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3D Moment Tensor Inversion of Underground Chemical Explosions from the Source Physics Experiments

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Abstract

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, spall, and heterogeneities in the Earth. 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 explore the application of the seismic moment tensor source to model far-field, low frequency (up to 6 Hz) waveform data of over-buried chemical explosions from the Source Physics Experiment, with a focus on S-wave generation and amplitude predictions. We use an inverse waveform modeling approach to estimate the source properties of the chemical explosions, and compare solutions using different velocity models. 1D and 3D subsurface velocity models are used to characterize wave propagation between the source and receiver. We also performed analysis on wavefield simulations from physic-based explosion source modeling. The analyses show scattering and phase conversion from 3D heterogonies dominate the generation of far-field, S-wave energy observed in data, and that the variability in the recovered deviatoric component of the moment tensor source model are largely a result of inadequately accounting for 3D wave propagation effects in the inversion process.

Introduction

The development and validation of physics-based explosion source models is necessary to improve our ability to predict seismic amplitudes from explosions. One key component to predicting explosion amplitudes is the knowledge of mechanisms that are actively contributing to the generation of S-waves and under what conditions. 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, spall, and heterogeneities in the Earth (e.g. Wallace et al., 1985; Johnson and Sammis, 2001; Patton et al. 2005; Vorobiev et al. 2015). To address these questions the Source Physics Experiment (SPE) was conducted in a hard rock geologic formation close to past underground nuclear tests. The experiment 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 1993 Non-Proliferation Experiment (NPE) showed that chemical explosions can be used as a proxy for seismic signals from nuclear explosions because they produce similar seismic observables except with an overall amplitude scaling factor (Denny et al., 1994). The goals of SPE are to advance current 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.

In this study we explore the application of the moment tensor (MT) source to model far-field (at distances within a few kilometers) seismic data from over-buried chemical explosions, particularly on S-wave amplitude predictions, what are the recovered source properties (e.g. moment, off-diagonal components of the tensor) and how they relate to depth of burial and subsurface velocity structure. All of these questions are relevant to MT-based methods for event discrimination and identification.

Research Accomplished

Waveform inversion to determine the seismic MT is a well-established method for determining the source properties of natural and anthropogenic seismicity, and can identify, or discriminate different types of seismic sources. The technique has been applied to underground explosions and other anthropogenic events, as well as earthquakes from geothermal (Guilhem et al., 2014) and volcanic environments (Shuler et al., 2013) and events induced by oil and gas operations (McNamara et al., 2015). MT analysis were done on SPE velocity data recorded along the five linear geophone arrays centered around the shot point. A few additional high-gain sensors were included in 1D MT inversions but not 3D because these stations are located outside the 3D Earth model domain.

3D Moment Tensor Inversion

Based on the representation theorem (Aki and Richards, 2002), velocities or displacements in the n direction (e.g. transverse, radial and vertical) is expressed as a linear convolution of the seismic MT and the spatial derivatives of the elastic Green's functions, assuming a point source approximation:

$$u_n(t,\vec{x}) = M_{ij} * G_{ni,j}(\vec{x},t)$$

i and j are the directions of the forces and derivatives (force couples).

The seismic MT is a 3 by 3 symmetric tensor where the nine generalized force couples can describe seismic sources including earthquakes, explosions, collapse, and volcanic eruptions. G is the impulse response of the medium at the receiver along the direction x,y and z. We use WPP (Wave Propagation Program) to calculate the Green's functions used in the 3D MT inversion. WPP is an elastic finite-difference code for seismic waveform modeling (Xu et al., 2014). WPP solves for the wave equation in Cartesian displacement formulation using a second order accurate numerical method (Nilsson et al., 2007). The code handles purely elastic calculations but also includes attenuation, topography, and arbitrary number of point force and/or moment tensor source. WPP was also used in subsequent physic-based far-field waveform simulations.

