20 Hz.

The covariance matrix for station ARR2 calculated using the trace attributes is:

$$C_{ARR2} = \begin{bmatrix} 1.00 & 0.98 & 0.98 & 0.99 & 0.95 & 0.98 \\ 0.98 & 1.00 & 0.89 & 0.94 & 0.76 & 0.74 \\ 0.98 & 0.99 & 1.00 & 0.95 & 0.81 & 0.81 \\ 0.99 & 0.94 & 0.95 & 1.00 & 0.99 & 0.99 \\ 0.95 & 0.88 & 0.89 & 0.99 & 1.00 & 0.99 \\ 0.98 & 0.92 & 0.93 & 0.99 & 0.99 & 1.00 \end{bmatrix}$$

The eigenvalues of this covariance matrix are:

$$\lambda_i = (0.907, 0.092, 0.0003, 1.25 \times 10^{-30}, 4.2 \times 10^{-31}, 0).$$

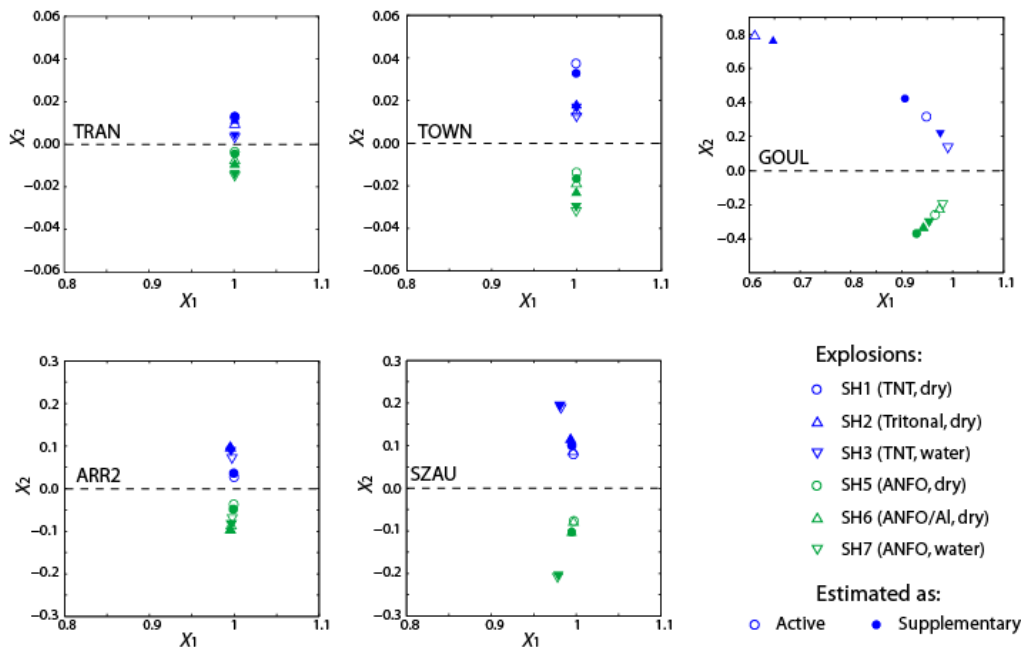


Figure 43. Loadings for the principal components 1 and 2 calculated using full waveforms for the local stations: TRAN, TOWN, GOUL, ARR2 and SZAU. For each station and event pair both active (open symbols) and supplementary (solid symbols) variable estimates are shown.

Figures 43 and 44 present the results of principal component calculations for the phase amplitude data. The first and second principal components follow the same pattern as the principal components computed for the entire traces. However, this technique only

functioned for the stations located close to the sources. For these stations the phases were not yet degraded due to scattering and attenuation, therefore their amplitudes could be extracted with high degree of confidence.

The results are only presented for the stations where the method indeed separated the TNT-based and ANFO-based explosions based on the sign of the second principal component.

It is important to note that this version of the method worked only for stations located less than 4 – 5 km from the sources, while the version using the full waveforms performed well even for more remote stations with lower SNR and secondary phases degraded by the scattering. The method appears to perform better for stations with good coupling, low noise and low site amplification.

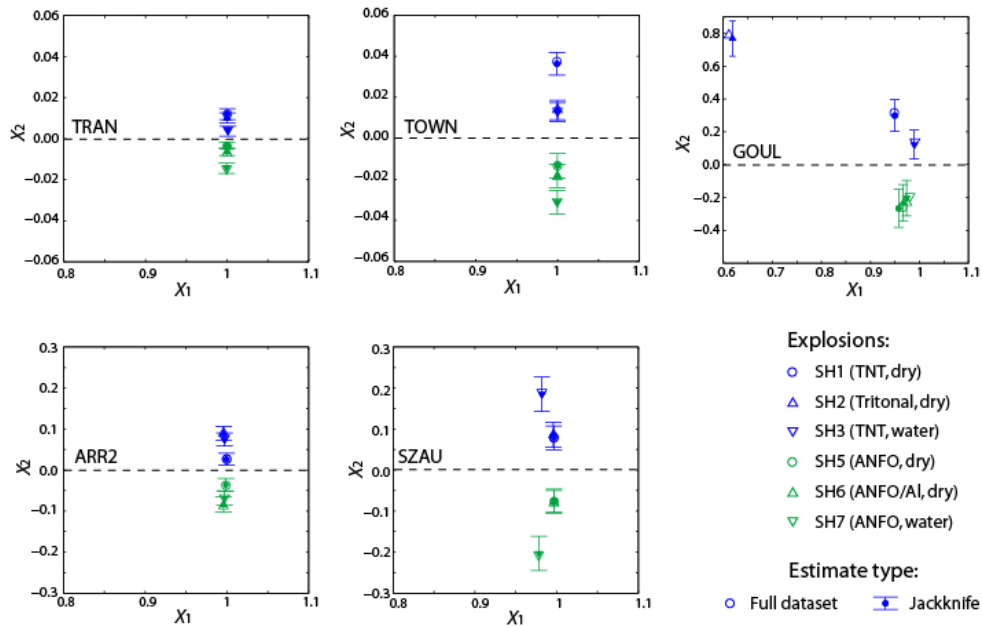


Figure 44. Cross-plot between the first and the second principal components calculated using phase amplitudes extracted from the seismic records from stations: TRAN, TOWN, GOUL, ARR2 and SZAU. The solid symbols and the error bars show the mean and the standard deviation calculated using the jackknife method.

6.5. Conclusions Regarding Principal Component Analysis

Principal component analysis was applied to a set of six underground chemical explosions conducted in granitic rocks using different types of explosives. Analysis of the seismic data revealed subtle but systematic differences between the waveforms from TNT-based and ANFO-based explosives, which may be attributed to the differences in the source processes. While differences in the P -wave spectra can be used to quantify some of the differences in the seismic sources, the PCA using the entire waveform may offer additional information and discrimination power.

Principal component analysis using full waveforms revealed that the largest eigenvector can explain between 72% and 89.7% of the variance between the explosion waveforms from most of the local stations. The second eigenvector is responsible for approximately 5.7-19.6% of the waveform characteristics. The sign of the second principal component can, with high degree of accuracy, predict the type of the explosive (TNT vs. ANFO).

Applying PCA to extracted amplitudes of various seismic phases show similar results as for PCA applied to the full waveforms for low-noise stations along the paths with low scattering. The first eigenvector in this case is responsible for between 76.1% and 99.9% of the total variance. The second eigenvector is responsible for the remaining 0.04 – 23.9% of the variance. In this case the first and the second principal components combined represent 99 – 100% of the total signal.

The application of the method to phase amplitudes can provide good results for shorter distances and for the travel paths with low scattering and low noise. Using the full-waveform version of the method, one can determine the type of the explosive even at longer ranges where the amplitudes of the secondary phases are degraded due to scattering and attenuation.

In this study, the PCA approach using the extracted phase amplitudes show similar results to the full waveform approach for the low-noise traces with low scattering and high amplitude seismic phases. The PCA using phase amplitudes performs poorly in cases where the phase identification is ambiguous due to propagation effects (e.g. scattering, basin amplification) or low SNR. However, PCA using extracted trace attributes can be expanded to include traces with low correlation coefficients between the traces, which cannot be used for the full waveform correlation. Other input data types will be studied in the future. In practice, selection of the suitable data representation should be tailored to a specific problem.

7. RELATIVE FOCAL MECHANISM ESTIMATION USING NON-LINEAR INVERSION

7.1. Introduction

Non-isotropic seismic source components from explosions have been the subject of debate for decades. Tectonic pre-stress is one of the causes of source anisotropy. Another proposed mechanism involves damage and failure in an inverted conical region above an explosion (e.g. Eisler and Chilton, 1964). The failure and damage in this cone has been modeled well with a compensated linear-vector dipole source moment tensor representation (e.g., Patton and Taylor, 2008; Stevens *et al.*, 2003). Rock fracturing and fragmentation in the source region of underground explosions has been proposed as a mechanism for high-frequency *P* and *S* -wave generation (e.g. Ashby and Sammis, 1990; Johnson and Sammis, 2001).

Explosion source anisotropy effect is multifold. First, it can change the radiation pattern of both body and the surface waves. For instance, Ekstrom and Richards (1994) showed that

tectonic release is responsible for strong radiation patterns including polarity reversal for the Rayleigh waves radiating from explosions conducted at Shagan River testing area of the Semipalatinsk Test Site. Another mechanism was proposed by Patton and Taylor (2008), who hypothesized that the damage-related CLVD component results in weakening of surface waves compared to the isotropic source.

Recent studies related to the ongoing Source Physics Experiment (SPE) conducted at the Nevada National Security Site have shown that the shear waves can be generated by slip on the joints surrounding the explosion (e.g. Vorobiev et al., 2015; Steedman et al., 2016) through the release of accumulated strain. Vorobiev et al (2015) shows that the aligned joints and fractures tend to generate stronger tangential motion in the near field, which may propagate into the far field and result in source asymmetry. Randomly distributed joints result in more isotropic seismic radiation.

Data from the chemical explosion experiment in New Hampshire (GAS2016) were analyzed to interpret the body and the surface wave focal mechanisms. The explosions of the experiment were detonated using aluminized and non-aluminized explosive pairs and was intended to study the effect of gaseous detonation products released during explosions on seismic radiation. Post-explosion damage inferred from the well logs was correlated with the seismic data in order to provide insight on body and surface wave generation. While we did not specifically address shear waves, their generation is implied by the presence of the source anisotropy.

7.2. Method

As shown in Chapter 6, P waves from the explosions of the dataset exhibit non-isotropic radiation, which is inconsistent with tensile fracture openings for the fracture directions inferred from the well logging. It was shown that the radiation pattern is consistent with either shear failure along the pre-existing fractures, or along the vertical borehole fractures.

Conventional moment tensor inversion requires calculation of the Green's functions and is usually carried out for very low frequencies. Generally Green's functions (G^P and G^{Rg}) are very difficult to calculate for complex media at high frequencies. To avoid the need to calculate the Green's function, the focal mechanism can be estimated using the amplitude ratios with respect to a reference event (or events). However, a velocity model is still needed to calculate the takeoff angles and azimuths.

