LA-UR-15-28388
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Intended for: Stanford Geothermal Workshop, 2016-02-22/2016-02-24 (Stanford, California, United States)

Issued: 2016-03-31 (rev.1)

PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Anisotropic seismic-waveform inversion: Application to a seismic velocity model from Eleven-Mile Canyon in Nevada

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Keywords: Fracture zone, anisotropic waveform inversion, modified total-variation regularization, geothermal energy exploration

ABSTRACT

Accurate imaging and characterization of fracture zones is crucial for geothermal energy exploration. Aligned fractures within fracture zones behave as anisotropic media for seismic-wave propagation. The anisotropic properties in fracture zones introduce extra difficulties for seismic imaging and waveform inversion. We have recently developed a new anisotropic elastic-waveform inversion method using a modified total-variation regularization scheme and a wave-energy-base preconditioning technique. Our new inversion method uses the parameterization of elasticity constants to describe anisotropic media, and hence it can properly handle arbitrary anisotropy. We apply our new inversion method to a seismic velocity model along a 2D-line seismic data acquired at Eleven-Mile Canyon located at the Southern Dixie Valley in Nevada for geothermal energy exploration. Our inversion results show that anisotropic elastic-waveform inversion has potential to reconstruct subsurface anisotropic elastic parameters for imaging and characterization of fracture zones.

1. INTRODUCTION

Imaging and characterizing fracture zone is important for geothermal exploration and optimizing enhanced geothermal systems, since the fracture zones provide paths for hydrothermal flow mobility in some situations, while in others, fractures can be effective barriers to geothermal flow. Alignment of fractures, fracture density and concentration of fractures lead to anisotropic propagation of seismic waves (e.g., Sayers and Kachanov, 1995; Ba et al., 2015). Imaging a complex fracture system is always a great challenge to seismic imaging and waveform inversion.

Full waveform inversion can extract quantitative information of geophysical properties from seismic data (e.g., Virieux and Operto, 2009; Tarantola, 1984, 1986). We have recently developed a new anisotropic elastic-waveform inversion (AEWI) method using a modified total-variation regularization scheme to directly invert elasticity parameters in heterogeneous and anisotropic elastic media (Gao et al., 2015). Seismic-waveform inversion with conventional Tikhonov regularization usually produces smoothed reconstruction results. The modified total-variation (MTV) regularization scheme (Lin and Huang, 2015) is used in the AEWI to preserve sharp interfaces and improve the reconstruction accuracy. A wave-energy-base precondition method is also employed to reduce the artifacts in the gradients caused by the geometrical spreading and defocusing effects (Zhang et al., 2012).

We apply our new anisotropic elastic-waveform inversion method to a seismic velocity model derived from a 2D active seismic data acquired at Eleven-Mile Canyon located at the Southern Dixie Valley in Nevada for geothermal energy exploration. The geophysical model is constructed based on petrologic information at a well log and a pre-stack migration image at the Eleven-Mile geothermal field. The model contains six stratigraphic layers and five fracture zones with widths of 50 m. We demonstrate that our new anisotropic elastic-waveform inversion method has potential to reconstruct subsurface anisotropic elastic parameters for imaging and characterization of fracture zones.

2. ANISOTROPIC ELASTIC-WAVEFORM INVERSION METHOD

We briefly describe the anisotropic elastic-waveform inversion (AEWI) method developed by Gao et al., 2015. The velocity-stress equations for wave propagation is given by (e.g., Carcione, 2015),

$$\frac{\partial \sigma}{\partial t} = C\Lambda^T v, \qquad \frac{\partial v}{\partial t} = \rho^{-1}\Lambda\sigma, \tag{1}$$

where $\sigma = (\sigma_{11}, \sigma_{33}, \sigma_{13})$ is the stress wavefield, $v = (\mathrm{v}_1, \mathrm{v}_3)$ is the particle velocity wavefield, ρ is the mass density of the medium, C is the elasticity tensor in Voigt notation defined as

$$C = \begin{pmatrix} C_{11} & C_{13} & C_{15} \\ C_{13} & C_{33} & C_{35} \\ C_{15} & C_{35} & C_{55} \end{pmatrix}, \tag{2}$$

and Λ is the differential operator defined as

$$\Lambda = \begin{pmatrix} \frac{\partial}{\partial x_1} & 0 & \frac{\partial}{\partial x_3} \\ 0 & \frac{\partial}{\partial x_3} & \frac{\partial}{\partial x_1} \end{pmatrix}. \tag{3}$$