Because of the linear relation between the six elements of the symmetric MT and waveforms (u_n) the solution can be obtained using a least-squares formulation that minimizes the misfit between observation and synthetics. Mathematically the inversion can be done by directly using the six single components of the MT; however we follow the approach of Kikuchi and Kanamori (1991) and parameterize the MT as a linear combination of six elementary MTs (M^m), also known as Green's functions (GFs):

$$M_{ij} = \sum_{m=1}^{6} a_m M^m$$

$$M^1 = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad M^2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad M^3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$M^4 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad M^5 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad M^6 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and from the a_m coefficients we can obtain the full moment tensor M:

$$M_{ij} = \begin{bmatrix} a_2 - a_5 - a_6 & a_1 & a_4 \\ a_1 & -a_2 + a_6 & a_3 \\ a_4 & a_3 & a_5 + a_6 \end{bmatrix}$$

The advantage of using the elementary MT system over the single MT component is that the subgroups of this system have specific solutions that have direct physical meaning in their source mechanisms, such that we can parameterize the linear inversion into solving the generalized complete moment tensor that includes volumetric components using $M^{1\text{-}6}$ or a purely deviatoric moment tensor using $M^{1\text{-}5}$ (the five double-couple tensors) to estimate earthquake source parameters. 1D MT inversions follow the same approach as 3D except that GFs are defined following the Minson and Dreger (2008) formulation and calculated using frequency-wavenumber integration (e.g. Wang and Herrmann,1980; Herrmann, 2012).

Subsurface Velocity Structure

Subsurface velocity models are needed to simulate explosion wavefields and calculate the GFs for MT inversion. The reliability and robustness of the calculated source parameters are strongly dependent on our confidence in the detailed subsurface velocity structure.

The 1D model is based on granite properties and has a thin low velocity layer that represents the approximately 10 to 25 meter-thick highly fractured and weathered granite horizon observed in SPE geological and borehole data (Townsend et al., 2012). The 3D model, also known as the Geological Framework Model (GFM) is based on seismological (Pitarka et al., 2015), geological (Wagoner, 2014), and geophysical observations (Townsend et al., 2012). The top 200-m is a high-resolution 3D tomographic model developed using seismic interferometry (Matzel et al, 2016). Three techniques including ambient noise correlation (Hennino et al., 2001; Lobkis anf Weaver, 2001), shot interferometry, and coda wave interferometry (Campillo and Paul, 2003) were used to compute Green's function between seismometers and between the shots and seismometers. Each technique has its advantages over the other (e.g. frequency content, coverage, etc.) and collectively the three techniques give thousands of seismograms that cover the SPE site with the highest path densities along the five geophone lines. Similar to the 1D model a low velocity layer in the upper 30-m or so is observed in the 3D model but with more detailed structures laterally. At depth the 3D model transitions from tomography into a geological model that consists of Quaternary alluvium, Tertiary volcanic rocks, and Paleozoic sedimentary basement rocks with compressional wavespeeds from borehole data collected from the SPE site and various locations in Yucca Flat. We used the empirical relationships of Brocher (2005) to calculate shear wavespeeds and densities.

Results

The MT source model that fits most of the SPE Phase I series from both 1D and 3D inversions is a major ISO (explosion) source plus a minor deviatoric component (Figure 1). In general the deviatoric component can be decomposed into a combination of normal faulting and compensated-linear-vector-dipole (CLVD) with the major vector dipole in tension, and the strength of the deviatoric component is about 30% of the total seismic moment. The two instances that differ from this MT source model are SPE-5 and SPE-6 1D MT solutions. The variability in the deviatoric component from 1D MT is a result of fitting mostly radial and vertical components but not accurately predicting the transverse component. SPE data have substantial transverse motions sometimes with amplitudes comparable to the radial and vertical components. In the case where the 1D MT is fitting the transverse components (SPE-6) the solution becomes predominantly CLVD, which is inconsistent with most other solutions in this study. The reduction of variability in the deviatoric component and improvement in predicting transverse motion from 1D to 3D MT suggests the 3D Earth model is a better representation of the subsurface velocity structure, where uncertainties in source properties due to wave propagation effects are reduced. The 3D MTs also increase fits to waveforms along L3 and L4 where the arrays extend into alluvium deposits, and are not well-represented by the 1D granite model.