The amplitude inversion is formulated as follows. Consider a point source represented by a second order moment tensor M_{pq} , then the displacement due to this source is (Aki and Richards, 2002):

$$u_n(x, t) = M_{pq} * G_{np,q} , \quad (22)$$

where $G_{np,q}$ is the Green's function. The far-field P -wave displacement from a point source is given by (Aki and Richards, 2002):

$$u^{FP}(x, t) = \frac{1}{4\pi\rho\alpha^3} \dot{M}_0 \left(t - \frac{r}{\alpha} \right) A^{FP} = G^P(x, t) A^{FP}, \quad (23)$$

where $M_0(t)$ is the time-dependent seismic moment, $G^P(t)$ is a Green's function depending only on time and distance, and A^{FP} is the azimuthal radiation pattern.

There are various methods of moment tensor decomposition. The most common method is to decompose it into an isotropic, double-couple and CLVD parts:

$$M = M_I + M_{DC} + M_{CLVD}. \quad (24)$$

Let us first consider a source represented by the sum of an isotropic and double-couple components: $M = M_I + M_{DC}$.

For the short period Rayleigh wave (Rg) the displacement amplitudes are given by (Aki and Richards, 2002):

$$u^{Rg}(x, \omega) = (U_1 + U_2 \cos 2\phi + U_3 \sin 2\phi) G^{Rg} \quad (25)$$

where

$$\begin{aligned} U_1 &= \frac{1}{2} (M_{xx} + M_{yy}) - (1 - 2\beta^2/\alpha^2) M_{zz}, \\ U_2 &= \frac{1}{2} (M_{xx} - M_{yy}), \text{ and} \\ U_3 &= M_{xy}. \end{aligned} \quad (26)$$

For the sum of an isotropic and a double-couple mechanism the expressions are:

$$u^{Rg} = (2\beta^2/\alpha^2 M_I + A_{DC}^{Rg} M_{DC}) G^{Rg} \quad (27)$$

where

$$A_{DC}^{Rg} = \frac{1}{2} \left(3 - \frac{4\beta^2}{\alpha^2} + \cos 2(\phi - \phi_s) \right) \sin 2\delta \sin \lambda + \sin \delta \cos \lambda \sin 2(\phi - \phi_s) \quad (28)$$

Let us assume that we have a reference event, for which the non-isotropic component is small. Then we can write for the amplitude ratios:

$$\bar{u}_1^{Rg} = \frac{u_1^{Rg}}{u_0^{Rg}} = C \frac{2\beta^2/\alpha^2 M_{I1} + A_{DC}^{Rg} M_{DC1}}{2\beta^2/\alpha^2 M_{I0}}, \quad (29)$$

where $\bar{u}_1^{Rg}$ is the normalized Rg amplitude that can be explained by the radiation pattern (a ratio between the event being tested and the reference event) and C is a constant to correct for the differences in the event sizes.

This is a nonlinear system of equations, which is usually solved either by linearization (e.g., the Levenberg–Marquardt method) or by using a nonlinear solver (simplex method, simulated annealing, etc.). In this study the system was solved using the simplex search method (Lagarias et al.,1998).

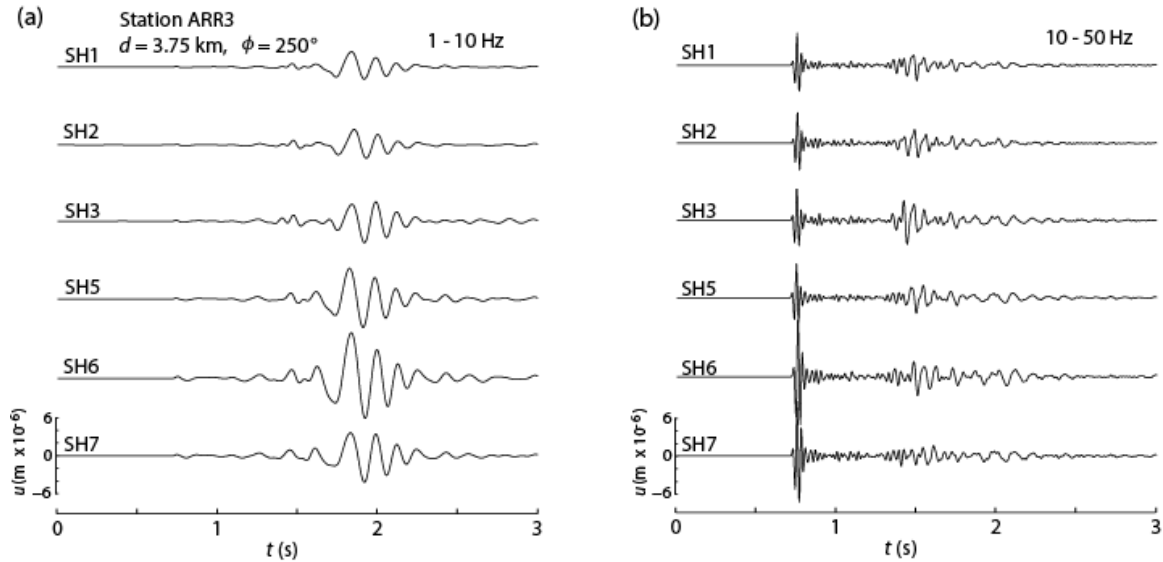


Figure 45. Vertical component displacement seismograms recorded by Station ARR3 located at a distance of 3.75 km from the sources filtered in different frequency bands: (a) 1 – 10 Hz and (b) 10 – 50 Hz.

7.3. Results

While the averaged SH1 and SH2 amplitudes were used as a reference, it was possible to find the ratios between each of them individually (SH1 and SH2) with respect to the average. The amplitudes were very similar between SH1 and SH2 with subtle differences, and the axes of symmetry appear to be almost orthogonal. Using the average value helps the noise reduction, as well as smoothing out the reference radiation pattern.

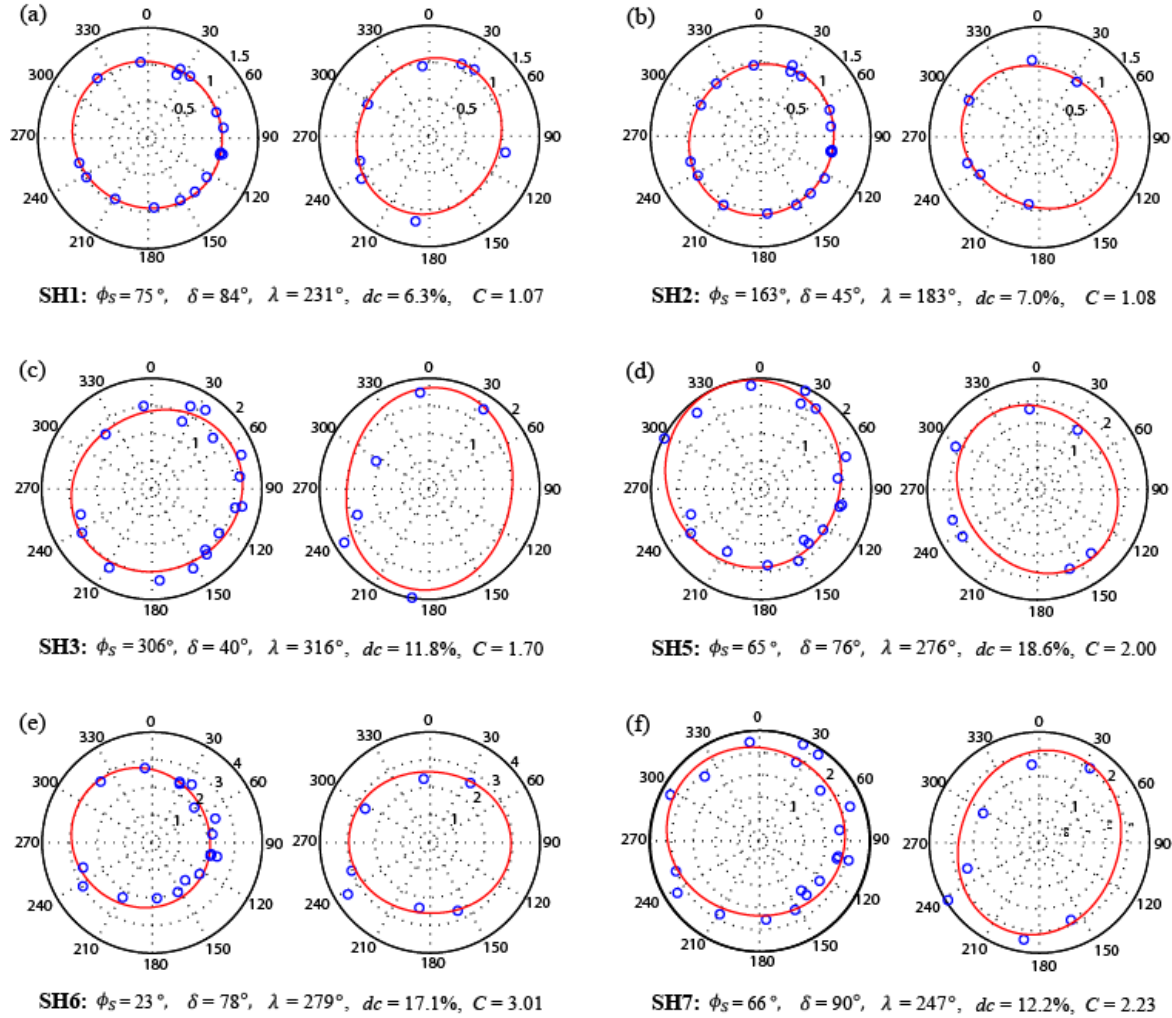


Figure 46. Comparison between the observed P (left plots) and Rg (right plots) amplitude ratios (blue circles) and theoretical radiation patterns for the sum of isotropic and a double-couple seismic source (red lines) corresponding for the shots: (a) SH1, (b) SH2; (c) SH3, (d) SH5, (e) SH6, and (f) SH7. The data were filtered in the frequency band 1 – 10 Hz. The amplitude ratios were taken with respect to the averaged SH1 and SH2 amplitudes of the first peak.

The inversion was performed in two separate frequency bands: 1 – 10 Hz and 10 – 50 Hz. Calculation of the focal mechanism for different frequencies may shed light on different source processes affecting source symmetry. Figure 45 shows the waveforms from station ARR3 for the six events filtered in these frequency bands. As expected, the Rg phase has the highest amplitude for 1 – 10 Hz, while the P wave dominates the waveforms at higher frequencies (10 – 50 Hz). Shear wave arrival is also prominent for this particular station; however, there are questions regarding the nature of the S waves from explosions (i.e. which part is produced by the source and which part is a result of scattering). Therefore, it may be wise to avoid using S -waves for the inversion and use the resolved focal mechanisms to compare the calculated and observed amplitudes.