Anisotropic elastic waveform inversion with modified total-variation regularization can help preserve sharp interfaces of subsurface structures and improve inversion accuracy (Lin and Huang, 2015). The misfit function of AEWI with MTV regularization is given by

$$E(\mathbf{m},\mathbf{u}) = \min_{\mathbf{m},\mathbf{u}}\{\| d - f(\mathbf{m}) \|_2^2 + \lambda_1 \| \mathbf{m}-\mathbf{u} \|_2^2 + \lambda_2 \| \mathbf{u} \|_{TV} \}, \tag{4}$$

where $\mathbf{m}$ is the model parameter vector including the density ρ and elastic parameters C_{ij}; $f(\mathbf{m})$ is the forward modeling wavefield for model $\mathbf{m}$; $\| \bullet \|_2$ stands for the L_2 norm; $\delta d = \| d - f(\mathbf{m}) \|_2^2$ is the data misfit; the regularization parameter λ_1 controls the trade-off between the data misfit term and the Tikhonov regularization term; and λ_2 balances the amount of interface-preservation in inversion. Equation (4) can be further decoupled into two minimization subproblems using and alternating minimization algorithm.

$$\mathbf{m}^{(k)} = \underset{\mathbf{m}}{argmin}\{E_1(\mathbf{m})\} = \underset{\mathbf{m}}{argmin}\{\| d - f(\mathbf{m}) \|_2^2 + \lambda_1 \| \mathbf{m} - \mathbf{u}^{(k-1)} \|_2^2\}, \tag{5}$$

$$\mathbf{u}^{(k)} = \underset{\mathbf{u}}{argmin}\{E_2(\mathbf{u})\} = \underset{\mathbf{u}}{argmin}\{\| \mathbf{m}^{(k)} - \mathbf{u} \|_2^2 + \lambda_2 \| \mathbf{u} \|_{TV}\}, \tag{6}$$

for iteration step k = 1, 2, …. These two subproblems play different roles: The first subproblem is to solve for $\mathbf{m}^{(k)}$ using a standard AEWI with the Tikhonov regularization and prior model $\mathbf{u}^{(k-1)}$; The second subproblem is to solve for $\mathbf{u}^{(k)}$ using a standard $L_2 - TV$ minimization method to preserve the sharpness of interfaces in inversion result $\mathbf{m}^{(k)}$.

A wave-energy-based precondition method is used to calculate the gradients (Zhang et al., 2012). The gradients are then regularized with the first-order Tikhonov term as described in equation (5). An anisotropic diffusion method (Grasmair and Lenzen, 2010) is used to remove unwanted artifacts in the gradients. The Polak-Ribiere formula (e.g., Norcedal and Wright, 2006) is employed to obtain the search direction in the $k-th$ iteration. A line search method is used to update the model. The step lengths are different for each parameter C_{ij}. The MTV regularization is implemented for each model parameter.

3. ANISOTROPIC INVERSION RESULTS

We apply our AEWI method to synthetic surface seismic data for a seismic velocity model with anisotropic fracture zones that is built along a 2D seismic survey line at Eleven-Mile Canyon. Figure 1 shows six elasticity models built based on the seismic velocity model and dipping angles of the fracture zones. We generate synthetic seismic data for 799 receivers with an interval of 10 m and 267 explosive sources with a source interval of 30 m along the top surface of the model.