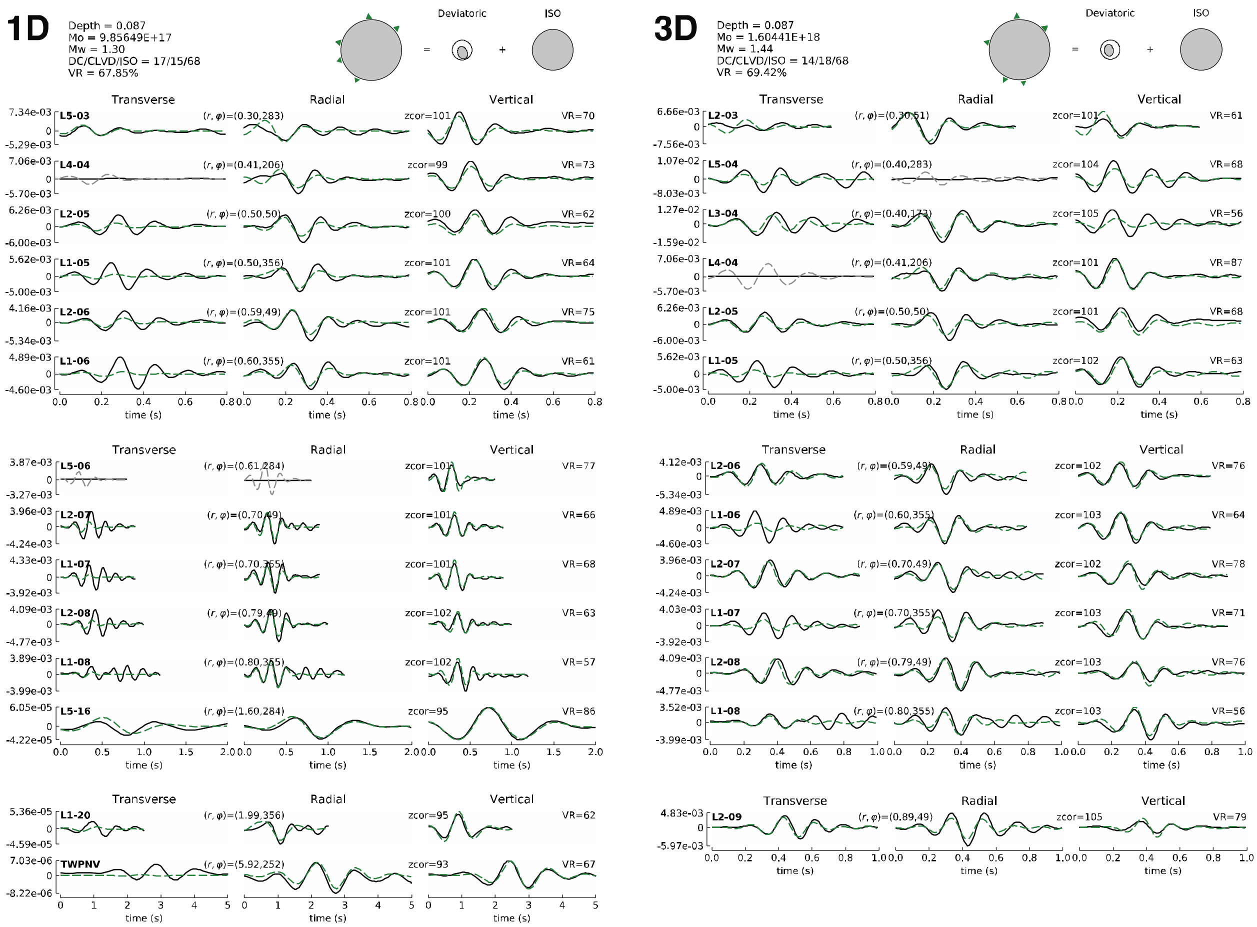

Figure 1. 1D and 3D moment tensor analysis of SPE-4P. The full moment tensor mechanism (lower hemisphere projection) are shown along with the deviatoric and isotropic (ISO) components. The diameter of the mechanism is related to its relative moment and the triangles around the circumference show the azimuthal coverage. Plotted below are data (solid black) compared with synthetics (dashed) predicted by the full mechanism filtered between 0.4 to 6 Hz. Gray dashed lines are predicted synthetics not included in the inversion. The station name, distance (*r*), azimuth (*φ*), time shifts (ZCOR, in number of points) and variance reduction (VR) are also shown for each station.