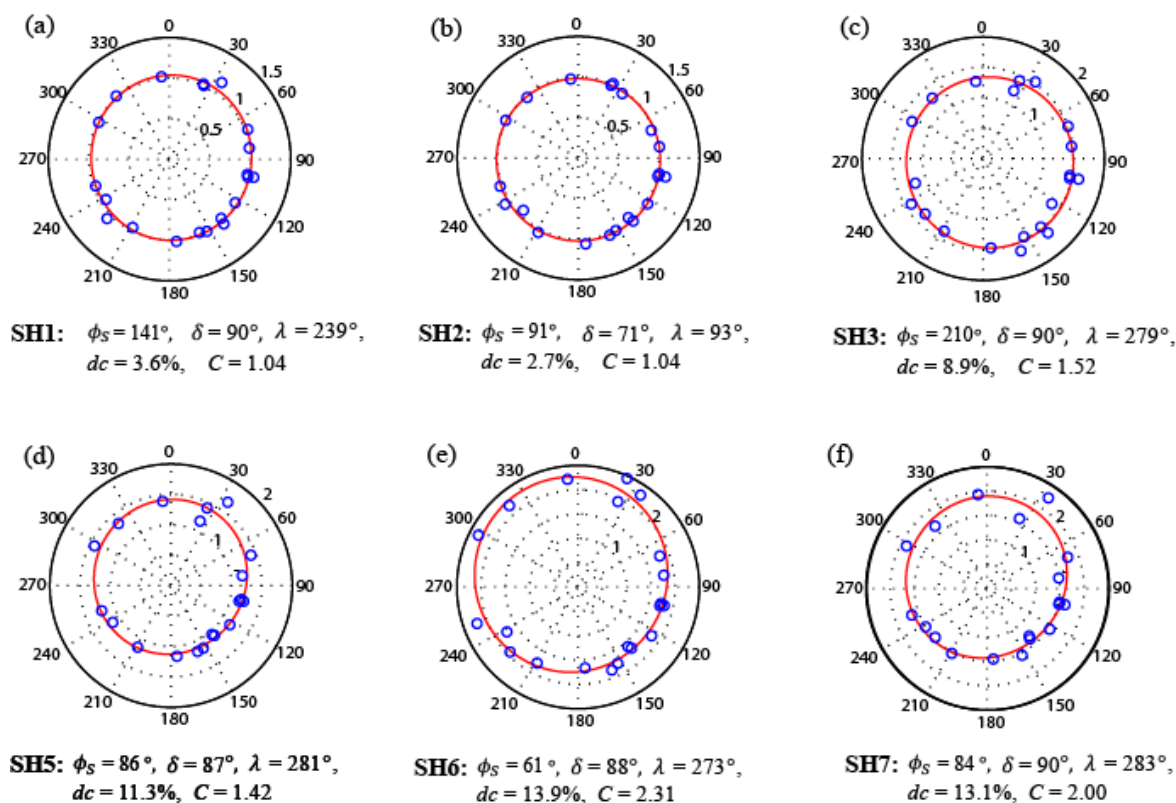


Figure 47. Comparison between the observed P -wave amplitude ratios (blue circles) and theoretical radiation patterns for the sum of isotropic and a double-couple seismic source (red lines) corresponding for the shots: (a) SH1, (b) SH2; (c) SH3, (d) SH5, (e) SH6, and (f) SH7. The data were filtered in the frequency band 10 – 50 Hz. The amplitude ratios were taken with respect to the averaged SH1 and SH2 amplitudes of the first peak.

Using the averaged amplitudes from SH1 and SH2 shots as a reference, the amplitude ratios were inverted (for both P and R_g) for the best sum of an isotropic and double-couple focal mechanism. Figure 46 shows the resulting focal mechanisms calculated using the data filtered in 1 – 10 Hz frequency band. The percentages of the double couple, as well as the strikes, dip and rake orientation for the double couple components are shown below each plot. The radiation patterns can be well explained by a combination of an isotropic explosion and a shear faulting. The percentage of the resolved double-couple component varies between 6-7% for SH1 and SH2 to 17-18% for SH5 – SH7. There is a correlation between the explosion type and the amount of the non-isotropic component: the TNT-based explosives tend to be more isotropic than the ANFO-based explosives. The TNT shot in the water-filled borehole is somewhere in between the TNT and ANFO explosions in dry boreholes. The differences between these explosive types can be attributed to higher amount of gaseous explosive products for ANFO, which supports the idea of pore pressure increase in a larger volume, which promotes slip along pre-existing joints and fractures. It

is interesting, that the TNT and ANFO shots in water-filled boreholes produced similar amplitudes.

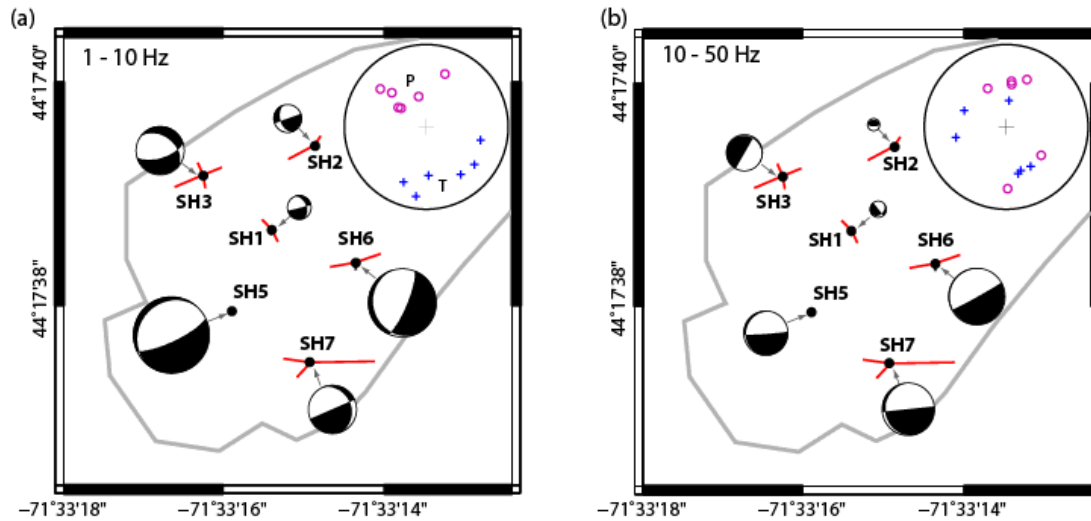


Figure 48. Orientation of the vertical fractures from the OTV logs (red lines) and the deviatoric parts of the focal mechanisms obtained from the inversion of the amplitude ratios: (a) seismic data filtered between 1 and 10 Hz and (b) seismic data filtered between 10 and 50 Hz. The sizes of the beach balls are proportional to the percentage of the double-couple component. The circular inserts in the upper right corners of each plot show the lower hemisphere projections of the P and T axes for the focal mechanisms.

The focal mechanism results in the 10 – 50 Hz frequency band are shown in Figure 47. These results were obtained by inverting *P*-waves only, because high-pass *R_g* amplitudes are very small for most of the stations (e.g. Figure 45b). As in the low-pass case, the radiation patterns can be explained by a combination of isotropic and double-couple components. The percentage of the resolved double-couple component is smaller than for the low-frequency band and varies between 2.7-3.6% for SH1 and SH2 to 8.9-13.9% for SH5 through SH7.

Figures 48a and 48b show the double-couple components of the focal mechanisms obtained from the inversion of the amplitude ratios in 1 – 10 Hz and 10 – 50 Hz frequency bands respectively. The orientations of the vertical fractures from the OTV logs are also shown for comparison (red lines). In the 1 – 10 Hz frequency band most of the resolved double-couple solutions are consistent with nearly vertical dip slips. The *P* axes corresponding to the deviatoric parts of the solutions are concentrated in the NNW with average plunge of approximately 45°, while the *T* axes are grouped toward the SSE with the average plunges of also close to 45°. Notice that for the focal plane solutions using the data filtered between 10 and 50 Hz, the orientation of the vertical focal planes are close to the orientations of the observed fractures. Thus, it is possible that the vertical fractures were created due to a shear failure as opposed to tensile opening (near-vertical dip slip).

7.4. Conclusions Regarding Nonlinear Focal Mechanism Estimation

The active source explosion experiment was conducted in New Hampshire in August, 2016. The purpose of the experiment was to study the seismic signatures of the explosion sources using different explosive types that generated different amounts of gaseous products.

The relative amplitudes of the P and Rg phases as a function of azimuth were used to determine the focal mechanisms of the explosions. Using the averaged SH1 and SH2 amplitudes as a reference, the amplitude ratios as a function of azimuth exhibit a radiation pattern that can be explained by a combination of isotropic and shear components. The following observations can be made from this exercise:

1. The TNT and Tritonal explosions detonated in dry boreholes have the smallest non-isotropic components. Post-shot well logging also shows fewer large fractures outside of the cavity for these shots. ANFO-based shots and TNT shot in water filled borehole resulted in large aperture fractures. This result is in a good agreement with the results from NEDE experiments (e.g. Stroujkova et al, 2012).
2. The resolved focal mechanisms are different for the data filtered in different frequency bands.
3. The focal mechanisms calculated in the high-frequency band show a lower percentage of non-isotropic component than the results using low-pass filtered data.
4. The P and T axis calculated using the low-pass data are more consistent with each other than the axes calculated using the high-pass filtered data.
5. Focal mechanisms calculated using the high-pass filtered data are, to some extent, consistent with the fractures inferred from the well logs assuming shear (not tensile) failure.

The results suggest that the focal mechanisms inferred from low-pass filtered data may be affected by the principal stress orientation in the area. The high-frequency focal mechanisms are likely affected by the local heterogeneities (including fractures and joints) in the volume surrounding the working point.

8. RELATIVE MOMENT TENSOR INVERSION

8.1. Introduction

The moment tensor (MT) inversion of seismic data has been routinely used for many years (e.g., Stump and Johnson, 1977; Gilbert and Dziewonski, 1975). Generally the MT inversion requires knowledge of the velocity model in order to calculate the Green's functions between the source and the receivers. As a result, the MT solutions are usually

obtained in the low frequency range, because the long period amplitudes are less sensitive to small velocity perturbations. The solutions for explosions and small earthquakes are often obtained in the intermediate frequency range between 0.02 and 0.1 Hz (periods between 10 and 50 seconds, e.g. Ford et al, 2009). For smaller events recorded at local distances, the entire waveform duration can be just a few seconds – less than the period used in the inversion. Being able to calculate short period moment tensor solutions can provide important information about the source processes, but calculation of the moment tensors using high-frequency local and near-regional seismic data poses significant challenges due to poorly constrained medium structure.

In contrast, the relative moment tensor inversion (RMTI) is performed simultaneously for a set of events located close to each other and requires very minimal knowledge about the medium. The only information about the medium needed for the inversion is the knowledge of the takeoff angles and the azimuths between the sources and the receivers. Dahm (1996) proposed a RMTI method using the body wave (P , SV and SH) amplitudes from multiple closely located events and showed that the method performs well for the sets of events with different focal mechanisms.