For anisotropic elastic-waveform inversion, we smooth the six elasticity models (Fig. 2) over one wavelength for the center frequency of 10 Hz, and use the smoothed models as the starting models of the inversion. We present the misfits between the true models and the starting models for six elasticity parameters in Fig. 3. We perform the AEWI using the synthetic data and the starting models. Figure 4 shows the resulting inversion results with both the horizontal layers and fracture zones more manifested than the starting models (Fig. 2). The misfits of the six elasticity parameters shown in Fig. 5 are converging to those in Fig. 3 after 20 iterations. Figure 5 demonstrates that our AEWI method can reconstruct not only isotropic properties, but also anisotropic properties at the same time. Therefore, it has the potential to invert surface seismic data for anisotropic properties of fracture zones.

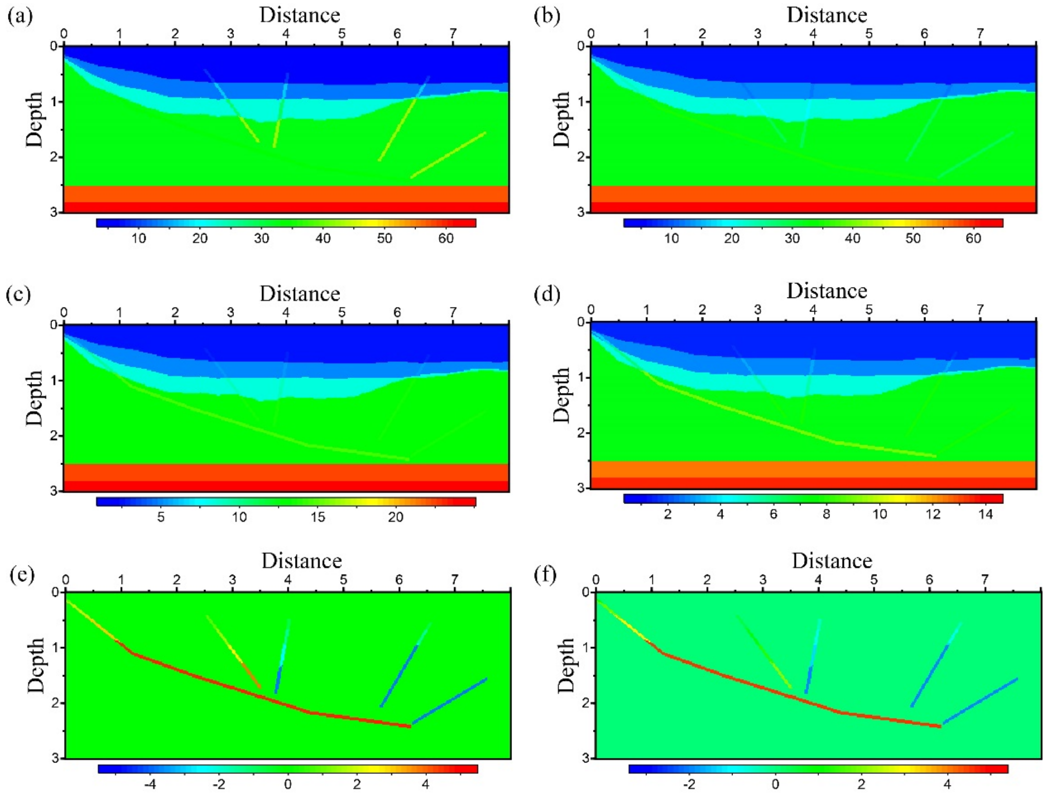

Figure 1: True models for AEWI built using geologic features and a prestack migration image along a 2D active seismic survey line at Eleven-Mile Canyon: (a) C_{11}, (b) C_{33}, (c) C_{55}, (d) C_{13}, (e) C_{15}, and (f) C_{35}. Unit is GPa.