Table 1 and Figure 2 summarize the SPE Phase I source parameters from 1D and 3D MT analysis. The seismic moment predicted by 1D MT are consistently smaller compare to that of the 3D due to minimal transverse energy predicted by the 1D mechanism. Generally, there is an improvement in the overall fits to the data in amplitude and phase (represented by the variance reduction, VR) from 1D to 3D, though it is not necessarily a one-to-one comparison since different stations were included in the 1D and 3D MT analysis. Instead of using a fixed set of stations for all MT analysis we selected stations to maximize distance and azimuthal coverage for each analysis to obtain a well-constrained mechanism. The relative strength of the MT components is similar with respect to scaled depth of burial (sDOB) and depth of burial (DOB), and the anomalous solution of SPE-6 1D MT solution is more likely caused by errors in the velocity model and not necessarily the emplacement conditions. When we examine the individual MT elements we observe the Mzz component contributes to most of the variability seen in Figure 2.

Table 1. SPE Phase I near source parameters and predicted seismic moment from full moment tensor analysis.

SHOT	YIELD (kg)	DEPTH (m)	sDOB ($m/kt^{1/3}$)	MODEL	Mo	Mw	VR (%)
SPE-1	90	55.1	976	1D	9.82231e17	1.29	51
				3D	1.59675e18	1.44	64
SPE-2	997	45.7	363	1D	1.51328e19	2.09	54
				3D	2.22615e19	2.20	58
SPE-3	905	47.2	387	1D	1.67337e19	2.12	57
				3D	2.45958e19	2.23	62
SPE-4P	89	87.2	1550	1D	9.85649e17	1.30	68
				3D	1.60441e18	1.44	69
SPE-5	5035	76.5	354	1D	6.00195e19	2.49	54
				3D	9.21861e19	2.61	53
SPE-6	2245	31.4	190	1D	2.12538e19	2.18	56
				3D	3.32300e19	2.31	55

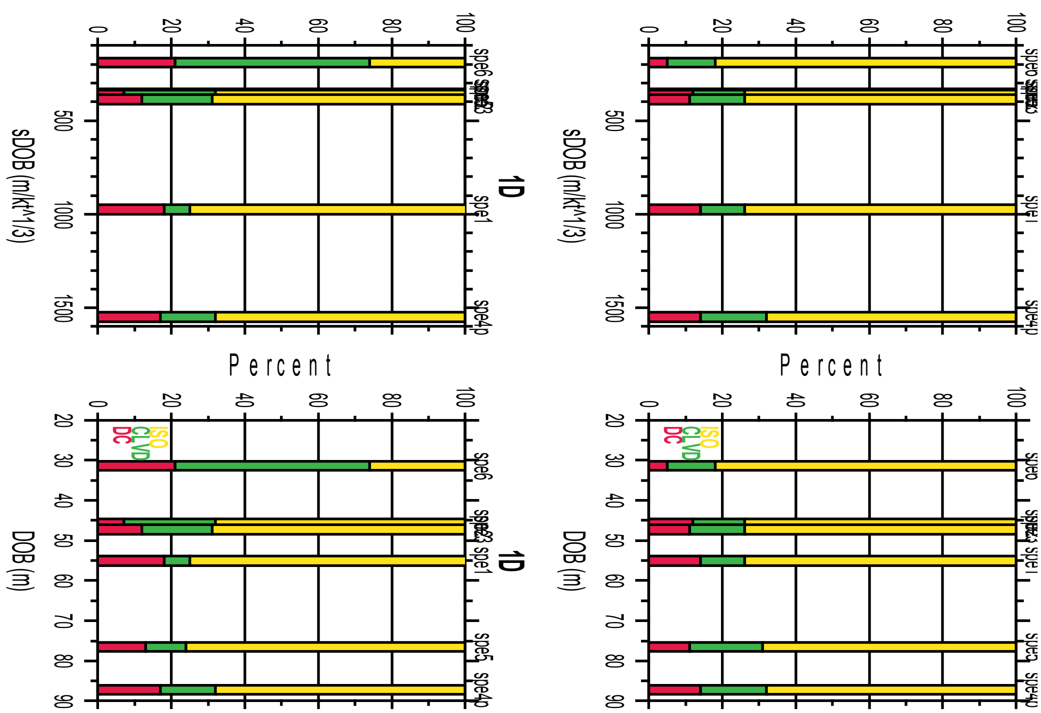

Figure 2. 1D and 3D full moment tensor decomposition of SPE Phase I chemical experiments as a function of scaled depth of burial (sDOB) and depth of burial (DOB). The height of the vertical color bar relates to the relative strength of the isotropic (ISO, yellow), compensated-linear-vector-dipole (CLVD, green) and double-couple (DC, red) components.