In this chapter we describe an extension of the RMTI method, which was developed to include explosions and other shallow events recorded at local to near regional distances, for which the fundamental mode Rayleigh waves (Rg) are prominent, but S waves are difficult to identify due to the interference with other phases. In this study, the RMTI method proposed by Dahm (1996) was reformulated using the least-square approach using both P and Rg amplitudes. Other phases (e.g. S waves) can be easily incorporated into the inversion, provided they can be reliably identified in the explosion records. In addition, a least square solution is developed to calculate the Green's functions. The RMTI technique using the body wave amplitudes was applied in the past to earthquake swarms (e.g. Dahm et al, 2000), induced microearthquakes (e.g. Dahm et al, 1999) and aftershock sequences (Shomali et al, 2009). In this report the modified RMTI approach was tested using the data from chemical explosion experiment (GAS2016).

8.2. Method description

An extension of the RMTI method was developed to include explosions and other shallow events recorded at local to near regional distances, for which the fundamental mode Rayleigh waves (Rg) are prominent, but S waves are difficult to identify due to the interference with other phases. In this study, the RMTI method proposed by Dahm (1996) was reformulated using the least-square approach using both P and Rg amplitudes. Other phases (e.g. S waves) can be easily incorporated into the inversion, provided they can be reliably identified in the explosion records. In addition, a least square solution is developed to calculate the Green's functions.

The relative MT technique involves simultaneously finding moment tensors for N events recorded by L stations described in the local coordinate system around the source as shown

in Figure 49. The P wave amplitudes from events k and s recorded by station l are given by:

$$\begin{aligned} A_l^k &= G_l^P \sum_{i=1}^6 a_{li} M_i^k \\ A_l^s &= G_l^P \sum_{i=1}^6 a_{li} M_i^s, \end{aligned} \quad (30)$$

where G_l^P is the Green's function for station l , and M_i^k and M_i^s are i^{th} moment tensor components for events with indices k and s respectively. Here we will use event k as a reference event with respect to which all moment tensors are calculated and using Equation 30 we can eliminate the Green's function.

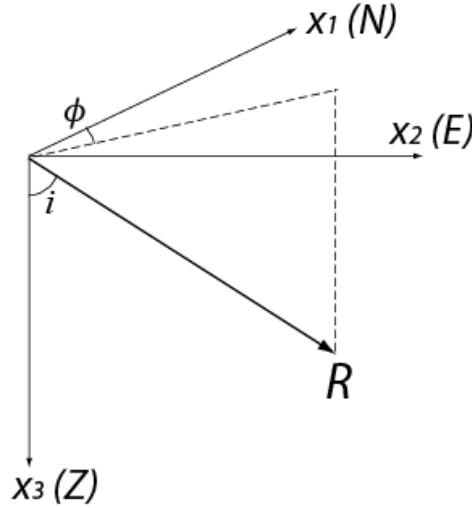


Figure 49. Geometry of the local coordinate system at the source (x_1, x_2, x_3) . Azimuth ϕ is measured clockwise from the north (x_1). The takeoff angle i is measured from the positive vertical direction (x_3) pointing downward.

The radiation pattern coefficients a_{li} for the P waves are given by:

$$\begin{aligned} a_{l1} &= \sin^2 i_l \cos^2 \phi_l, \quad a_{l2} = \sin^2 i_l \sin^2 \phi_l, \quad a_{l3} = \cos^2 i_l \\ a_{l4} &= \sin^2 i_l \sin 2\phi_l, \quad a_{l5} = \sin 2i_l \cos \phi_l, \quad a_{l6} = \sin 2i_l \sin \phi_l. \end{aligned} \quad (31)$$

To formulate a least square problem we write an objective function for each s -th event ($s = 1, \dots, N$) with respect to each k -th event:

$$\chi = \sum_{\substack{k=1 \\ s \neq k}}^N \frac{1}{L} \sum_{l=1}^L \left[A_l^k \sum_{i=1}^6 a_{li} M_i^s - A_l^s \sum_{i=1}^6 a_{li} M_i^k \right]^2. \quad (32)$$

Note that the summation is over all event indices $s \neq k$, because in the case $s = k$ the terms cancel each other. The function can be minimized by finding zeros of the derivatives with respect to the unknown moment tensor components M_j^s (e.g. Menke, 2012). Differentiation with respect to the components of the reference event with index k yields:

$$\frac{\partial \chi}{\partial M_j^k} = \sum_{s=1}^N \sum_{s \neq k} \frac{2}{L} \sum_{l=1}^L [-A_l^s a_{lj} (A_l^k \sum_{i=1}^6 a_{li} M_i^s - A_l^s \sum_{i=1}^6 a_{li} M_i^k)] = 0. \quad (33)$$

For the remaining non-reference events with index $m \neq k$ minimization of Equation 33 results in

$$\frac{\partial \chi}{\partial M_j^m} = \frac{2}{L} \sum_{l=1}^L [A_l^k a_{lj} (A_l^k \sum_{i=1}^6 a_{li} M_i^m - A_l^m \sum_{i=1}^6 a_{li} M_i^k)] = 0. \quad (34)$$

It is convenient to introduce a matrix $\mathbf{T}$:

$$T_{ij}^{mk} = \langle A_l^m a_{li} A_l^k a_{lj} \rangle = \frac{1}{L} \sum_{l=1}^L A_l^m a_{li} A_l^k a_{lj} = \frac{1}{L} \sum_{l=1}^L A_l^m A_l^k a_{li} a_{lj}. \quad (35)$$

In this representation the system of equations has the following form

$$\begin{aligned} -\sum_{s=1}^N \sum_{s \neq k} \sum_{i=1}^6 T_{ij}^{sk} M_i^s + \sum_{s=1}^N \sum_{s \neq k} \sum_{i=1}^6 T_{ij}^{ss} M_i^k &= 0, \text{ where } j = 1, \dots, 6 \\ \sum_{i=1}^6 T_{ij}^{kk} M_i^m - \sum_{i=1}^6 T_{ij}^{km} M_i^k &= 0, \text{ where } j = 1, \dots, 6, m \neq k. \end{aligned} \quad (36)$$

In matrix form the system of equations is written as follows:

$$\begin{bmatrix} \tilde{\mathbf{T}}^{11} & -\mathbf{T}^{12} & -\mathbf{T}^{13} & -\mathbf{T}^{14} & -\mathbf{T}^{15} & -\mathbf{T}^{16} & \dots & -\mathbf{T}^{1N} \\ -\mathbf{T}^{12} & \mathbf{T}^{11} & 0 & 0 & 0 & 0 & \dots & 0 \\ -\mathbf{T}^{13} & 0 & \mathbf{T}^{11} & 0 & 0 & 0 & \dots & 0 \\ -\mathbf{T}^{14} & 0 & 0 & \mathbf{T}^{11} & 0 & 0 & \dots & 0 \\ -\mathbf{T}^{15} & 0 & 0 & 0 & \mathbf{T}^{11} & 0 & \dots & 0 \\ -\mathbf{T}^{16} & 0 & 0 & 0 & 0 & \mathbf{T}^{11} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ -\mathbf{T}^{1N} & 0 & 0 & 0 & 0 & 0 & \dots & \mathbf{T}^{11} \end{bmatrix} \begin{bmatrix} \mathbf{M}^1 \\ \mathbf{M}^2 \\ \mathbf{M}^3 \\ \mathbf{M}^4 \\ \mathbf{M}^5 \\ \mathbf{M}^6 \\ \vdots \\ \mathbf{M}^N \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad (37)$$

where we have assumed that $k = 1$ and defined $\tilde{T}_{ij}^{11} = \sum_{s=2}^N T_{ij}^{ss}$.

In Equation 37 the elements of the unknown vector $\mathbf{M}^s$ represent the moment tensor elements arranged into vectors for all events ($s = 1, \dots, N$): $\mathbf{M}^s = (M_1^s, M_2^s, M_3^s, M_4^s, M_5^s, M_6^s)$. The last row in (37) is added because without it the matrix is rank deficient. This causes the scalar seismic moment to be estimated up to a constant. Alternately, a linear constraint affecting one or more events can be selected. For instance, we can maximize the diagonal terms of the moment tensor and minimize the off-diagonal terms for explosion datasets. If one or more events in the dataset have an independent estimate of the moment tensor, it can be selected as a reference mechanism by adding the equations to the system:

$$\mathbf{I} \cdot \mathbf{M}^k = \mathbf{M}^0, \quad (38)$$

where $\mathbf{I}$ is an identity matrix and $\mathbf{M}^0$ is a moment tensor for a known (reference) mechanism.

Following Dahm (1996), the term *reference mechanism* indicates the source for which the moment tensor is known *a priori*. It should not be confused with the *reference event*, which indicates the source with index k (in Equation 37 $k = 1$) and is used to eliminate the unknown Green's functions. If all events used in the inversion are of the same quality, the system of equations (37) can be modified to include all sources as reference events as described in Dahm (1996).

Once the MT components are found, one can solve for the Green's functions by minimizing the objective function χ_G written as:

$$\chi_G = \frac{1}{N} \sum_{k=1}^N \frac{1}{L} \sum_{l=1}^L [A_l^k - G_l \sum_{i=1}^6 a_{li} M_i^k]^2. \quad (39)$$

To minimize the objective function we differentiate with respect to each Green's function (for all stations l):

$$\frac{\partial \chi_G}{\partial G_l} = \frac{2}{LN} \sum_{\substack{s=1 \\ s \neq k}}^N [A_l^k - G_l \sum_{i=1}^6 a_{li} M_i^k] (-\sum_{j=1}^6 a_{lj} M_j^k) = 0. \quad (40)$$

The Green's functions can be found by solving (11) with respect to G_l :

$$G_l = \frac{\sum_{k=1}^N A_l^k \sum_{i=1}^6 a_{li} M_i^k}{\sum_{k=1}^N (\sum_{i=1}^6 a_{li} M_i^k)^2}. \quad (41)$$

The approach developed above can be easily extended to include Rayleigh waves. For Rayleigh waves the corresponding amplitudes are

$$\begin{aligned} B_l^k &= G_l^R \sum_{i=1}^6 b_{li} M_i^k, \\ B_l^s &= G_l^R \sum_{i=1}^6 b_{li} M_i^s. \end{aligned} \quad (42)$$

where G_l^R is the Green's function for station l , and M_i^k and M_i^s are i^{th} moment tensor components for events with indices k and s respectively.

For shallow seismic events the radiation pattern coefficients for the fundamental Rayleigh wave b_{l1} are given by (Aki and Richards, 2002):

$$\begin{aligned} b_{l1} &= (1 + \cos^2 \phi_l), \quad b_{l2} = (1 - \cos^2 \phi_l), \quad b_{l3} = \left(\frac{2\beta^2}{\alpha^2} - 1 \right), \\ b_{l4} &= \sin 2\phi_l, \quad b_{l5} = 0, \quad b_{l6} = 0, \end{aligned} \quad (43)$$

where α and β are P - and S -wave velocities respectively. Notice that the radiation terms for the Rayleigh waves are independent of the M_{xz} and M_{yz} components. The coefficients corresponding to these terms are proportional to $\sin \phi_l$ and $\cos \phi_l$. It was shown by Ekström and Richards (1994) that these terms can be ignored, while the terms proportional to $\sin 2\phi_l$ and $\cos 2\phi_l$ have substantial strength in nuclear explosion records. This means that the surface waves from shallow dip-slip focal mechanisms can be neglected. However,

as will be shown in the data example section, the body wave radiation patterns show the symmetry associated with the $\sin \phi_l$ and $\cos \phi_l$ terms (Equation 31), while the surface wave radiation pattern symmetry is consistent with only $\sin 2\phi_l$ and $\cos 2\phi_l$ being present. Therefore, the M_{xz} and M_{yz} were retained for the body wave amplitude calculations and neglected from the surface wave calculations. These terms, however, can be added to the surface wave calculations if necessary. The amplitudes of the surface waves should be multiplied by their polarity signs, which can change from station to station even for underground explosions (e.g. Ekström and Richards, 1994).