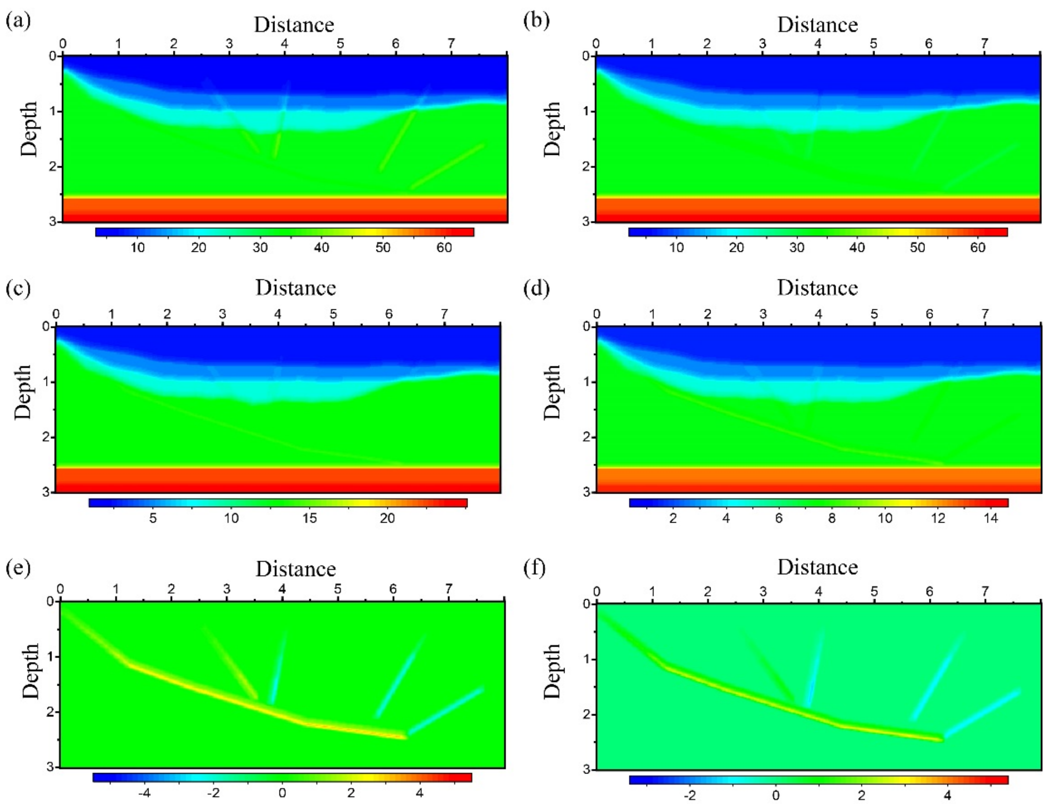

Figure 2: Initial models for AEWI obtained by smoothing those in Fig. 1: (a) C_{11}, (b) C_{33}, (c) C_{55}, (d) C_{13}, (e) C_{15}, and (f) C_{35}. Unit is GPa.