Discussion

Forward Simulations from Hydrodynamic-to-Elastic Coupling

A major improvement in ground motion simulation capabilities for explosion monitoring during SPE Phase I is the development of a wave propagation solver that can propagate explosion generated non-linear near field ground motions to the far-field. The advancement in ground motion simulation capabilities gives us the opportunity to assess MT inversion of a realistic volumetric source with near-field effects in a controlled setting, where we can evaluate the recovered source properties as a function of modeling parameters and can provide insights into source properties of SPE Phase I chemical experiments and other historical nuclear explosions.

The forward simulation combines the hydrodynamic modeling of the seismic source with elastic modeling of wave propagation. The calculation is done using a hybrid modeling approach with a one-way hydrodynamic-to-elastic coupling in three dimensions where near-field motions are calculated using GEODYN-L, a Lagrangian hydrodynamics code (Vorobiev, 2010; Vorobiev, 2012), and then passed to WPP, as described previously.

The physics-based explosion source model used to simulate near-field, non-linear ground motions is a spherical explosion in a heavily jointed granite formation (Vorobiev et al., 2015; Vorobiev, 2017). The spatially varying joint and rock properties are inferred from experimental, geophysical and geological data collected as part of the SPE experiment (Townsend et al., 2012). The source region is characterized by a dominantly granitic outcrop and the resulting source model is developed through modeling near-field acceleration records from SPE Phase I, and multiple stochastic simulations were performed to capture the uncertainties resulted from the geological properties. Vorobiev et al. (2015) demonstrated that the movement along rock joints during explosion was the main mechanisms of shear wave generation in the near-field, however Pitarka et al. (2015) show that near-field source anisotropy and nonlinear effects combined with wave-scattering are needed to explain the observed far-field shear wave amplitudes and irregular radiation patterns.

SPE-4P, SPE-5 and SPE-6 physics-based source models were used in the coupled simulations. Similar to the MT analysis of actual SPE recordings, the preferred MT source model that fits the simulated data consists of a major ISO component and a minor deviatoric component (Figure 3, 3D/3D). The difference is that the deviatoric component is a CLVD mechanism with a vertically oriented vector dipole in tension and very little DC. In comparison to a pure ISO source, the additional CLVD improves the fits to the horizontals in terms of both phase and timing. There is a slight delay in phase arrival for a pure ISO model. Unlike S-wave generation in the near-field, most of the transverse energy seen in Figure 3 are due to 3D heterogeneities in the subsurface structure. If we propagate the same physics-based explosion volume source through a 1D Earth model less transverse energy is observed but the resulting MT source model is similar.