Including both wave types, the objective function accounting for both types of waves is given by:

$$\chi = \frac{w_1}{N} \sum_{\substack{k=1 \\ s \neq k}}^N \frac{1}{L} \sum_{l=1}^L \left[A_l^k \sum_{i=1}^6 a_{li} M_i^s - A_l^s \sum_{i=1}^6 a_{li} M_i^k \right]^2 + \frac{w_2}{N_R} \sum_{\substack{k=1 \\ s \neq k}}^{N_R} \frac{1}{L} \sum_{l=1}^L \left[B_l^k \sum_{i=1}^6 b_{li} M_i^s - B_l^s \sum_{i=1}^6 b_{li} M_i^k \right]^2, \quad (44)$$

where w_1 and w_2 are weights, and N_R is the number of events with identified Rayleigh waves recorded on L stations. The numerical results shown in this report were obtained by setting $w_1 = 1$ and $w_2 = 1$.

8.3. Synthetic Test

The purpose of the synthetic testing was to determine the method stability and robustness using a source-receiver geometry similar to the experimental explosion dataset, which will be discussed in the following section. Two synthetic datasets were selected: Set A containing 6 events with different focal mechanisms (including double-couple events of different orientations, dipole events and explosion-like events with large isotropic components), and Set B containing 6 events with high isotropic components and all positive eigenvalues. The moment tensor components for Sets A and B used for the estimation of the forward problem are provided in Tables 11 and 12, respectively. To perform the synthetic tests multiple realizations of the analytic amplitudes with added noise were calculated for both sets.

The resulting moment tensors were decomposed into an isotropic (ISO), double-couple (DC) and compensated linear vector dipole (CLVD) components (e.g. Knopoff and Randall, 1970) as follows:

$$\begin{aligned} M_{ISO} &= \frac{1}{3}(M_1 + M_2 + M_3), \\ M_{CLVD} &= \frac{2}{3}(M_1 + M_3 - 2M_2), \\ M_{ISO} &= \frac{1}{2}(M_1 - M_3 - |M_1 + M_3 - 2M_2|), \end{aligned}$$

where M_1 , M_2 , and M_3 are the eigenvalues of the moment tensor ($M_1 \geq M_2 \geq M_3$).

Table 11. Moment tensor components for the synthetic events from Set A (events with different focal mechanisms)

Event	M_{xx}	M_{yy}	M_{zz}	M_{xy}	M_{xz}	M_{yz}
1	1	1	1	0	0	0
2	1	0	-1	0	0	0
3	-0.5	-0.5	1	0	0	0
4	-1	1	0	0	0	0
5	-0.87	0.85	0.02	0.48	0.01	-0.17
6	-0.13	0.31	-0.18	0.45	-0.82	-0.22

Table 12. Moment tensor components for the synthetic events from Set B (events with similar focal mechanisms)

Event	M_{xx}	M_{yy}	M_{zz}	M_{xy}	M_{xz}	M_{yz}
1	1	1	1	0	0	0
2	1	1.1	0.9	0.08	0.01	-0.17
3	1.2	1.1	1.3	0.05	-0.12	-0.02
4	1.4	1.3	1.0	0.1	0.01	0.02
5	2.0	2.1	1.9	0.01	0.01	0.02
6	1.6	1.4	1.6	0.1	-0.08	0.06

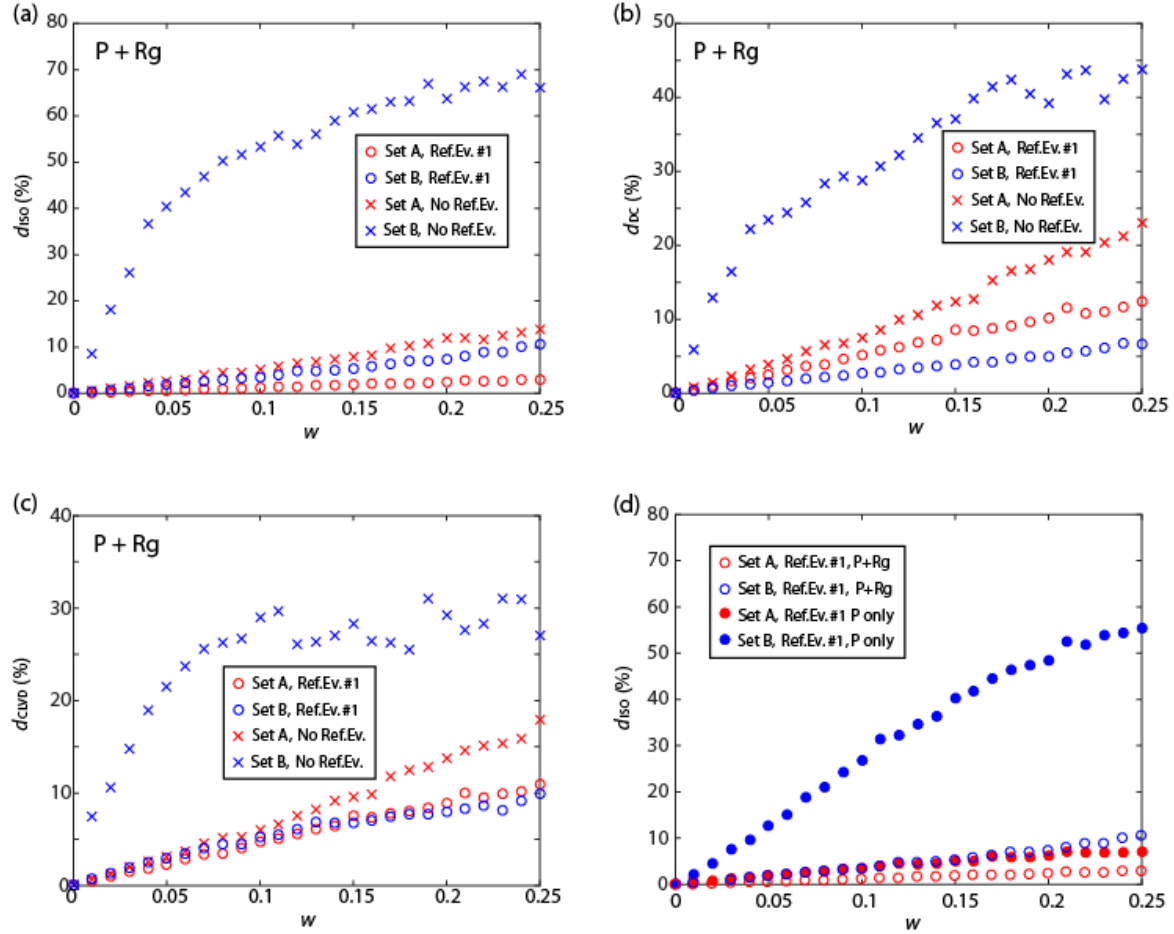


Figure 50. Errors in the different moment tensor components as a function of the noise fraction w for Set A (red symbols) and Set B (blue symbols) obtained using both P and R_g amplitudes for: (a) isotropic component, (b) double-couple component and (c) CLVD component. Circles show the errors for the case when a known reference mechanism was used, while crosses show the errors for the case when no reference mechanism was used and the sum of all MT elements was set to a constant as shown in Equation 37. (d) Errors in the isotropic component as a function of the noise fraction w for Set A (red circles) and Set B (blue circles) using only P amplitudes (solid circles) and both P and R_g amplitudes (open circles).

The first test was to determine the error in the solution as a function of the noise level. To perform this test, the synthetic data points were generated using Equation 30 with added noise:

$$A_l^k = G_l^P \sum_{i=1}^6 a_{li} M_i^k + e_l, \quad (45)$$

where e_l is the normally distributed error $n(0, \sigma_l)$. For the purpose of the numerical testing, the error standard deviation was expressed in terms of the signal amplitudes and varied from 0 to $0.2A_l^k$. We define $\sigma_l = wA_l^k$, where w is the fraction of the noise in the total signal. One hundred random noise realizations were generated for each value of w .

Computation of the synthetic data points requires knowing the propagation terms. The propagation constants were calculated from the inversion of the field data (described in the next section) and then used for the synthetic inversion to estimate the parameter resolution for these specific values. Information about the stations including the distances to the sources, azimuths and takeoff angles, used for the inversion is presented in Table 13. The propagation constants G_P and G_{Rg} are also provided for P and Rg phases respectively. It was determined from the inversion with synthetic data that the moment tensor solutions are virtually insensitive to the choice of the propagation constants.

In this study the SNR was defined as the ratio between the signal amplitude and the noise standard deviation in 1000-sample pre-event window:

$$SNR_l = \frac{A_l}{\sigma_l^*}, \quad (46)$$

where l is the station number and

$$\sigma_l^* = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2}. \quad (47)$$

In this notation, the measured SNR can be compared with the inverse of the noise standard deviation.

Columns 6 and 7 of Table 13 show the signal-to-noise ratios (SNRs) estimated in the frequency band used for the inversion for each station. According to Table 13, the SNR for P waves varies between 14 and 397.9 depending on the distance to the station and the noise level at the site. The average SNR for P waves over all stations is 155.9, which corresponds to $w = 0.0064$. Thus the average noise fraction in the observed data is 0.64%, which is very low.

Figure 50 shows the errors in the resolved moment tensor components (isotropic, double-couple and CLVD) as a function of the noise fraction w for Sets A (events with the variety of focal mechanisms) and B (events with similar explosion-like mechanisms). The errors are shown as percentages of the deviation for the moment tensor components (isotropic – ISO, double couple – DC, and compensated linear vector dipole – CLVD) calculated with respect to the total moment. Each point in Figure 50 was obtained by averaging over 100 random noise realizations for each noise fraction. As expected, the errors for Set A are considerably smaller than the errors for Set B.

The method performance with and without using the Rg data was also investigated. As shown in Figure 50d, the errors are significantly higher if only P data are used compared to the inversion using both P and Rg phases. If both P and Rg amplitudes are used without the reference mechanism, the errors in the isotropic components are under 15% for the double-couple and the errors in the CLVD components are under 25% (Figure 50d). Thus, adding the surface waves to the relative MT inversion can offer significant improvements compared to the case when the surface waves are not used.

8.4. Application to an Explosion Dataset

The experimental data used for the relative moment tensor inversion are from a chemical explosion experiment conducted in New Hampshire in 2016 (GAS2016, Stroujkova et al, 2017). Six single-shot explosions and three calibration shots were conducted during the experiment (Tables 2 and 3). The following explosives were used to conduct the shots: trinitrotoluene (TNT), Tritonal (TNT/Al 80/20), Ammonium Nitrate and Fuel Oil (ANFO), aluminized ANFO (ANFO/Al 80/20).