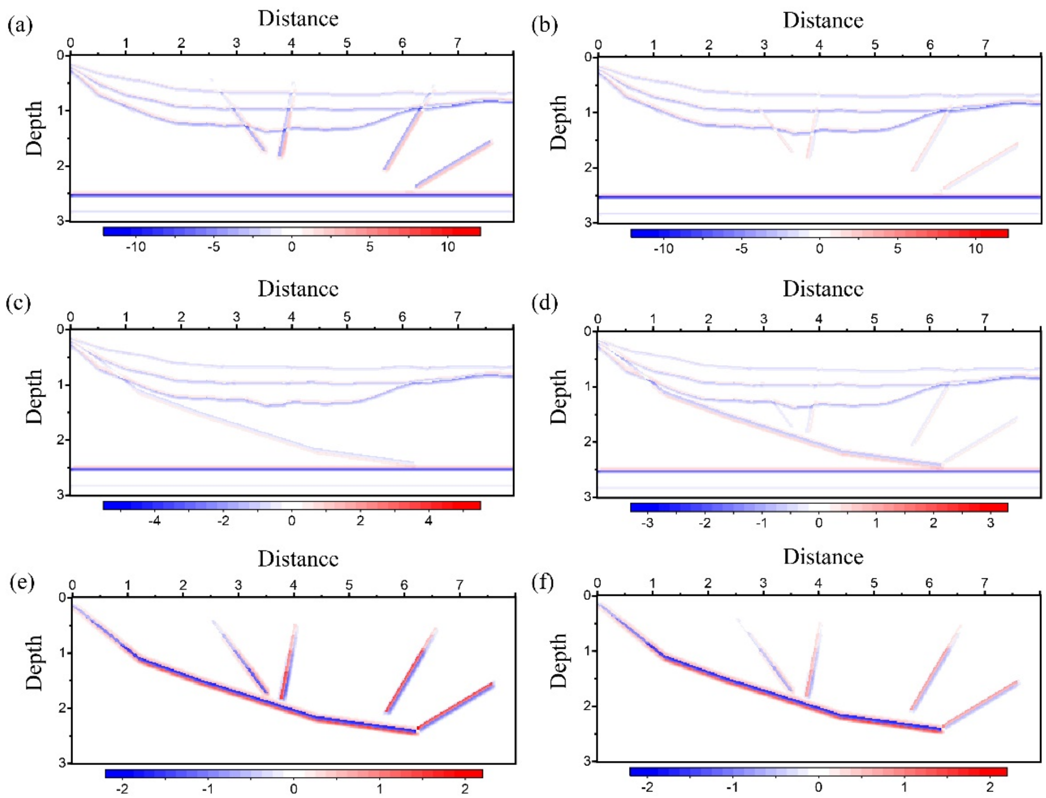

Figure 3: Model parameter misfits between the true models and the initial models of: (a) C_{11}, (b) C_{33}, (c) C_{55}, (d) C_{13}, (e) C_{15}, and (f) C_{35}. Unit is GPa.

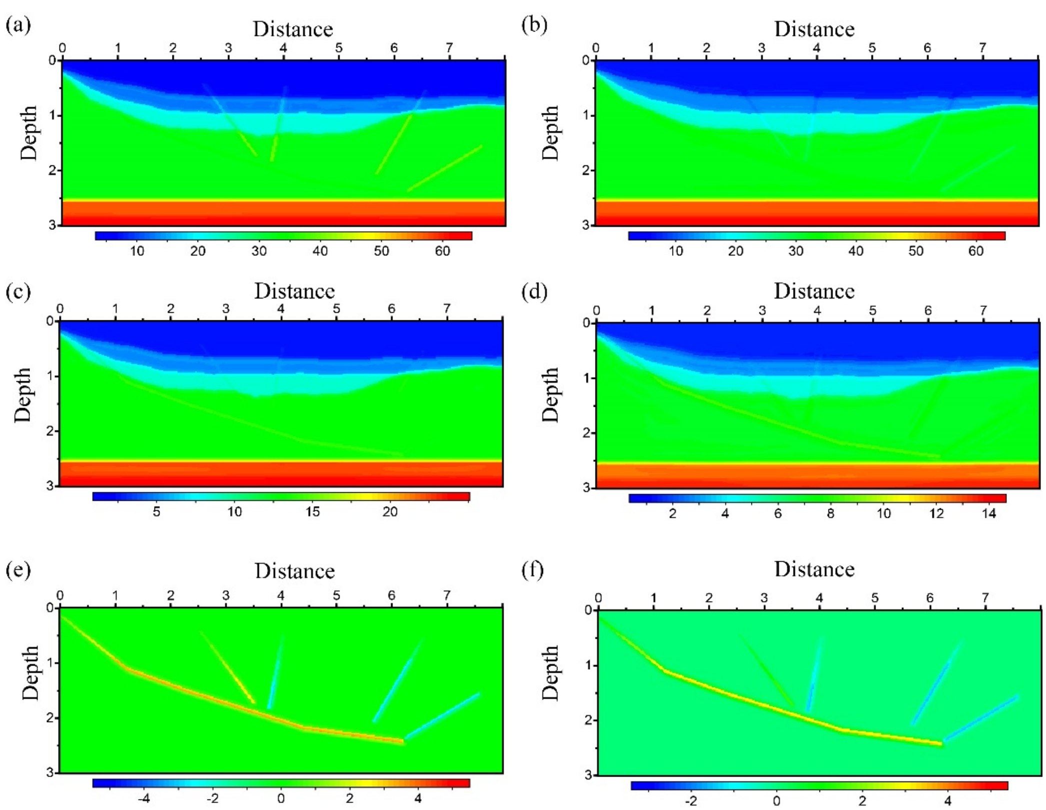

Figure 4: Anisotropic elastic-waveform inversion results of: (a) C_{11}, (b) C_{33}, (c) C_{55}, (d) C_{13}, (e) C_{15}, and (f) C_{35}. Unit is GPa.