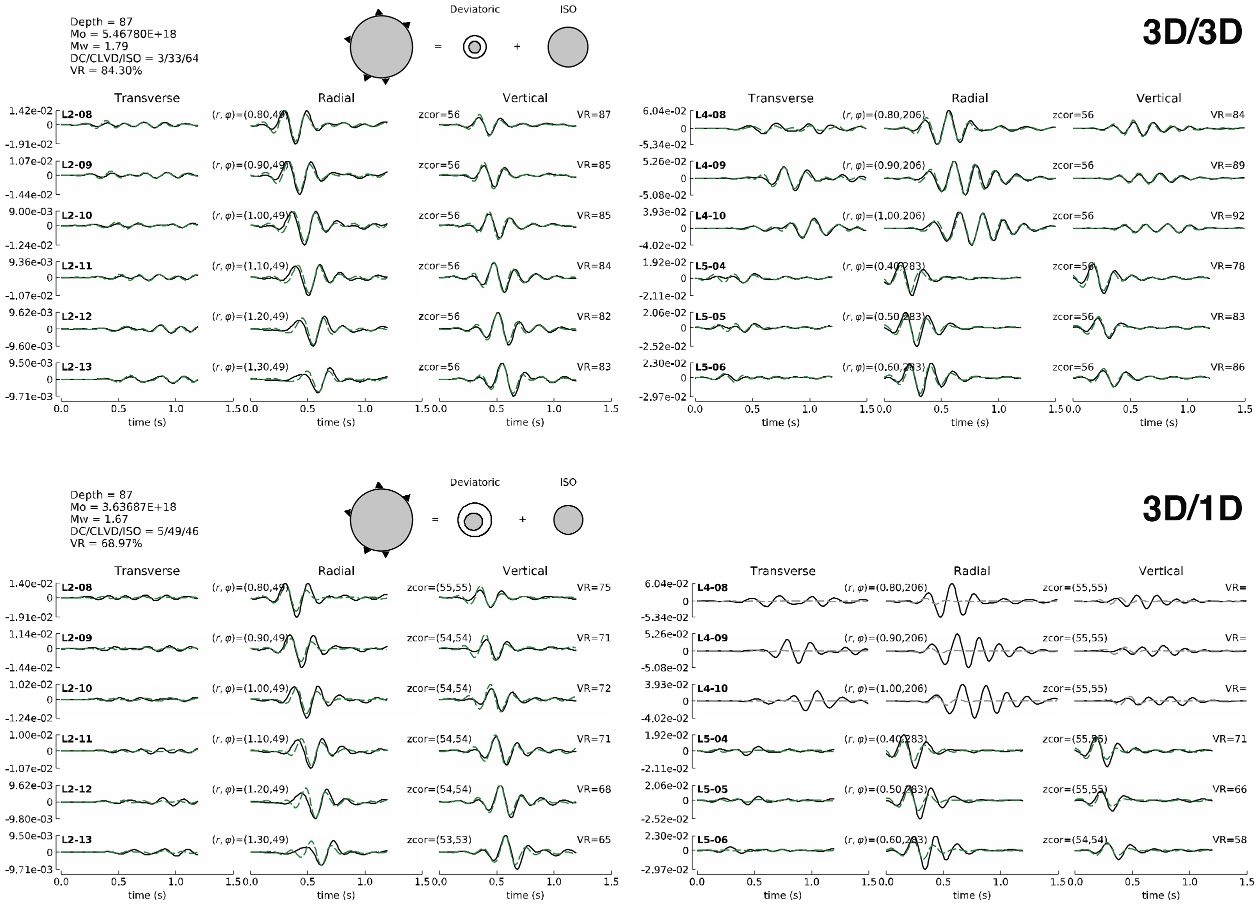

Figure 3. 3D and 1D moment tensor analysis of SPE-4P physics-based simulation. A subset of data (solid black) simulated from a physics-based explosion source model and propagated out to far-field distances using a 3D Earth model are plotted, as well as 3D (top, same model as data) and 1D (bottom) synthetics (dashed lines) predicted by the full mechanism. All data and synthetics are calculated with topography included and filtered between to 2 to 6 Hz. Refer to Figure 1 for additional description.

When velocity model errors are introduced in the MT analysis (Figure 3, 3D/1D) the deviatoric to isotropic moment ratio tends to increase. There is also a change in the orientation of the major vector dipole where it is no longer vertically-oriented and the MT source model also fails to predict wave propagation along paths where the 3D model diverges from a simple 1D granite model, such as stations along L4. MT analysis of the physics-based, simulated wavefield reproduce the result from the analysis of actual SPE Phase I experiments. It implies scattering and phase conversion from 3D heterogonies dominate the generation of far-field, low frequency (relative to near-field) transverse energy observed in data, and that the variability observed in the MT source model (Figure 1&2) are from inadequately accounting for wave propagation effects in the source inversion process.

Conclusions

A predominantly isotropic MT source model with a minor deviatoric component from 3D MT inversion best explains the observed far-field seismic wavefield produced by the SPE Phase I chemical experiments. Decomposition of the deviatoric component results in a combination of CLVD and normal mechanisms, and variability in the deviatoric component and the relative strengths of the MT elements are largely the result of inadequately accounting for 3D wave propagation effects in the source inversion process. S-wave generation in the far-field is dominated by scattering and phase conversion from 3D heterogeneities in the subsurface and not the MT source. These observations are supported by modeling of physics-based seismic wavefield simulations from hydrodynamic-to-elastic coupling in which the preferred MT source model for a realistic volumetric explosion with nonlinear source properties is predominately isotropic with a vertically-oriented CLVD in tension.

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