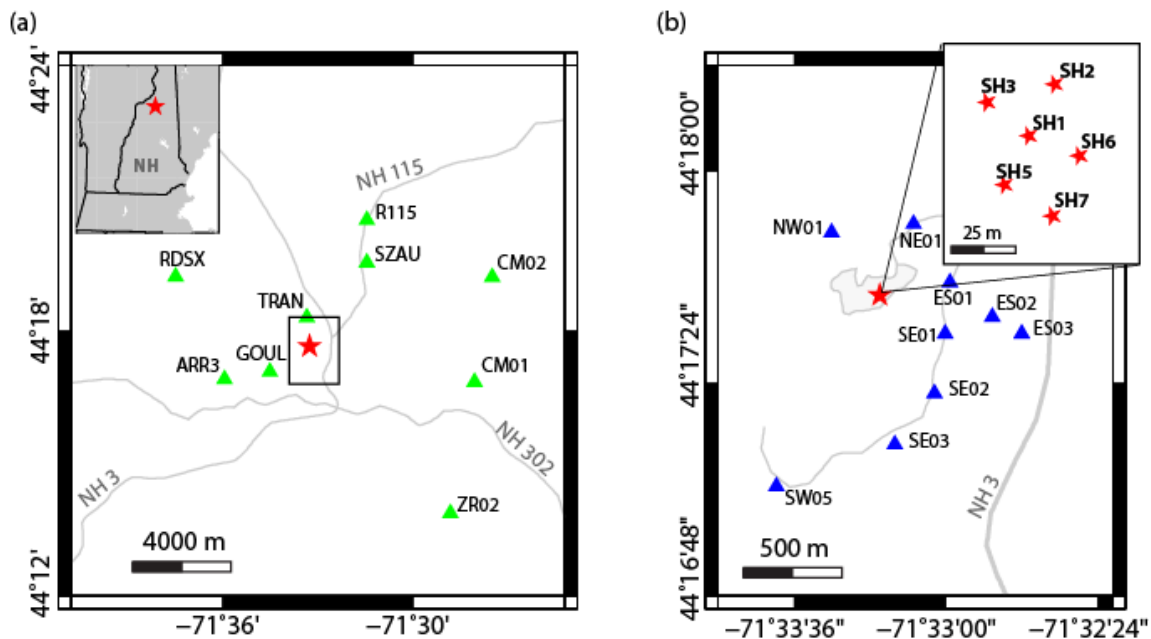


Figure 51. (a) Seismic stations deployed at local distances from the explosions near Carroll, New Hampshire (USA). The green triangles show the local stations used for the moment tensor studies, the star shows the location of the test bed. The insert in the upper left shows the map of New England with the experiment location marked as a red star. The rectangular area surrounding the experiment site is enlarged in 1b. (b) The near-source short-period seismometers located in the quarry and used in this study are shown with blue triangles. The insert in the upper right shows the enlarged view of the test bed. The shot locations are shown with red stars.

To compare the performance of aluminized and non-aluminized explosives, equal weight TNT and Tritonal charges were detonated in drained boreholes (SH1 and SH2 respectively). Shots SH1 and SH3 were conducted using identical TNT charges, however SH1 was detonated in a dry borehole, while SH3 was placed into a water-filled borehole. Both TNT charges had assembled lengths of 1.25 m, while the Tritonal charge had a length of 1.19 m. All TNT and Tritonal charges measured 20.3 cm in diameter. Thus the emplacement geometry for the TNT/Tritonal explosion series was very similar. In addition, a pair of aluminized and non-aluminized ANFO shots of equal weights was detonated in

dry boreholes (SH5 and SH6 respectively). The charges were loaded into the hole liners placed directly into the boreholes. The lengths of both SH5 and SH6 charges were approximately 2.1 m. For the last shot (SH7), the borehole wall was narrowed to less than 20 cm, due to the ground shock from previous shots. As a result, we were unable to use the charge with a 20 cm diameter and the SH7 charge was composed of two segments with diameters of 15 cm and 16.25 cm. The total length of the charge was approximately 4 m, compared to the length of the ANFO charge (SH5) of approximately 2.1 m. All explosions were conducted in boreholes approximately 25 cm in diameter, which were stemmed with crushed stone after loading the charges. The depths to the top and bottom of each charge are shown in Table 14.

The explosions were recorded using a 45-station seismic network fielded from near-source to local distances (between 1.5 m and 10 km). Eighteen of the short-period stations located at distances between 0.37 and 9.14 km were used for the moment tensor inversion. Table 13 shows the relevant information about these stations.

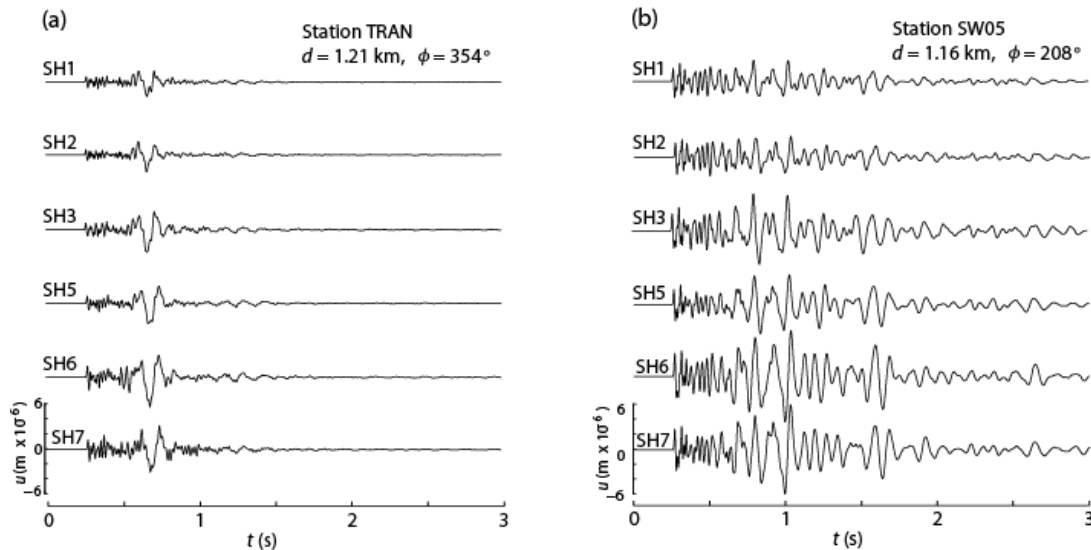


Figure 52. Vertical component displacement seismograms recorded by (a) Station TRAN located at a distance of 1.21 km from the test bed and (b) Station SW05 located at a range of 1.15 km from the test bed. All traces are plotted to the same vertical scale.

The area surrounding the test bed has rugged topography and heterogeneous subsurface structure. Therefore, the details of the velocity structure for the area are poorly known. In addition, the coupling between the sensors and the rock vary between the stations, which may produce additional amplitude bias for individual stations. As a result, calculation of realistic Green's functions needed for the moment tensor estimate is problematic. An example of the waveform variability is shown in Figure 52. Stations TRAN and SW05 are located at similar distances from the sources (1.21 km and 1.16 km respectively). The waveforms would have been similar if the velocity structure were laterally homogeneous. However, the seismic waveforms are very different between the two stations: waveforms from Station TRAN show lower *P*-wave amplitudes and a clear *R_g* arrival, while

waveforms from Station SW05 exhibit higher amplitudes and longer signal duration with scattered Rg due to the station's location in the valley alluvial sediments. Other stations also exhibit significant waveform complexities. Thus calculation of the Green's functions using a simple 1D velocity structure would produce a poor match to the data. On the other hand, developing a 3D velocity model on such small scale is simply unrealistic. Therefore, given the fact that several explosions were conducted close to one another, application of the RMTI method to this dataset is appropriate.

Table 13. Stations used for the synthetic moment tensor tests

Station	Station name	Distance (km)	Azimuth (°)	G_P	G_{Rg}	SNR^P	SNR^{Rg}
1	R115	5.83	24	0.08	1.37	18.7	232.6
2	NE01	0.42	25	1.75	-	224.5	-
3	SZAU	4.27	34	0.13	1.38	48.0	401.3
4	CM02	8.19	69	0.05		19.5	-
5	ES01	0.37	79	1.06	-	259.8	-
6	ES02	0.60	101	2.61	-	142.1	-
7	CM01	7.07	102	0.10		21.5	-
8	ES03	0.77	105	2.00	-	55.7	-
9	SE01	0.40	120	3.62	-	521.0	-
10	ZR02	9.14	140	0.04	0.25	15.0	70.7
11	SE02	0.58	151	2.85	-	322.0	-
12	SE03	0.78	174	3.13	-	304.5	-
13	SW05	1.14	209	0.93	-	190.5	-
14	GOUL	1.97	238	0.18	5.18	69.9	1493.5
15	ARR3	3.73	250	0.11	3.40	43.5	1059.1
16	RDSX	6.35	298	0.04	1.11	14.0	283.2
17	NW01	0.45	325	1.82	-	397.9	-
18	TRAN	1.23	355	0.39	20.2	137.7	4823.0

The data used for the inversion included P and Rg amplitudes measured from the band-pass filtered (1 – 10 Hz) waveforms. Figure 45 shows the waveforms from Station ARR3 band-pass filtered between 1 – 10 Hz (left panel) and 10 – 50 Hz (right panel). The amplitudes of the fundamental mode Rayleigh wave (Rg) are prominent in the 1 – 10 Hz pass band and practically absent in the 10 – 50 Hz band. Between 1 and 10 Hz P -wave amplitudes are significantly lower than the Rg amplitudes; however the SNR for the P waves is still high due to low noise level, as shown in Table 13.