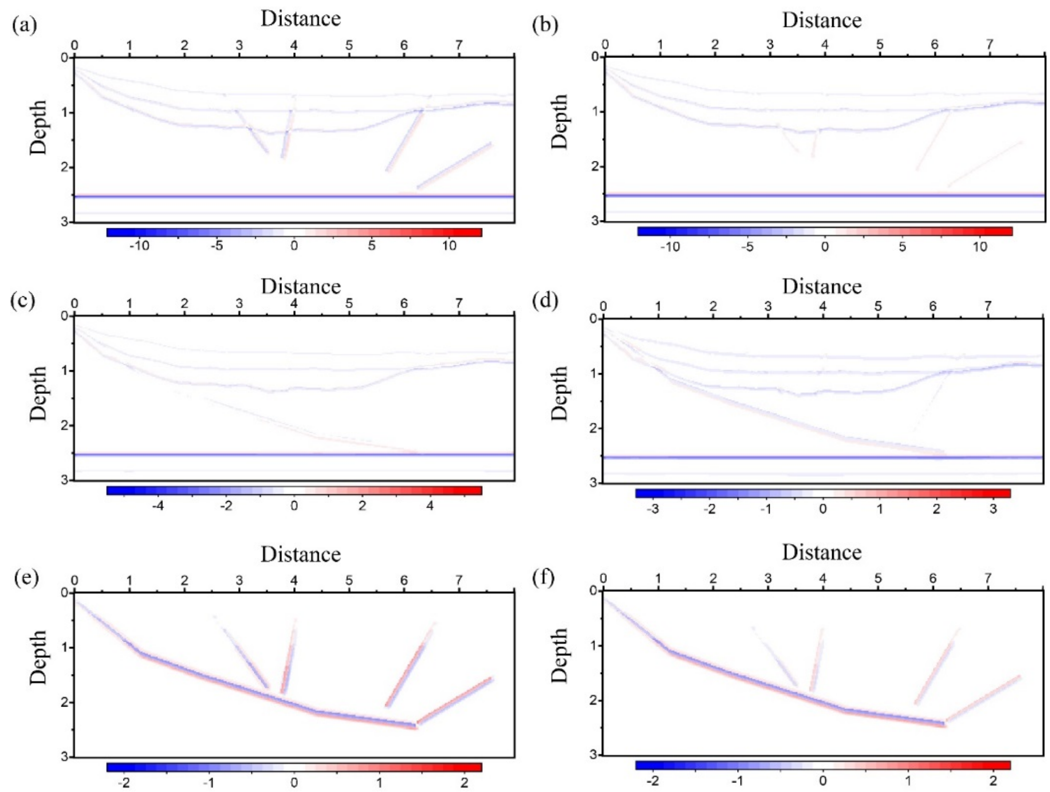

Figure 5: Model parameter misfits between the true models and the anisotropic elastic-waveform inversion results of: (a) C_{11}, (b) C_{33}, (c) C_{55}, (d) C_{13}, (e) C_{15}, and (f) C_{35}. Unit is GPa.

4. CONCLUSIONS

We have applied our newly developed anisotropic elastic-inversion method with a modified total-variation regularization scheme, to the synthetic surface seismic data for a seismic velocity model of Eleven-Mile Canyon at Dixie Valley in Nevada. The model contains several fracture zones with anisotropic properties. Our inversion results demonstrate that our inversion method can reconstruct isotropic elastic properties of the stratigraphic layers and anisotropic properties of fracture zones, illustrating the potential of our inversion method for fracture imaging and characterization.

ACKNOWLEDGEMENTS

This work was supported by the Geothermal Technologies Office of the U.S. Department of Energy through contract DE-AC52-06NA25396 to Los Alamos National Laboratory. The computation was performed on super-computers provided by the Institutional Computing Program of Los Alamos National Laboratory.

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