Source Analysis of Underground Chemical Explosions from the Source Physics Experiment
Andrea Chiang¹, Arben Pitarka and Sean Ford

The project is a long-term NNSA research and development effort to improve U.S. nuclear nonproliferation verification and monitoring capabilities, including detection, identification and yield determination of small nuclear tests. The goal of SPE is to advance our understanding of source phenomenology, near-field wave propagation, coupling of energy into the seismic wavefield and the generation of shear waves (Snelson et al., 2013). A comprehensive study of explosion-related physical processes is crucial to replacing semi-empirical models with physics-based numerical techniques. The SPE Phase I series was conducted in a hard rock geologic formation close to past underground nuclear tests (Fig. 1).

Here we employ a technique called moment tensor inversion to determine the explosion source mechanism by modeling seismic waves recorded at various locations around the explosion. One important aspect to consider in MT inversion is accounting for how seismic waves travel between the source and receivers, this can be achieved by having an Earth model that describes the subsurface structure (velocity, density and attenuation) in the region of interest.

Methodology

Several physical mechanisms have been proposed to explain the generation of S-waves from underground explosions, such as asymmetries in the source, release of tectonic pre-stress, interactions with the free-surface, and heterogeneities in the Earth (Fig. 2). An accurate description of the explosion source processes is an important step towards understanding which of these plausible mechanisms are actively contributing to the generation of S-waves and under what conditions. In this study we investigate the sensitivity of far-field waveforms to seismic source mechanisms by comparing simulated and recorded data from the SPE Phase I series.

Table 1. SPE Phase I Series Source Parameters.

<table>
<thead>
<tr>
<th>SHOT</th>
<th>YIELD (kg)</th>
<th>DEPTH (m)</th>
<th>dOR (m/s/°/T3)</th>
<th>MODEL</th>
<th>DC</th>
<th>CLVD</th>
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<tr>
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For this study we tested three velocity models:

(1) 1D: a simple layer over half-space 1D velocity model constructed from modeling local Rg dispersion.
(2) GFM-S1: a 3D geologic background model based on geological and geophysical data.
(3) GFM-TS: a high-resolution 3D tomographic model calculated using seismic interferometry.

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Figure 1. Map and Cross-Section of SPE Phase I series and Geophone Network.
(a) Because we focus on analyzing far-field seismic recordings only the geophone network is displayed. (b) Illustration of the six shots from Phase I labeled by depth and size of the explosion.

Figure 2. Explosion Source Phenomenology (H. Patton, LANL)

The moment tensor (MT) is a mathematical representation of rupture processes in the Earth. It is routinely used in earthquake monitoring to determine the movement on a fault during an earthquake. The full tensor is comprised of nine generalized force couples that can be used to describe and distinguish various seismic source types including explosions.

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Figure 3. 3D Shear Wave Velocities.
Map of the shot location and station configuration where the background colors represent the shear wave velocities from (a) GFM-S1 and (b) GFM-TS. SPE-6 shot location is denoted by a star.

Table 2. Moment Tensor Solutions.

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Table 6. Focal Mechanisms.
SPE-4P and SPE-5 focal mechanisms from Table 1. The non-volumetric component varies quite a bit between velocity models. Station azimuths and seismic moments are labeled as triangles around and below the focal mechanism.

Figure 4. SPE-4P Data and Synthetics.
Data are in black, 1D synthetics are in cyan, GFM-S1 synthetics are in purple, and GFM-TS synthetics are in pink. Station distance, azimuth and maximum absolute amplitude are plotted above the vertical component, and VR are plotted next to the vertical traces.

Figure 5. SPE-5 Data and Synthetics.

Solutions for the two deepest shots (SPE-4P and SPE-5) have the best fits to data, shots at less than 50 m have relatively poor fits. Fits to SPE-6 increases when waveforms shorter than 3 Hz are used.

Overall the 1D and GFM-S1 models have better fits to the data, GFM-TS is not fitting some of the radial components hence lowering the VR.

None of the models were able to fit the tangential components very well or stations along lines 3 and 4, where strong scattering are observed. Models with better resolution at depth are needed to improve fits to the far-field geophone data.

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Lawrence Livermore National Laboratory

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