Table 14. Explosion Information

Shot	Explosive type	Yield (kg TNTe)	Charge bottom (m)	Charge top (m)	Seismic M_0 , $10^{11} \times \text{N} \cdot \text{m}$	Fracture apertures (cm)	Water content
SH1	TNT	63.2	12.95	11.67	3.87	0.2 - 1	Dry
SH2	Tritonal	96.2	13.0	11.81	4.35	0.2 – 1.3	Dry
SH3	TNT	63.2	12.65	11.37	6.44	0.6 – 2.5	Saturated
SH5	ANFO/Al	63.1	12.70	10.6	5.39	-	Dry
SH6	ANFO	94.1	12.65	10.52	8.44	0.6 – 3	Dry
SH7	ANFO	60.9	12.5	8.23	5.93	0.8 – 4.8	Saturated

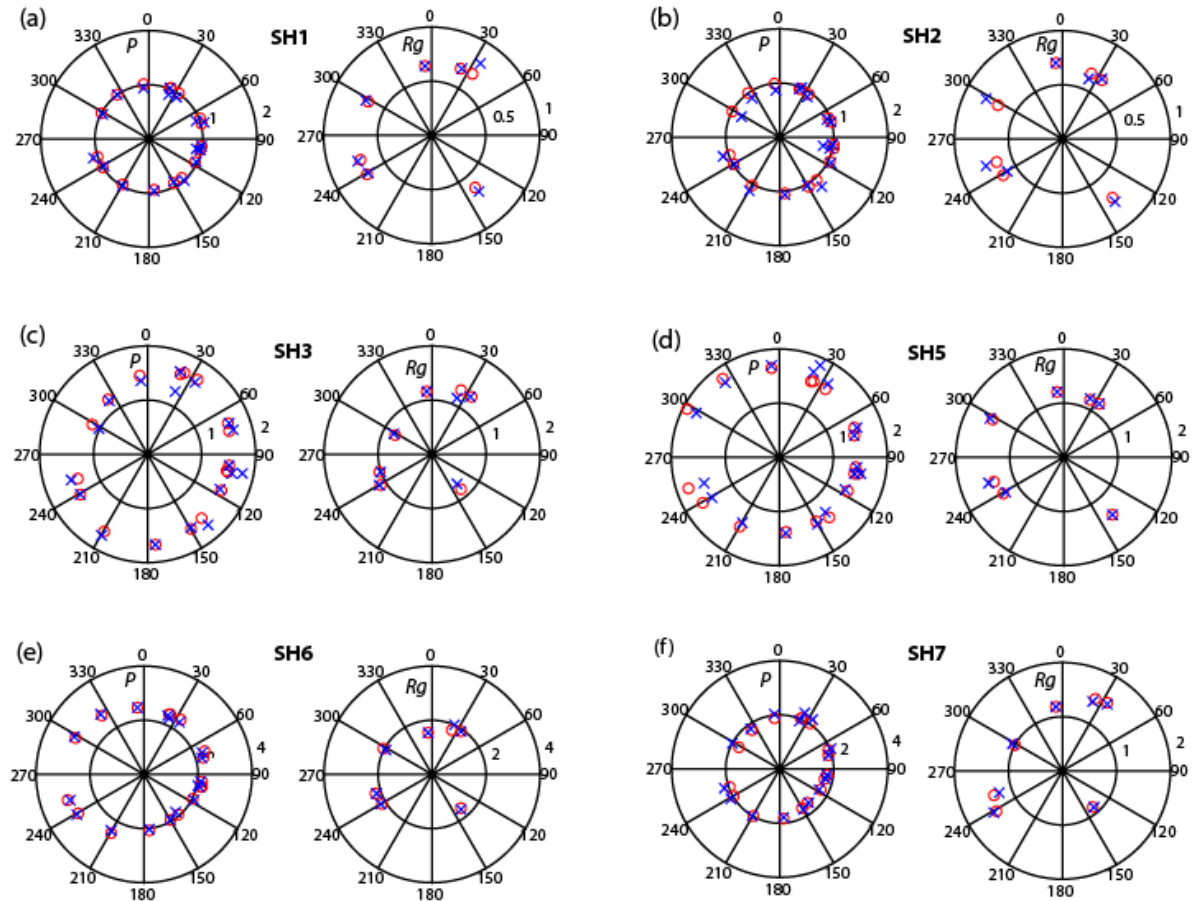


Figure 53. Comparison between the observed P (left plots) and R_g (right plots) amplitudes (blue crosses) and the estimated using RMTI (red circles) for the shots: (a) SH1, (b) SH2; (c) SH3, (d) SH5, (e) SH6 and (f) SH7. Note that the observed amplitudes were divided by the corresponding propagation terms G_P and G_{R_g} in order to match with the calculated values. Both P and R_g amplitudes of the waveforms filtered in the frequency band 1 – 10 Hz were used to perform the inversion.

P-wave amplitudes were picked from the first positive peaks because this phase is the least affected by the interactions with the medium. The first motion polarities were positive for all stations. *Rg* amplitudes were measured as the maximum of the envelopes in the *Rg* window. *Rg* phases were only selected from the stations with distances greater than 1 km showing prominent dispersive arrivals. Because of the strongly heterogeneous medium and uneven topography in the area, some of the stations were missing *Rg* phases, while at other stations it was obscured by the scattered arrivals or the basin oscillations. Thus, only 7 stations had usable *Rg* phases.

The RMTI was constrained by using SH1 or SH2 sources as reference mechanisms. At the first stage of the inversion, the reference moment tensors were set to purely isotropic mechanisms. The reason for choosing these two events is because SH1 and SH2 were detonated using high-velocity explosives (TNT and Tritonal respectively) in dry boreholes. Past studies (e.g. Stroujkova et al, 2012; Stroujkova et al, 2015) show that explosives with high velocity of detonation and low gas content (e.g. TNT) tend to produce a higher percentage of isotropic component. The increase in the non-isotropic component is attributed to more extensive fracturing generated by low-velocity high-gas explosives (e.g. ANFO). In our case, the higher intensity of explosion-generated fracturing for Shots SH3, SH6 and SH7 was verified by performing post-detonation drilling and well logging. Explosions detonated using low-velocity ANFO (SH6 and SH7), as well as one of the TNT shots in a water-filled borehole (SH3), produced more extensive fractures with larger apertures.

Figure 33 shows the amplitude ratios between different pairs of explosions. *P*-wave ratios between SH1 and SH2 are very similar and close to 1 at all azimuths. The ratios for other explosions show systematic azimuthal variations. Thus, these two explosions appear to have the smallest non-isotropic components among the events of the set. This is why the use of the TNT and Tritonal shots as the reference was justified.

Figure 53 shows the inversion results using SH1 as a reference mechanism. Each panel shows the comparison between the measured and estimated amplitudes for both *P* and *Rg* phases. To perform the inversion, either SH1 or SH2 was set to purely isotropic ($M_{xx} = M_{yy} = M_{zz} = 1$, $M_{xy} = M_{xz} = M_{yz} = 0$). With the exception of a few outliers, the observed and estimated amplitudes agree and the errors are under 20%. The moment tensor components and the scalar moments (M_0) are presented in Table 15. The diagonal MT components are within 10% between the two cases. The off-diagonal components, however, have greater variations. Using SH2 as a reference results in higher off-diagonal components.

A Hudson diagram and the deviatoric moment tensor solutions are shown in Figure 54. The results obtained by using SH1 and SH2 as references are shown in Figure 54b to compare the sensitivity of the solution to a choice of the reference event. Using SH2 as a reference results in higher percentage of deviatoric components than using SH1.

Table 15. Moment tensors for the explosions from Table 14 calculated using SH1 and SH2 events as reference events

Shot	SH1 used as a reference							SH2 used as a reference						
	M_0^*	M_{xx}	M_{yy}	M_{zz}	M_{xy}	M_{xz}	M_{yz}	M_0^*	M_{xx}	M_{yy}	M_{zz}	M_{xy}	M_{xz}	M_{yz}
SH1	1.00	1.00	1.00	1.00	0.00	0.00	0.00	1.01	0.98	0.95	1.09	0.10	0.11	0.00
SH2	1.00	1.02	1.03	0.94	-0.12	-0.11	0.00	0.99	1.00	0.99	1.02	-0.03	0.00	0.00
SH3	1.51	1.16	0.86	0.98	0.11	-0.10	0.10	1.50	1.13	0.80	1.06	0.23	0.02	0.13
SH5	1.64	1.03	1.14	0.82	-0.09	0.05	-0.10	1.67	1.00	1.08	0.92	0.02	0.14	-0.11
SH6	2.50	0.96	1.14	0.90	0.04	0.04	-0.14	2.52	0.94	1.08	0.99	0.16	0.14	-0.13
SH7	1.86	1.04	0.93	1.03	0.14	-0.01	-0.02	1.86	1.02	0.87	1.11	0.25	0.10	0.01

* The scalar moments are calculated with respect to the reference events.

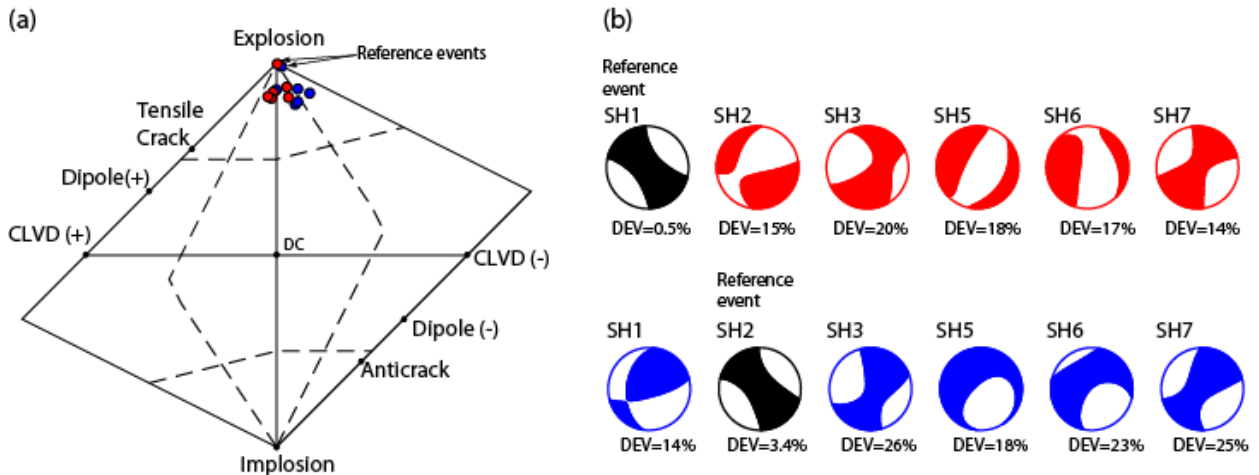


Figure 54. (a) Hudson diagram showing the focal mechanisms obtained by using events SH1 (red circles) and SH2 (blue circles) as a reference. (b) Deviatoric moment tensors for SH1, SH2, SH3, SH5, SH6 and SH7 using events SH1 (upper panel) and SH2 (lower panel) as a reference. The reference mechanisms are shown in black.

To evaluate the effect of the bias in the reference mechanism, a numerical experiment was performed, where the reference moment tensor used for the inversion $\mathbf{M}^{ref}$ was different from the moment tensor $\mathbf{M}^0$ used to calculate the forward problem ($M_{xx}^0 = M_{yy}^0 = M_{zz}^0 =$

1, $M_{xy}^0 = M_{xz}^0 = M_{yz}^0 = 0$). Figure 55a shows the results of the inversion using Set B (explosion-like events) with added noise derived from the observational data (using SNR data from Table 13, columns 7 and 8). The vertical dipole of the reference moment tensor (M_{zz}^{ref}) varied between 0.5 and 2.5, while the horizontal dipoles remained the same as in $\mathbf{M}^0$ ($M_{xx}^{ref} = M_{yy}^{ref} = 1$). The RMS error calculated in each case is shown in Figure 8a. Notice that the RMS error reaches the minimum at the correct value of $M_{zz}^{min} = 1$.

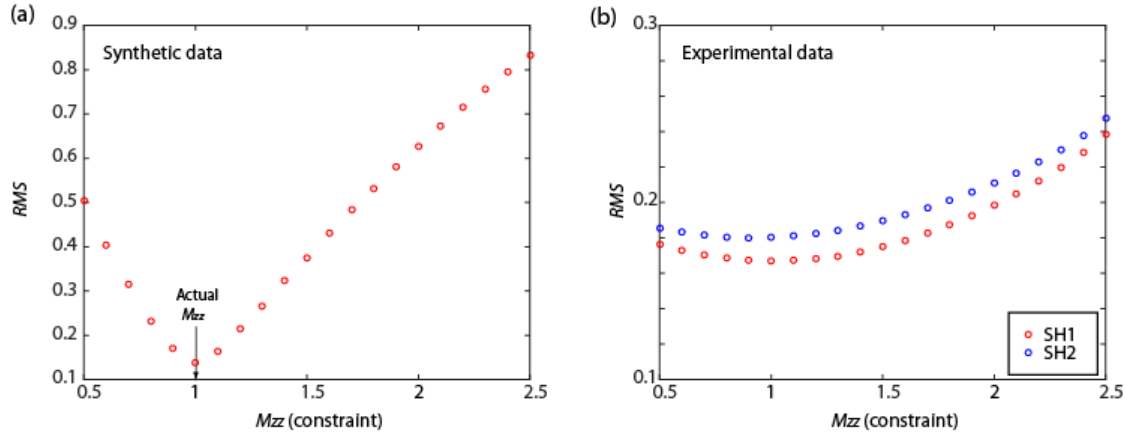


Figure 55. (a) RMS error of the inversion calculated using the reference event with perturbed M_{zz} component plotted as a function of M_{zz} . The event used for the forward problem calculation was a pure explosion with $M_{xx} = M_{yy} = M_{zz} = 1$. (b) The inversion RMS using the experimental data for the six explosions with different choice of reference events: SH1 (red circles) and SH2 (blue circles).

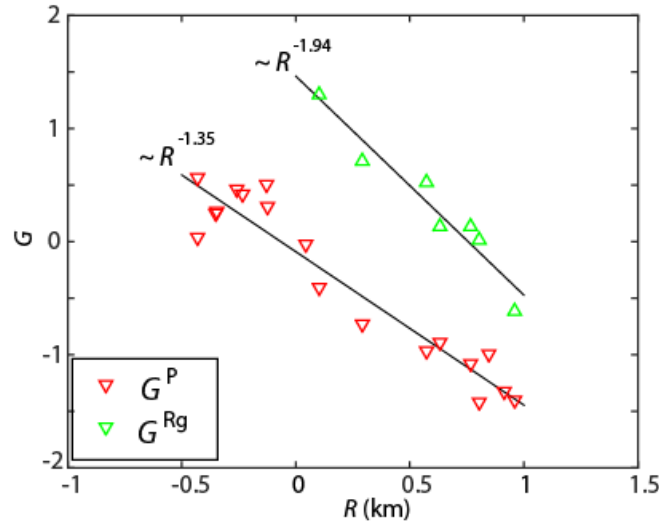


Figure 56. Calculated propagation terms (Green's functions) for each station plotted as a function of the distance from the source array. Red inverted triangles show the Green's functions for P, while the green inverted triangles correspond to Rg. Linear regression lines are also shown.

Figure 55b shows a similar plot corresponding to the experimental data. For this experiment, 5 of the moment tensor components of the reference events SH1 and SH2 were set to $M_{xx}^{ref} = M_{yy}^{ref} = 1$, $M_{xy}^{ref} = M_{xz}^{ref} = M_{yz}^{ref} = 0$, while the strength of the vertical dipole M_{zz}^{ref} varied between 0.5 and 2.5. The minimum in this case is reached at approximately $M_{zz}^{ref} = 1$ when SH1 was used as a reference, and $M_{zz}^{ref} = 0.9$ when SH2 is used as a reference. The absolute minimum of the RMS error is reached when SH1 used as a reference mechanism is set to isotropic. Also notice that according to Table 15, the horizontal diagonal MT components of SH2 calculated using SH1 as a reference are nearly equal ($M_{xx}^{inv} \approx 1.02$, $M_{yy}^{inv} \approx 1.03$), while the vertical component is approximately 8% lower ($M_{zz}^{inv} \approx 0.94$). According to Figure 55b, if SH2 is used as a reference the minimum of the RMS is reached when $M_{zz} = 0.9$. Therefore, it appears SH2 has a consistently lower M_{zz} component than SH1, while SH1 is consistent with having approximately isotropic mechanism ($M_{xx} \approx M_{yy} \approx M_{zz} \approx 1$). While this is not a rigorous proof, this example demonstrates that the uncertainties in the reference mechanisms can be mitigated by performing a grid search over the possible values of the parameters to find the minimum of the variance.

It is important to point out that the resulting moment tensors show no evidence of the vertical dipole (M_{zz}) being larger than the horizontal dipoles (M_{xx} and M_{yy}). Patton and Taylor (2008) proposed an explosion model, which explains weaker surface waves by a superposition of an isotropic component and a vertical CLVD. The additional CLVD source is attributed to a shock-induced extensional deformation along the vertical axis accompanied by medium damage. Our results, however, suggest that the vertical dipoles have approximately the same sizes as the horizontal dipoles.

The empirical propagation terms obtained using Equation 41 are plotted in Figure 56 as a function of distance between the source array and the stations (R). The propagation terms incorporate the effects of the geometrical spreading, reflection/refraction, scattering and attenuation. The P wave propagation terms decrease with distance approximately as $R^{-1.35}$, while the Rg phases show faster decay with $R^{-1.94}$. Rapid surface wave decay is likely due to strong near-surface scattering from topography and velocity perturbation. The exponents for P and Rg amplitude decay are not very sensitive to the choice of the reference mechanism (the P exponent changes between 1.31 and 1.35, while the Rg exponent varies between 1.94 and 2 when M_{zz} of the reference mechanism changes between 0.5 and 2.5).

8.5. Conclusions Regarding Relative Moment Tensor Inversion

We present the modified RMTI method formulated to include the amplitudes and polarity information for P waves and short period fundamental mode Rayleigh waves (Rg) for a cluster of events located within one wavelength from each other. This demonstrates the potential utilization of the method beyond earthquake sequences. The method also produces the Green's functions in the arbitrary frequency range as a by-product. These

Green's functions can later be used to create a library for future identification and classification of the events.

The method's performance is tested on synthetic data and applied to the small chemical explosion dataset (Stroujkova et al, 2017). The results of the synthetic testing have shown that the resolution of the different MT components depends on the SNR. It is shown that adding the surface wave information significantly improves the method's performance in the presence of noise. However, the uncertainties in the reference mechanism can propagate into the solution and influence the results for the entire dataset. To mitigate the effects of the errors in the reference mechanisms, it is possible to perform a grid search over the possible values of moment tensor components for the reference event. For instance, it was shown in the synthetic example that the minimum of the variance in the solution corresponds to the correct value of the reference mechanism.

The RMTI method was applied to a small chemical explosion dataset using one of the two events of the dataset (SH1 or SH2) as a reference mechanism. Using SH1 as a reference resulted in lower RMS error and lower deviatoric components that vary between 14 and 20% for the non-reference events. A grid search minimization of the residuals over the range of the possible values of M_{zz} shows that the vertical dipoles have comparable strengths to the horizontal dipoles. This result suggests that the potential effect of the rock damage on the focal mechanism expressed as a significant CLVD component, proposed by Patton and Taylor (2008), may not be pronounced for small fully contained explosions in hard rock.

9. OVERALL CONCLUSIONS AND FUTURE WORK

The active source explosion experiment (GAS2016) was conducted in New Hampshire in August, 2016. The purpose of the experiment was to study the seismic signatures of the explosion sources using different explosive types, including TNT, Tritonal, ANFO and aluminized ANFO in both dry and water-saturated emplacement media. In addition we performed post-explosion well logging study of the shot boreholes and analyzed the damage and its relation to the seismic radiation. To the best of our knowledge, this is the first seismic field experiment of this kind. Seismic and well log data from GAS2016 experiment can be used for future explosion source studies, explosion monitoring, seismic event detection, discrimination and yield estimation.

The analysis of the seismic data demonstrated that the amount of explosive gas and/or water present in the cavity during or after the detonation improves seismic coupling and results in higher seismic amplitudes, particularly in the low-frequency range. Post-shot well logging study have shown that the amount of gas or water during the detonation results in an increase in the length and aperture of the fractures produced by the explosions. No correlation between the cavity size and the seismic amplitudes, predicted by the classical explosion source theory, has been demonstrated. Thus, the amplitude increase is likely related to the rock damage rather than the increase in the static moment during the initial shock wave passage.

The important part of the data analysis involved a study of the seismic radiation pattern. The results of the radiation pattern analysis shows a nearly constant ratio of 1 for SH2 with respect to SH1 (Tritonal vs TNT shots), and azimuthally dependent ratios for the other events relative to SH1. The radiation patterns are different between the signals band-passed in a low frequency range (1–15 Hz) and a high frequency range (15–100 Hz). For four out of five explosions, the radiation pattern is consistent with shear failure along the natural fracture set observed in the televiewer. Shear failure along the vertical borehole-parallel fractures can also be responsible for the observed radiation pattern.

As a part of this project, a relative moment tensor inversion (RMTI) applicable to shallow events and incorporating both P and short period surface waves (Rg) was developed and tested using the data from GAS2016 experiment. It was shown that adding the surface wave amplitudes significantly improves the method's performance in the presence of noise. The proposed implementation of the RMTI also produces the Green's functions in the arbitrary frequency range as a by-product. These Green's functions can later be used to create a library for future identification and classification of the events. A grid search minimization of the residuals over the range of the possible values of M_{zz} shows that the vertical dipoles have comparable strengths to the horizontal dipoles. Thus, our results indicate that the increase in CLVD component proposed by Patton and Taylor (2008, 2011) is not a significant factor for the small overburied explosions in hard rock described in this report. This result may not be applicable for the explosions conducted with normal DOB in different rock types. Future work includes incorporating shear waves from shallow events into the RMTI, as well as evaluating various weighting schemes and constraint application.

In addition, we explored use of the multivariate analysis (principal component analysis) for explosion discrimination. In this study, the PCA approach using the extracted phase amplitudes show similar results to the full waveform approach for the low-noise traces with low scattering and high amplitude seismic phases. The PCA using phase amplitudes performs poorly in cases where the phase identification is ambiguous due to propagation effects (e.g. scattering, basin amplification) or low SNR. However, PCA using extracted trace attributes can be expanded to include traces with low correlation coefficients between the traces, in which cases the full waveform correlation analysis fails. Future directions include incorporation of the multivariate analysis into machine learning techniques for improved event identification.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AFWA	Air Force Weather Agency
ATV	Acoustic Televiewer
ANFO	Ammonium Nitrate and Fuel Oil
BKW	Becker-Kistiakowski-Wilson
CLVD	Compensated Linear Vector Dipole
COMP B	Composition B
EOS	Equation of State
IRIS	Incorporated Research Institutions for Seismology
MT	Moment Tensor
OSI	On-Site Inspection
OTV	Optical Televiewer
PASSCAL	Program for the Array Seismic Studies of the Continental Lithosphere
PCA	Principal Component Analysis
RDP	Reduced Displacement Potential
RMTI	Relative Moment Tensor Inversion
SNR	Signal-to-Noise Ratio
TNT	Trinitrotoluene
VOD	Velocity of Detonation
WGC	Weston Geophysical Corp.

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